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Andris Ratkus

ANALYSIS OF MATERIAL SURFACE RENEWAL TECHNOLOGIES AND RESEARCH OF LASER CLADDING TECHNOLOGY

Summary of the Doctoral Thesis

RTU Press
Riga 2020

RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Mechanics and Mechanical Engineering

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Summary of the Doctoral Thesis

Scientific Supervisor
Professor Dr. sc. ing.
TOMS TORIMS

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I extend my thanks to Gatis Muižnieks for his support and assistance in preparing this Doctoral Thesis. Above all, my thanks go to the supervisor of the scientific work Professor Toms Torims who devoted great effort and attention to this work during the process of writing and defence.

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 25 November 2020 at 13:00 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6B Kipsalas Street, Room 417.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Andris Ratkus ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian, it contains an introduction, 7 chapters; conclusions; 21 appendix; 64 figures; 27 tables; the total number of pages is 129. The Bibliography contains 60 titles.

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ABBREVIATIONS AND SYMBOLS

Abbreviations

ANOVA – analysis of variance technique;
COAX12 – Fraunhofer IWS coaxial laser nozzle;
COAXid – Fraunhofer IWS bore cladding nozzle;
F – flat cladding position;
MAG – metal active gas welding;
OH – overhead cladding position;
VD – vertical down cladding position;
VU – vertical up cladding position.

Symbols

A_{b} – melting area, mm^2;
A_{c} – cladding area, mm^2;
A_{cMod} – calculated cladding area, mm^2;
α – nozzle angle, °;
Ar – argon;
A_{vc} – effective cross-sectional area, mm^2;
CO_2 – carbon dioxide;
C_{v} – cladding efficiency index, %;
D_{c} – dilution, %;
E_{pm} – powder cladding efficiency, %;
E_{w} – wire cladding efficiency, %;
F_{pm} – powder feed, g/min;
f – cladding nozzle track distance, mm/rev;
L_{p} – laser spot diameter, mm;
G – laser cladding impact parameter, $\frac{\mathrm{W \cdot g}}{\mathrm{mm^3}}$;
G_{izm} – correction value of laser cladding impact parameter, $\frac{\mathrm{W \cdot g}}{\mathrm{mm^3}}$;
H – cladding thickness, mm;
H_{diff} – height difference between maximum and minimum thicknesses, mm;
H_{kontr} – actual cladding thickness in process, mm;
H_{max} – maximal cladding thickness, mm;
H_{min} – minimal cladding thickness, mm;
HV – micro-hardness according to the Vickers scale – 200 g – HV 0,2, kg/mm^2;
I_{av} – actual process current, A;
I_{LP} – laser power intensity, W/mm^2;
I_{PF} – powder feed intensity, %;
K_{pos} – nozzle position coefficient for laser cladding characteristics;
η – energy transmission efficiency (MAG $\eta = 0{,}8$);

p – penetration depth, mm;
P – laser power, W;
P_{izm} – laser power correction value, W;
s – standard deviation;
S – laser point area, mm^2;
$s_{\mathrm{Ac\ vid}}$ – arithmetic mean standard error;
ρ – density, g/mm^3;
Q – amount of heat, J/mm;
$S_{0.8\mathrm{st}}$ – cladding wire cross-section area, mm^2;
T_{A} – numerical value of cladding bath environment;
U – voltage, V;
U_{av} – actual process voltage, V;
v – cladding speed, m/min;
v_{izm} – cladding speed correction value, m/min;
V – coefficient of variation, %;
w – wire feed rate, m/min;
W_{c} – cladding width, mm;
w/v – material amount coefficient.

GENERAL CHARACTERISTICS OF THE DOCTORAL THESIS

Novelty of the Subject

There is a growing industrial demand for surface renewal and modification technologies that restore and improve the performance characteristics of components. Similarly, cladding is gaining popularity because cladding technology offers the potential for local, lower-cost, technology-based overlays that make it possible to renew and even improve the surface performance characteristics of the original material.

Material surface renewal technologies are applied to both external and internal surfaces to prevent mechanical damage or deterioration of re-usable products and thereby avoid the need to purchase new, expensive equipment. In turn, improving the surface treatment of materials reduces the recurrence of further defects and ensures longer performance of the industrial equipment.

MAG cladding technology, which has been tested and is accessible, is still relevant for renewing the damaged material of external and internal surfaces, including cylinder bores. A significant step forward in the industry is laser cladding technology whose versatility has led to its fast-growing usage in an increasing number of applications. The main advantages of laser cladding technology are its high and easily controlled energy density along with is short processing time. Laser cladding technology is suitable for a wide range of materials, results in a smaller heat-affected area and offers an excellent degree of cladding coalescence.

Laser cladding is popular for modifying the external surfaces of new products, but as the technology has become more accessible, it is also being used more widely for repairing metal products. As this is a relatively new, modern, repair and renewal technology, research into its use for renewal is being promoted in order to identify technologically sound solutions and technological options.

Research work for this Doctoral Thesis provided the opportunity to develop laser cladding and MAG cladding technology with scientifically sound characteristics, which enables the manufacturer to develop a cladding layer with the required specifications.

The research into renewal technology carried out under this Doctoral Thesis enables the scientifically based applicability of laser cladding and MAG cladding technologies to be expanded by evaluating the influence of technological parameters on cladding characteristics. It thus provides a significant contribution to the field of mechanical engineering science.

Goal and Tasks of the Work

The goal of the Doctoral Thesis “Analysis of Material Surface Renewal Technologies and Research of Laser Cladding Technology” is to find out the influence of MAG and laser cladding technological parameters on the cladding characteristics, to compare technologies, and to draw up the mathematical expressions for predicting characteristics. To achieve this goal, the following tasks were defined.

1. To carry out analysis of available surface renewal technologies.
2. To perform cladding experiments and analyse the results to determine the dependence of the laser cladding characteristics on the cladding position and nozzle angle. To compare the results of the MAG and laser cladding experiments.
3. To test the hardness of the cladding and determine the factors influencing hardness in laser cladding.
4. To develop mathematical expressions for predicting characteristics of the cladding technology and compare them with the results of the experiment.
5. To provide recommendations for the practical application of the technology for cladding external and internal surface materials.

Hypothesis

Laser cladding with powder can be successfully implemented in the flat (F) and overhead (OH) positions, and the results obtained are predictable and purposeful.

Research Methods

The Doctoral Thesis used both qualitative and quantitative research methods, which enabled a comprehensive and scientifically substantiated performance of the tasks set out and achievement of the stated goal.

During the cladding experiment, the influence of technological parameters on the formation of the cladding characteristics was tested. The results of the experiment were used to develop mathematical expressions for predicting characteristics. The calculation of laser cladding characteristics was validated using the correlation coefficient square R^2. In turn, mathematical statistical methods *SYSTAT* and *Excel* software were used for processing data from the MAG and laser cladding experiments.

The equipment used in the study included the cladding process monitoring system *E-MAqS* (Fraunhofer IWS, Germany), the laser beam analyzer Primes Laser Diagnose Focus Monitor FM (Primes, Germany), and the welding equipment FRONIUS TransPlus Synergic 3200 (FRONIUS, Austria). The results have been determined by samples, analysing cross-sections that had been ground, polished and treated with copper chloride (10 % $CuClNH_4Cl$ solution in water), and photographed with a reference ruler using a KEYENCE VHX digital microscope followed by data processing using *SolidWorks*. In turn, the hardness of the cross-sections of the samples was determined using the INNOVATEST NEXUS 4000^{TM} equipment.

Scientific Novelty

In the Doctoral Thesis, the mathematical expressions for predicting the cladding characteristics (A_c, H_min, H, and D_c) were developed using the technological parameters of cladding. The mathematical expressions presented are relevant for future scientific research and practical work and are adaptable to different types of cladding applications. Importantly, the previously unpredictable aspects of laser cladding have been investigated by monitoring the nozzle angle (α) and the influence of the cladding positions: flat F, vertical up VU, overhead OH, and the vertical down VD on the cladding characteristics. In a manufacturing context, it provides the ability to define characteristics in all cladding positions with different nozzle angles, which is important in real working conditions where access to the cladding area is difficult.

A new, previously unused laser cladding impact parameter G (W·g/mm^3) for describing the technological parameters used to define cladding characteristics has been introduced in laser cladding technology. Along with this, theoretical expressions for calculating and correcting technological parameters during the process have also been developed.

The results of the Doctoral Thesis offer a new contribution to the discipline of mechanical engineering science in the field of engineering, to the development of bore cladding and to cladding technology in general.

Author's Defence

The author of the Doctoral Thesis analysed the influence of the nozzle angle and position on the cladding, which has not been studied before that justifies the scientific novelty of the work. The author defends the following:

1) introduction of the laser cladding impact parameter (G) and its application for the prognosis of characteristics;
2) mathematical expressions for the calculation of cladding characteristics (A_c, H, H_min and D_c);
3) mathematical expressions for calculating and correcting cladding technological parameters;
4) recommendations for practical application and refinement of cladding technologies.

Practical Application

The results of the Doctoral Thesis are of practical importance to Latvian and European companies, which use external surface and internal surface cladding technologies, especially companies that specialise in cylinder bore renewal technologies. It contributes to the development of mechanical engineering technologies providing predictable values for cladding characteristics. The obtained data considerably facilitates the development of the technological process and its practical application. The obtained information, data, and knowledge are applicable in a wide range of surface cladding contexts, since the work not only identifies the technological parameters of the cladding but also the influence of the nozzle angle and position on the characteristics of the cladding.

The results of the research are applicable not only to repair technology but also more generally for the introduction of advanced laser cladding technology in production, to bring about essential improvements in the end product's performance for relatively inaccessible cladding areas.

Approbation of the Work

Approbation of the work has been achieved through oral presentations at international scientific conferences.

1. *ASME* 2014 *International Mechanical Engineering Congress & Exposition, IMECE2014*, 14–20 *November* 2014, *Montreal, Quebec, Canada*. *Danube Adria Association For Automation & Manufacturing – DAAAM International Vienna*, 24–27 *October* 2012, *Zadar, Croatia*.
2. *Technische Universität Dresden, Fraunhofer-Institut für Werkstoff- und Strahltechnik IWS Dresden. Summer School: Trends and new developments in Laser Technology*, 27–31 August 2012, *Dresden, Germany.*
3. *8th International Conference of DAAAM Baltic Industrial Engineering,* 19–21 *April* 2012, *Tallinn, Estonia*.

Publication in Indexed Scientific Journals

1. Ratkus, A., Torims, T. Powder Laser Cladding Position Impact on Results and Result Prediction. *Proceedings of the Estonian Academy of Sciences*. 2020, Vol. 69, Issue 3, pp. 257–265.
2. Torims, T., Pikurs, G., Ratkus, A., Logins, A., Vilcāns, J., Škļariks, S. Development of Technological Equipment to Laboratory Test In-situ Laser Cladding for Marine Engine Crankshaft Renovation. *Procedia Engineering*. 2015, Vol. 100, pp. 559–568.
3. Torims, T., Ratkus, A., Zariņš, M., Brutāns, V., Vilcāns, J. In-Situ Laser Build-Up Welding of Shipboard Crankshafts. *Applied Mechanics and Materials*. 2012, Vol. 234, pp. 39–46.
4. Torims, T., Ratkus, A., Vilcāns, J., Zariņš, M., Rūsa, A. Analysis of In-Situ Renewal Technology for the Backhoe Bucket Bores. *Journal of International Scientific Publications: Materials, Methods & Technologies*. 2011, Vol. 5, Part 2, pp. 270–289.
5. Torims, T., Ratkus, A., Vilcāns, J., Zariņš, M., Rūsa, A. Analysis of the Impact of In-Situ Repair Technology on the Surface Integrity of Excavator Bucket Bores. *Applied Mechanics and Materials*. 2011, Vol. 87, pp. 113–118.

Publication of the Full Text Article

1. Torims, T., Pikurs, G., Ratkus, A., Logins, A., Vilcāns, J., Škļariks, S. Development of Technological Equipment to Laboratory Test In-situ Laser Cladding for Marine Engine Crankshaft Renovation. *Procedia Engineering*. 2015, Vol. 100, pp. 559–568.
2. Ratkus, A., Torims, T. Mathematical Model of the Influence of Process Parameters on Geometrical Values and Shape in Mig/Mag Multi-Track Cladding. *Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition. Vol. 2A: Advanced Manufacturing* . Montreal, Quebec, Canada. 14–20 November 2014.
3. Torims, T., Bruckner, F., Ratkus, A., Fokejevs, A., Logins, A., The application of laser cladding to marine crankshaft journal repair and renovation. *Proceedings of the*

ASME 2014: 12th Biennial Conference on Engineering Systems Design and Analysis – ESDA 2014. Copenhagen, Denmark, 25–27 June 2014. New York, American Society of Mechanical Engineers. 2014, pp. 001–010.

4. Ratkus, A., Torims, T. Research on the bucket bore renewal technologies. *Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium.* Zadara, Croatia, 24–27 October 2012. Vienna, Austria. 2012, pp. 675–678.
5. Ratkus, A., Torims, T., Gutakovskis, V. Research on Bucket Bore Renewal Technologies. *Proceedings of 8th International Conference of DAAAM Baltic "Industrial Engineering"*. Tallinn, Estonia, 19–21 April 2012. Tallinn University of Technology. 2012, pp. 222–226.
6. Torims, T., Vilcāns, J., Zariņš, M., Ratkus, A., Rūsa, A. Comprehensive Analysis of the New In-Situ Crankshaft Crankpin Bearings Renovation Technology for Sea Going Ships. *Applied Mechanics and Materials Conference (ASME 2011): Proceedings*. United States of America, Chicago, May 30 to June 1, 2011, ASME. 2011.
7. Torims, T., Geriņš, Ē., Ratkus, A., Zariņš, M., Brutāns, V. Shipboard Crankshaft Bearing In-Situ Repairs Utilizing Laser Build-Up Welding. *Annals of DAAAM & Proceedings 2011: The 22nd DAAAM World Symposium*. Vienna, Austria, 23–26 November 2011, DAAAM International. Vienna. 2011, pp. 597–598.
8. Torims, T., Ratkus, A., Vilcāns, J., Zariņš, M., Rūsa, A. Analysis of the Impact of In-Situ Repair Technology on the Surface Integrity of Excavator Bucket Bores. *International Conference on Applied Mechanics and Manufacturing Technology (AMMT 2011): Proceedings.* Bali, Indonesia, 4–5 August, 2011. 2011, pp. 113–118.

These publications are directly related to the research carried out in the Doctoral Thesis; altogether, the author of the Thesis has contributed to 20 scientific publications.

1. ANALYSIS, IMPROVEMENT AND EQUIPMENT OF MATERIAL SURFACE RENEWAL TECHNOLOGIES

Material Surface Renewal Technology

The author is working in the field of industrial machinery repairs and his experience has shown that maintenance is not only replacement of worn parts but sometimes, for economic reasons, it may also be necessary to repair the damaged equipment. Such repairs are often carried out by welding technology by replacing and reinforcing the damaged structural elements. There are also surface restoration repairs that restore the material layer with cladding technology for external and internal surfaces – bores.

Renewal of bores must be carried out precisely because the cladding must provide a new layer of material, which after machining creates a new, precisely dimensioned fit. Basically, these bore fitting points are components of larger equipment items, such as a hull, frame, boom or clamshell, where a damaged bore leads to wider equipment damage. The renewal of bores is technologically complicated, because the bore has limited access, which makes controlling of the cladding dimensions complex, and because the location of the bore – the cladding position – depends on its position within bulky industrial equipment. Consequently there are situations, when the bore is horizontal and the cladding is carried out in a spiral where the cladding position changes cyclically between flat cladding (F), vertical up (VU), overhead (OH) and vertical down (VD) positions.

Specialist mobile devices placed on the damaged machinery are used in bore renewal. Before the new layer is formed, the damaged area is milled to obtain a cylindrical surface. Subsequently, the surface of the material is renewed by continuous spiral cladding. Lastly, post-processing is performed, to achieve the required bore size.

Thanks to “Alfis” Ltd. the author had access to internal cylindrical surface renewal technology that applies a new material layer by means of MAG cladding technology. MAG technology is used for bore cladding, as it is affordable, reliable and self-proving. In addition, the author developed Master’s Thesis [2] on MAG cladding technology, which concludes that cladding offers better mechanical properties than base material S355J2 (LVS EN10149-3).

The most complicated application of surface renewal technology is in bore renewal where the operation of creating a new material layer is most important and which to the author’s knowledge has not been researched before. Therefore, this work focuses only on the operation of creating a new layer of material.

Necessity of Improvement of Renewal Technologies

The repair-technology industry has an interest in developing material surface renewal technologies using which renewal and upgrading of materials is economically and technologically viable [5], [14], [22]. Development in repair technologies provides cheaper and more affordable solutions that improve the demanded service. In addition, the industry is interested in developing flexible repair technology to provide a wide range of high-quality services and different repairs that can be performed with a single technological device. It can be developed, improved and, if necessary, adapted in the restoration of internal and external surfaces by renewing bores, plain bearings, guides, and large external fastening elements.

It is essential to improve the quality of renewable products because when the equipment needs to be repaired it can be concluded that the original did not provide the required performance. In addition, if the top layer is renewed and improved (wear and corrosion resistance, etc.), the need for repeated repairs reduces, which increases the demand for effective repair technology and thus proves its economic justification. These improvements are relevant given that industrial equipment is being used in aggressive environments: in port areas, to transport mineral waste, in metallurgy, quarrying, etc.

One area of great potential is the renewal of sliding bearings used for ground excavation, port cargo loading and manufacturing equipment, as well as shipbuilding and oil extraction platforms, which could significantly expand the applications of renewal technologies. For sliding bearings, it is essential to provide abrasion resistance of the overlay material [10], [13]. Such applications of technologies would potentially enable the provision of *in-situ* repair for large and difficult-to-replace plain bearings.

In addition, in these areas there is a high demand for the renewal of small and locally damaged bores, where damaged areas require surface cladding of restricted (up to 1 mm) heights. Local damage – scratches, dents or corrosion [20] – are eliminated by precisely-oriented cladding, in terms of the precision of the melt pool geometry and the intensity of the supplied power. In this way, preventive repairs can be made to forestall major damage to the equipment providing the shortest mechanical shutdown possible or avoiding it entirely. It is essential to conduct this type of repair with a small heat-affected zone (*HAZ*), reducing the residual stresses in the base material. Furthermore, providing a 5 % to 10 % degree of dilution (D_c) ensures optimal cladding and base material intermingling to avoid a decrease in the cladding material-technical benefits [16]. Research on local damage repairs was not undertaken in this work, but given their importance in the industry, it was taken into account that there is a possibility of such specialization when choosing the technology.

Cladding Technologies

Specialist cladding materials are available for MAG technology, but the available technological equipment is designed for use with 0.8 mm diameter wire, which limits the use of specialist wires, as these are mostly available in 1.2 mm and 1.6 mm diameters [30]–[32]. It is known that MAG cladding technology results in significant permeation, which ensures high D_c, making its application difficult for local cladding. Also, the MAG cladding technology provides a 2 mm to 4 mm thick cladding layer, which is both technologically and economically unreasonable for local, small-scale cladding, as a significant material layer has to be removed during after-treatment [2], [16].

Therefore, in order to provide a wider range of possibilities for the application of various specialist, customized, and composite cladding materials, it is necessary to use powder cladding. It offers a broader scope of material choices and combinations [16]. In industry, varios technologies are used with powder, but the most suitable technology for creating a new material layer is laser cladding technology taking into account technological developments and prospects. Laser cladding is used to apply corrosion-resistant and abrasion-resistant surface coatings, which can be of a thickness of 0.5 mm to 8.0 mm [16]. Laser cladding opportunities for the present study were provided under the traineeship at the Fraunhofer IWS Institute. In view of the above, the experiments for the Thesis were performed using powder laser cladding technology (hereinafter "laser cladding technology"). The tested MAG cladding technology basically serves as a reference technology to compare the obtained results with the laser cladding technology.

Review of the MAG and Laser Cladding Technologies Literature

An in-depth review of the sources of the MAG and laser cladding technologies was undertaken, identifying ranges of technological parameters, potential research directions and the available technological equipment. In the sources for both MAG technology [7], [19] and laser cladding technology [6], [11], [26]–[28], only studies on the individual geometry of the cladding were found, which was applied to the outer surface in a flat (F) position with a perpendicular nozzle angle ($\alpha = 90°$). No studies are available on the cladding of bore surfaces and areas.

Looking at the sources for MAG cladding technology [7], [19], it has been concluded that the cladding experiment developed in the Master's Thesis [2] was conducted on a reasonably wide range of materials and that the samples obtained are qualitative. However, the results of the source [2] do not address the values of the cladding (A_c) and permeation (A_b) area needed in order to determine the degree of dilution (D_c). Therefore, the samples created in this work [2] were re-examined to provide a detailed determination of sample characteristics using a more versatile dimensioning method.

The ranges of technological parameters offering good results as used in the literature reviewed are summarized in Table 1.1. These parameter ranges have been respected in experimental work where the technological parameters of the laser cladding were initially compared with the technological parameters of the MAG cladding in order to ensure the comparability of the technologies.

Table 1.1

Experimental Range of Technological Parameters

MAG Cladding Technology [2]			
U, V	v, m/min	–	w, m/min
16–22	0.5–0.8	–	3.5–10.5
Laser Cladding Technology			
P, W	v, m/min	L_P, mm	F_pm, g/min
1100–2000	0.5–0.8	4	10–33

Available Technological Equipment for Laser Cladding

An analysis of the laser cladding literature has shown that there are different laser cladding nozzles, which differ mainly by the type of material fed and the method of feeding the material. Nozzles are mainly developed to improve cladding productivity, efficiency and applicability. The most advanced are universal surface cladding nozzles, which are the most widely used, but bore cladding equipment is also available [33].

During the traineeship, the Fraunhofer IWS Institute provided world-class laser cladding equipment, including the COAXid bore cladding nozzle. It was decided not to use this specialized nozzle for experimental work, since the nozzle angle in relation to the workpiece cannot be modified and the OH positioning of the equipment is dangerous. The risk arises from the nozzle being perpendicular to the cladding surface as well as the nozzle's optical elements, the visor and mirror, being very close (30 mm to 35 mm) to the cladding area. Consequently, in the OH position, the unused powder combined with the laser's reflecting rays could in all probability damage the optics. Therefore, the universal cladding nozzle COAX12 was used where the distance between the cladding area and the nozzle and its optical elements is approximately 200 mm. The nozzle is suitable for cladding complicated configurations due to the variability of the nozzle angle (α), but the nozzle is not designed for bore cladding. Therefore, when using a COAX12 nozzle, the cladding in the essential bore positions (F–VU–OH–VD) was performed individually with a fixed nozzle position on a flat sample, the nozzle position being fixed throughout the sample cladding time. But to avoid the risk of damage to the equipment when working with the COX12 nozzle, the OH position cladding was simulated by changing the nozzle's angle of inclination ($\alpha = 36°$), which is identical to the angle of the MAG experiment nozzle, in order to allow comparison of the results; also in positions F, VU and VD an identical nozzle angle was used. The influence of nozzle angle (α) variations on cladding characteristics was tested in experimental work and has extended the amount of information obtained.

In the reviewed literature only the flat (F) position with a perpendicular ($\alpha = 90°$) angle of the cladding nozzle in relation to the workpiece was used to perform experiments. From this and the author's practical experience, **the hypothesis of the Doctoral Thesis** is put forward: laser cladding with powder can be successfully performed in flat (F) and overhead (OH) positions, and the results obtained are predictable and purposeful.

2. IDENTIFICATION OF CLADDING PARAMETERS AND CHARACTERISTICS

This chapter identifies the technological parameters and characteristics of cladding, which were applied and controlled in the experimental work. The parameters of the MAG and laser cladding technologies are mutually comparable to ensure mutual mathematical comparison of technologies under consideration.

Technological Parameters

Variations in the cladding voltage (U, V) and wire feed (w, m/min) using FRONIUS TransPlus Synergic 3200 welding equipment were applied in the MAG cladding experiment. Also in the experimental work, the cladding speed (v, m/min) and a constant cladding nozzle track distance (f, mm/rev) were provided by the SUPERCOMBINATA 40/1 equipment.

For the laser cladding experiment, the Laserline GmbH: LDF 20000–200 power source was used to provide laser power (P, W), the KUKA Roboter GmbH manipulator KR 60 HA managed the cladding speed (v, m/min) and the track distance (f, mm/rev), whilst the powder feed (F_{pm}, g/min) was controlled by the GTV GmbH MF–PF2/2 powder feed device.

Parameters of the Cladding Process

The process descriptive parameters that have been provided or calculated from the available information in the experimental work are summarized.

Amount of cladding thermal energy (Q, J/mm) describes the amount of energy supplied to the base material. For the MAG technology, Q is determined by Eq. (2.1), knowing the average voltage U_{av}, amperage I_{av}, and cladding speed v values. For the laser cladding technology, Eq. (2.2) is used [8], [18].

$$Q = \eta \frac{60 U_{\mathrm{av}} I_{\mathrm{av}}}{v}. \tag{2.1}$$

$$Q = \frac{60P}{v}. \tag{2.2}$$

Cladding conditions is a recording of the temperature of melt pool by means of the *E-MAqS* system. The system records the image element during the laser cladding process – the number of pixels (T_A) at which the temperature is the same or higher than the set temperature. The information gathered reflects the temperature distribution and conditions of the melting pool.

The laser intensity (I_{LP}, W/mm^2) describes the distribution of laser power to the laser point projected onto the workpiece. Basically, I_{LP} depends on laser power (P) and the area of the laser spot on the workpiece surface.

Powder flow rate (I_{PF}, %) describes the amount of powder that is applied to the base material, in the melting pool – within the laser point, in relation to the total amount of powder applied, expressed as a percentage.

Cladding Characteristics

Thickness of the cladding (H, mm). We also determined the minimum H_{min}, describing minimal possible area cladding thickness, the maximum cladding height H_{max}, and the height difference H_{diff} between the two.

The cladding efficiency index (C_{v}, %) represents the effective cross-sectional area (A_{vc}, mm^2) – the cladding area under H_{min} and the ratio to the entire cladding area (A_{c}, mm^2) (Eq. (2.3)).

$$C_v = \frac{A_{\mathrm{vc}}}{A_{\mathrm{c}}} \cdot 100. \tag{2.3}$$

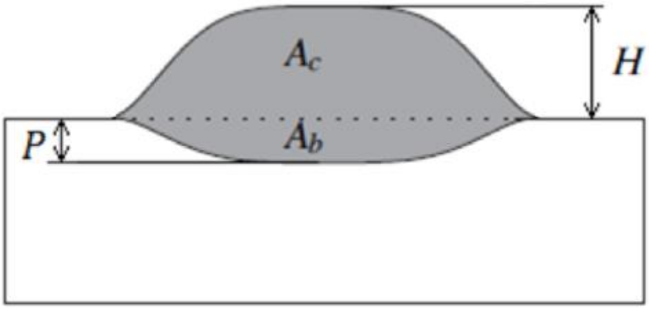

Fig. 2.1. Cross-section of the cladding [12].

The melting depth (*p*, mm) (Fig. 2.1).

The cladding dilution (D_{c}, %) is determined by Eq. (2.4), knowing the melting area (A_{b}, mm^2) and A_{c} (Fig. 2.1) [12].

$$D_{\mathrm{c}} = \frac{A_{\mathrm{b}}}{A_{\mathrm{b}} + A_{\mathrm{c}}}. \tag{2.4}$$

Hardness of the cladding cross-section (HV, kg/mm^2) or HV describes the layer of the new material and the mechanical properties of the base material.

Mathematical Alignment of Technological Parameters of Cladding Technologies

The cladding technology experiment was carried out using the technological parameters listed in Table 1.1 and within the specified ranges. As mentioned above, for the two technologies to be mathematically comparable – making it possible to evaluate the advantages and drawbacks of each technology – the theoretical alignment of the laser cladding technology parameters with the MAG parameters was achieved.

Power P for laser cladding is determined by Eq. (2.5), knowing the energy transmission efficiency of the arc MAG technology η, U_{av} and I_{av}:

$$P = \eta U_{\mathrm{av}} I_{\mathrm{av}}. \tag{2.5}$$

The amount of powder supplied to the laser cladding process (F_{pm}, g/min) equates to the volume of the MAG wire feed using Eq. (2.6), where the density of the cladding material (ρ, kg/m^3), wire field ($S_{0.8\mathrm{st}}$, m^2), wire feed (w, m/min), wire (E_{w}), and powder cladding efficiency (E_{pm}) must be known.

$$F_{\mathrm{pm}} = \frac{1000 \rho S_{0.8\mathrm{st}} w E_{\mathrm{w}}}{E_{\mathrm{pm}}}. \tag{2.6}$$

The work identifies the characteristics of cladding, which best describe the cladding, its geometry, and its mechanical characteristics. It has been found that the MAG and laser cladding technologies are theoretically mathematically comparable, because the technological parameters are comparable and the determined characteristics of the cladding match up.

3. MAG CLADDING EXPEREMENT

In this chapter, a thorough analysis of the cladding samples developed in Master’s Thesis [2] has been carried out to determine the characteristics of cladding (Chapter 2). The experiment [2] was carried out with the aim of finding out the influence of the detailed technological parameters on the characteristics of cladding. The data obtained in the analysis of samples is useful to compare the two technologies used, as well as to form the basis for the development of mathematical expressions for predicting the characteristics of cladding.

Equipment, Parameters and Materials of MAG Experiment

The experiment was performed with FRONIUS TransPlus Synergic 3200 welding equipment and SUPERCOMBINATA 40/1 mobile renewal equipment. The experiment followed the technological parameter ranges listed in Table 1.1 with a constant f = 2.8 mm/rev.

The cladding experiment was conducted in line with the diagram shown in Figure 3.1 by creating the cladding on a continuous spiral that evenly covers the cylindrical surface. The source [2] samples were made only in the cladding position F with $\alpha = 90°$).

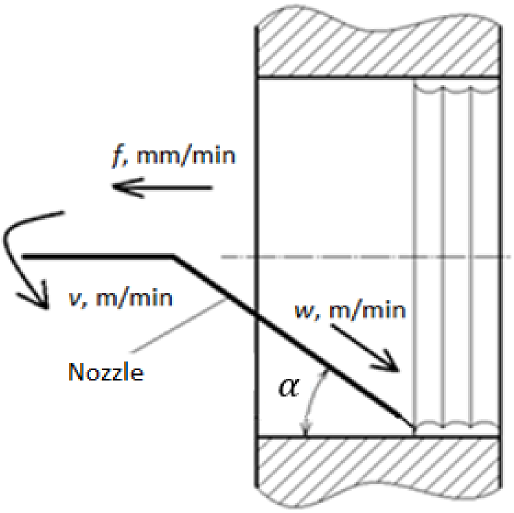

Fig. 3.1. Cladding scheme.

The experiment was performed on base material S355J2 (LVS EN 10149-3) using wire G3Si1 (Table 3.1) (0.8 mm) in accordance with ISO 14341-A and 13 l/min protective gas M21 EN 439 (80 % Ar and 20 % CO_2). The MAG cladding process was undertaken in accordance with DIN 1910 and LVS EN ISO 4063: 2011.

Table 3.1

Chemical Composition [38] of Welding Wire ISO 14341-A G3Si1 [1]

C,%	Si,%	Mn,%	P,%	S,%
0.06–0.12	0.7–1.0	1.3–1.6	≤0.025	≤0.025

Analysis of Samples From the Experiment

Macro sample cross-sections were made for cladding samples, etched with copper chloride (10 % CuCl·NH4Cl solution in water), and the SolidWorks software was used to determine the cladding characteristics by analyzing a scaled sample photo.

The results of the MAG cladding experiment showed that D_c reaches 20 % to 40 %, which can be assessed as a high degree of cladding dilution because according to the data provided in literature [16] MAG technology should provide 15 % to 25 %.

It was concluded that the essential cladding characteristics are influenced by the amount of material supplied, directly affected by w but indirectly by v. Therefore, a new coefficient w/v, has been introduced, which more fully describes the amount of material supplied to the cladding area. The dependence of the main characteristics $H_{\min}$, D_c, and C_v on coefficient w/v is included in Figure 3.2.

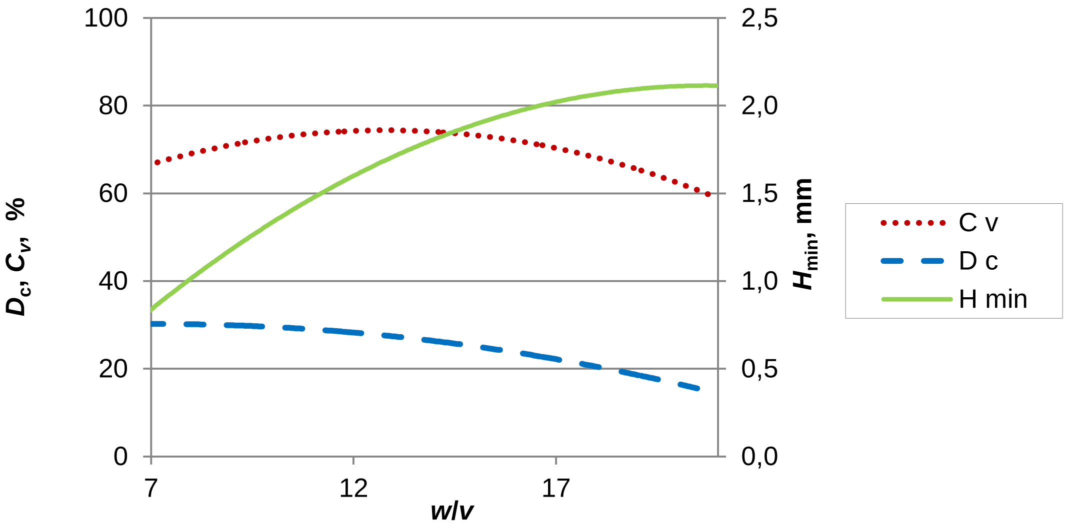

Fig. 3.2. $H_{\min}$, D_c, and C_v dependence on w/v.

It was found that $H_{\min}$ is direct, but D_c is inversely proportional to w/v, while the best C_v values are obtained when w/v = 10 to 15. Summarizing the results of the experiment, it is concluded that the best cladding results can be achieved at a wire feed speed w = 7.0 m/min to 7.5 m/min, combined with the values of coefficient w / v = 9 to 15. The best MAG cladding technological parameters are summarized in Appendix 1. The use of the highest w values together with the lowest v should also be avoided, as this creates a steadily growing cladding profile area with no economic or technological justification.

4. EXPERIMENTAL COMPARISON OF MAG AND LASER CLADDING TECHNOLOGIES

In this chapter, an experimental comparison of the MAG and laser cladding technologies has been performed clarifying the key technological benefits, disadvantages, and usability as well as differences in characteristics of cladding.

Equipment, Parameters, and Materials of Experiment

The laser cladding experiment was performed using the following technological equipment: Laserline GmbH LDF 20000–200 diode laser source, KUKA Roboter GmbH KR 60HA manipulator, GTV GmbH MF–PF 2/2 powder supply equipment, and COAX12 nozzle.

The best six samples of the MAG experiment were selected, which, when applying Eqs. (2.1), (2.2), (2.5), and (2.6), approximated certain technological parameters of laser cladding (Table 4.2). The experiments of both technologies were performed under the same conditions: $\alpha = 36°$ and F position.

Materials used in the laser cladding experiment were as follows:

1) flat iron – S355J2 (LVS EN 10149–3) (350 mm × 80 mm × 12 mm);
2) powder – STELLITE® 6, 150/63 µm (Table 4.1);
3) powder transport gas (Ar) 3 l/min; protective gas (Ar) 15 l/min.

Table 4.1

Nominal Chemical Composition of Cladding Powder STELLITE® 6 [37]

Co,%	Cr,%	W,%	C,%	Others
Base	27–32	4–6	0.9–1.4	Ni, Fe, Si, Mn, Mo

Table 4.2

Equivalent Technological Parameters of Comparative Experiment

Power							
MAG	**Sample No.**	**5**	**14**	**23**	**7**	**16**	**25**
	P, W	1687	1653	1651	2073	2021	2038
	Q, J/mm	202.5	152.6	123.8	248.7	186.6	152.8
Laser	**Sample No.**	**1**	**2**	**3**	**4**	**5**	**6**
	P, W	1660			2040		
	Q, J/mm	199.2	153.2	124.5	244.8	188.3	153.0
Speed							
MAG	v, m/min	0.50	0.65	0.80	0.50	0.65	0.80
Laser	v, m/s	0.0083	0.0108	0.0133	0.0083	0.0108	0.0133
Material feed							
MAG	w, m/min	7.0			7.5		
Laser	F_{pm}, g/min	30.7			32.9		

The choice of laser cladding materials is very wide, but in this work cladding powder STELLITE® 6 was applied, which is widely used in the Fraunhofer IWS Institute and in industry due to its very good performance: high abrasion resistance, corrosion resistance at high temperatures (500 °C), and expected hardness of HV 450–550 kg/mm^2. In addition, the cladding of this material for structural steel has been poorly studied, therefore the study conducted with STELLITE® 6 provides new knowledge [9], [11], [13], [24].

Analysis of Samples of the Experiment

During the laser cladding experiment, after the initial evaluation of the cladding samples, it was decided to reduce the nozzle track distance from initial f = 2.8 mm to f = 2 mm. Consequently, in laser cladding of samples with a reduced step f = 2 mm, the filling of the material was improved – the difference in the height of the cladding decreased in comparison with step f = 2.8 mm.

The results of the laser cladding and MAG cladding technologies are compared in Figure 4.1 where volume factor of F_{pm}/v (g/m), which is analogous to w/v coefficient of MAG technology, is introduced for laser cladding.

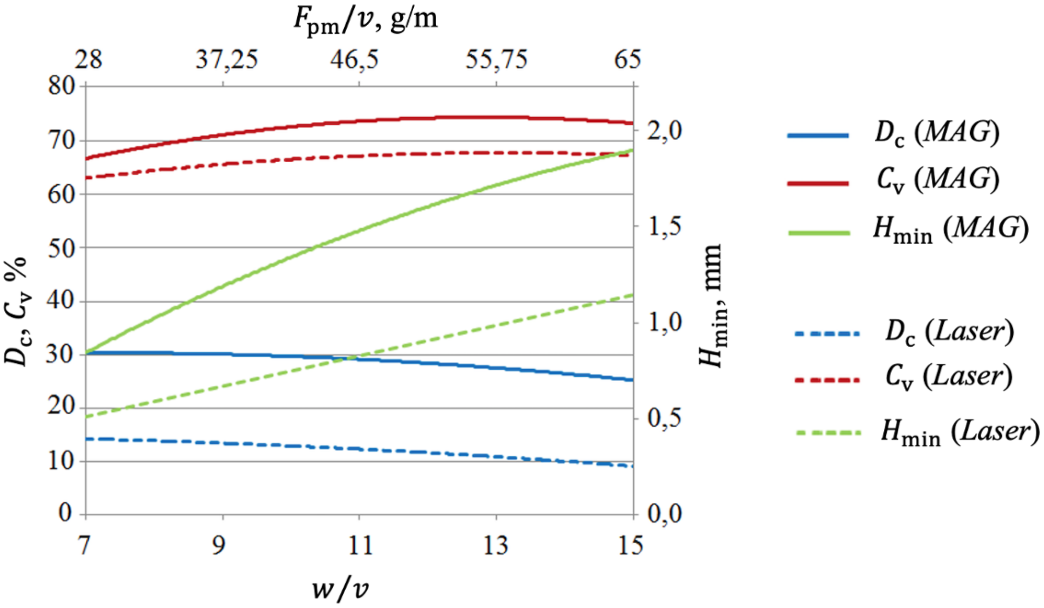

Fig. 4.1. The effect of F_{pm}/v and w/v on experiment results.

It was concluded that in laser cladding, a smaller amount of material is cladded on the base surface (A_c) even if the amount of supplied material is equal for both technologies. This can be explained by reduced cladding efficiency, which is potentially influenced by the nozzle angle α = 36. It has also been confirmed that MAG technology, due to the large values of D_c and $H_{\min}$, is not suitable for small-scale local cladding, but is more suitable for cladding large areas. In turn, it can be seen that the laser cladding technology showed significantly lower D_c values, which has a direct relevance for cladding with specific materials and also for small and local claddings.

5. LASER CLADDING EXPERIMENT

The experiment has been conducted with the aim of clarifying the influence of technological parameters on the cladding characteristics and obtaining the experimental data necessary for developing mathematical expressions for characteristics.

Equipment, Parameters and Materials Used in the Experiment

In laser cladding experiment identical technological equipment has been used as when comparing the cladding technologies. The technological parameters listed in Table 5.1 were used in the experiment, explaining the effect of the nozzle positions (F, OH, VU, and VD) and α on characteristics of laser cladding.

Table 5.1

Technological Parameters of Laser Cladding Experiment

Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
P, kW	1.66	1.66	1.66	2.04	2.04	2.04	1.20	1.40
v, m/min	0.50	0.65	0.80	0.50	0.65	0.80	0.50	0.50
F_{pm}, g/min	30.70	30.70	30.70	32.90	32.90	32.90	14.00	25.00

Analysis of Samples From the Experiment

It was found that the highest $H_{\min}$ values and the most uniform cladding can be ensured by using $\alpha = 90°$, which has the smallest nozzle step (f = 2 mm), the next alternative was to use $\alpha = 90°$ and f = 2.8 mm and only after these, $\alpha = 36°$ with f = 2 mm. Looking at the results, it can be concluded that f = 2 mm is only a recommended value for laser cladding where an empirical approach is needed to correct the f values.

Effect of nozzle tilt angle

The work determines the influence of α on the cladding characteristics (Fig. 5.1). It was concluded that a decrease in α values decreases the cladding efficiency (E_{pm}) due to a decrease in laser intensity (I_{LP}, W/mm^2) (5.1) and powder intensity (I_{PF}, %) (5.2).

$$I_{\mathrm{LP}} = \frac{P}{S} = \frac{4P\sin\alpha}{\pi D^2}. \tag{5.1}$$

$$I_{\mathrm{PF}} = \left[0.072\left(\frac{\alpha\pi}{180°}\right) + 0.701\right]100. \tag{5.2}$$

It was determined that decreasing I_{LP} by 42 % and I_{PF} by 8.5 % the result of A_{c} reduced by 37 % at $\alpha = 36°$. However, the percentage values do not reflect the quantitative dependencies of the characteristics and parameters. Therefore, the effects of listed and unidentified parameters and effects are included, by default, in a single numerical value if a mathematical expression is developed that describes the technological parameters used.

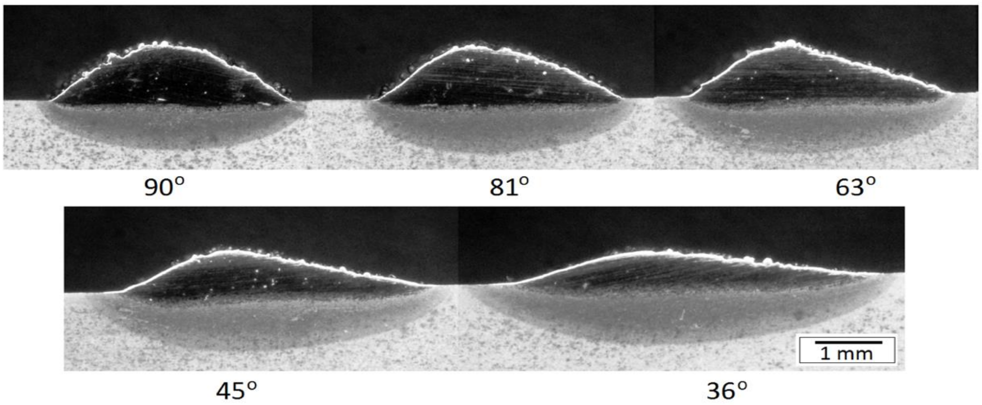

Fig. 5.1. The influence of α on the shape of the cladding cross-section.

The influence of cladding positions

The influence of positions F, VU, OH, and VD on the cladding characteristics H, A_c, and D_c has been experimentally determined. The defined coefficients summarised in Table 5.2 are applicable for the nozzle angle $\alpha = 36°$ and the amount of powder transport gas and protective gas supply (3 l/min and 15 l/min).

Table 5.2

Characteristic Coefficients in Different Nozzle Positions

Characteristic	Position No.	Position	Coefficient, K_pos
H	1	F	1.0
	2	VU	1.1
	3	OH	0.9
	4	VD	0.9
A_c	1	F	1.0
	2	VU	1.2
	3	OH	0.8
	4	VD	1.1
D_c	1	F	1.0
	2	VU	1.1
	3	OH	1.2
	4	VD	1.1

It has been found that bore cladding can be realized in all the required cladding nozzle positions with laser cladding technology. Summarizing the obtained coefficients K_pos at cladding nozzle positions F, VU, OH, and VD, it was concluded that the main factors influencing the results are powder flow and molten material flow, which are influenced by gravity.

It is concluded that in laser cladding with a coaxial type nozzle the highest melting efficiency values can be obtained at a perpendicular nozzle position ($\alpha = 90°$), therefore, if possible, this nozzle position should be used.

Measurements of laser cladding and base material hardness

Cladding hardness measurements have been taken to verify the quality of the cladding and its mechanical properties. Measurements of micro-hardness according to the Vickers scale (HV) (LVS EN ISO 6507-1:2006) were performed at work using a 0.2 kg weight and 10 s measuring time. Hardness measurements for HV cladding are the most appropriate mechanical properties test because they make it possible to determine the mechanical properties and their changes in the desired area and direction on the macro sample cross-section. Hardness control is the evaluation of mechanical properties of the sample cladding, which also provides information on the sample's wear resistance.

The hardness measurements were taken in two different directions and measurement locations, as shown in the measurement diagram (Fig. 5.2).

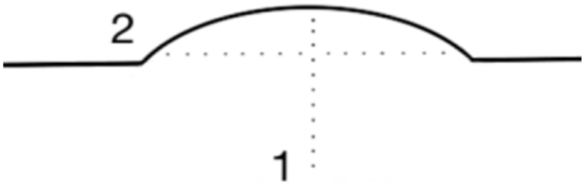

Fig. 5.2. Sketch of the cladding experiment hardness measuring scheme:
1 – vertical; 2 – horizontal over the cladding.

Analyzing the vertical hardness measurements it was found that the hardness of the cladding is influenced by the temperature of base material and by the cladding position (F, OH). These results are shown in Figure 5.3 where the negative distances refer to the cladding (a distance of 0 mm illustrates the surface level of the base material).

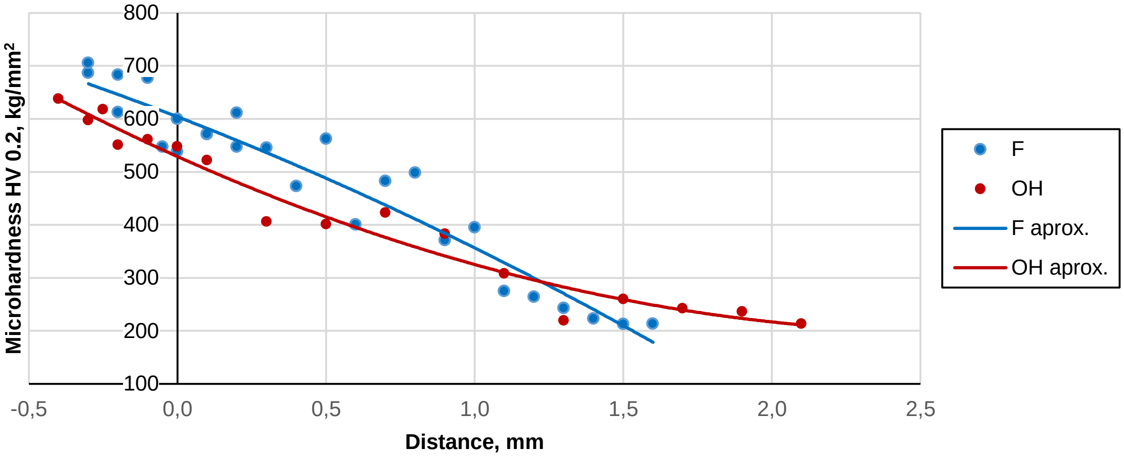

Fig. 5.3. Vertical hardness measurements at $\alpha = 36°$.

Horizontal measurements of the cladding hardness (Fig. 5.4) were carried out as shown in Figure 6.1, scheme 2, about 0.1 mm from the top of the base material. In this way, it was possible to identify changes in the hardness value for an individual cladding profile.

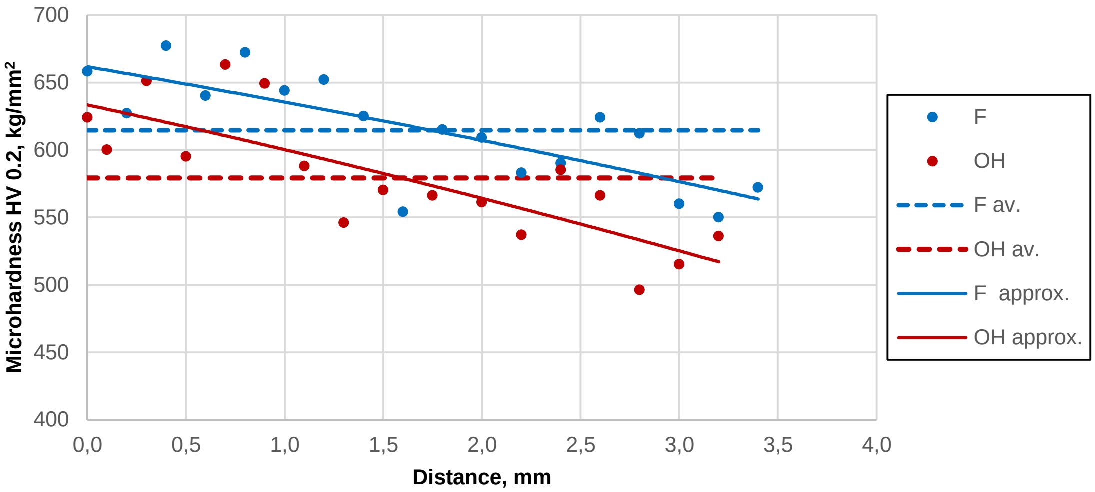

Fig. 5.4. Horizontal measurements of the cladding hardness at α = 36°.

In Figure 5.4, it can be seen that the nature of the horizontal hardness measurements is affected at α = 36°. In order to verify the effect of α on the horizontal hardness values, hardness measurements were performed on α = 90° samples. It is concluded that the approximate hardness values along the length of the profile at α = 90° are close to average values (HV 591 kg/mm^2), which are distributed symmetrically with a small increase of values at the edges of the profile.

The results show that the values of the horizontal profile HV in the middle of the α = 90° samples are equal to the values of HV in the middle of the sample profile α = 36° and further from the nozzle. In turn, analyzing the increase of horizontal hardness values of α = 90° samples at the edges of the cladding profile, it was found that it is influenced by the round laser point. For a round laser point, the laser beam action time is shorter on the profile edges compared to the middle of the profile, due to the differences in distances between the round point segments. This shorter action time results in more rapid cooling of the cladding and the base material, which contributes to the formation of higher HV values at the edges of the cladding profile. For comparison, at α = 90° laser point in the 0.5 mm middle segment, the processing time at v = 0.5 m/min takes 0.48 s, but at the profile edge, the 0.5 mm segment process time takes 0.32 s, which is about 34 % shorter (visualization included in Appendix 2). On the other hand, at α = 36°, at the edges of the profile, the processing time for a 0.5 mm laser point segment takes 0.25 s, which differs from the α = 90° laser point middle segment by 48 %. But the shortest cladding process time did not increase the HV values in the right (furthest) part of the melting profile, as noted above; the values in the furthest part of the profile are close to the HV values for the middle part α = 90°.

When the differences in the melt pool temperature distribution between α = 90° and α = 36° are considered in the work, it is concluded that the melt pool temperature distribution is mainly influenced by the powder flow intensity. Analyzing the distribution of powder flow intensity at α = 36° (Fig. 5.5), it was concluded that a significant difference in powder flow intensity is observed between the left (nearest) and right (farthest) cladding zone (about 70 %). This observation suggests that the concentration of the powder flow or the “shading” at HV values has some effect where the shading potentially absorbs more laser energy. However no direct explanation has been found in this dissertation.

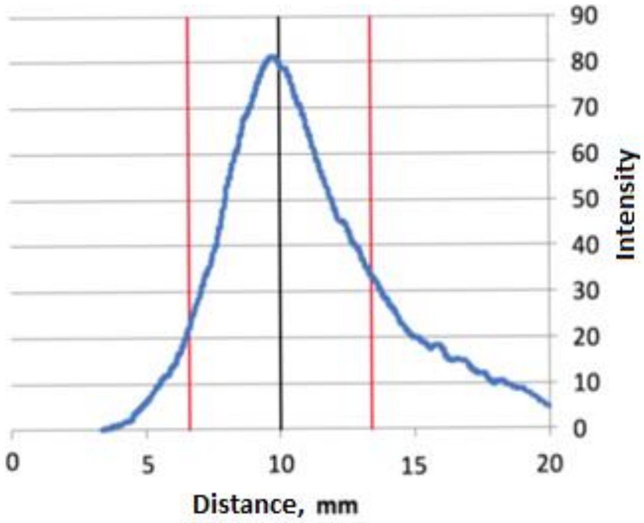

Fig. 5.5. Powder intensity distribution at $\alpha = 36°$.

Quantitative assessment of cladding conditions

The combination of these cladding parameters and conditions results in temperature distribution of the melt pool and geometry of the melt pool, which have been quantitatively analyzed in this work using *E-MAqS* system. During the cladding process, the number of pixels (T_A) above the set target temperature (1500 °C) was recorded, thus providing numerical information on the cladding conditions. Some 1,000 results were recorded at 5 s intervals during the cladding process. The obtained data has been summarised by measuring the effect of average T_A value of the process on the mean horizontal HV values (Fig. 5.6, left).

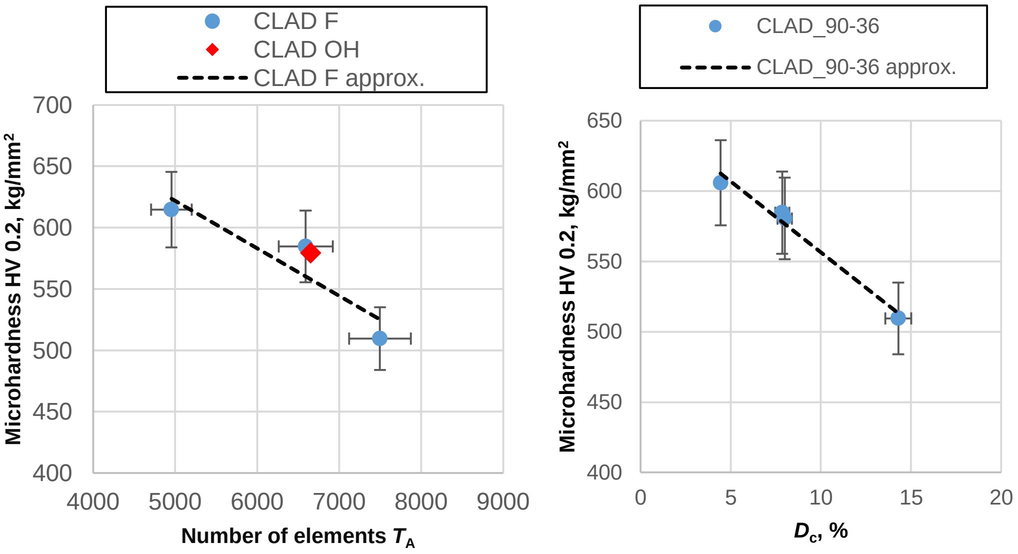

Fig. 5.6. Dependence of the HV value on T_A at $\alpha = 36°$ and the dependence of the HV value on D_c.

It can be seen that for samples with a higher T_A, HV values decreased, and that the change in the cladding and base material HV is of a similar order. The left graph in Figure 5.6 shows that HV values of OH cladding fall within a 5 % error in F cladding hardness values. This indicates that the information provided by T_A is applicable in evaluation of cladding conditions and determination of characteristics.

It has been found that as T_A increases, the degree of dilution D_c increases. Consequently, as D_c increases, the cladding material mixed with the base material also changes the cladding's mechanical properties. Therefore, it can be concluded that the HV characteristic depends on D_c, which is shown on the left in Figure 5.6. The effect of D_c has been confirmed in the vertical cladding (Fig. 5.3) where D_c at OH is 1.2 times higher than at position F. As a result, OH position samples have lower HV values compared to cladding position F.

Laser cladding technology together with cladding material STELLITE® 6 used in this work provides significantly higher hardness ratios compared to the MAG technology and the base material: an average HV 550 kg/mm^2 versus HV 250 kg/mm^2 cladding with the material mentioned in Table 3.1. For comparison, experimental base material S355J2 provides HV 200 kg/mm^2 surface hardness. The surface cladded with STELLITE® 6 creates a significant improvement in the mechanical properties of the surface of base material, which improves the wear resistance and corrosion resistance of the product. These improvements are obtained with an additional difficulty for subsequent machining, which can be overcome by high-speed milling or slow-speed turning. A potential solution is to heat the STELLITE® 6 cladding up to 500 ℃, to reduce the hardness of cladding to HV 300 kg/mm^2 [35]. Cladding with a lower hardness, around HV 300 kg/mm^2 can be obtained using a Ni based alloy powder Deloro™ 30 [37], to thereby facilitate processing.

It is concluded that the HV values are mainly influenced by nozzle angle, cladding position, and laser point shape. Also, the obtained information on the effect of T_A on cladding characteristics is important in laser cladding, but for there is not enough data for fundamental findings.

By combining T_A with the *E-MAqS* system data, the results can potentially be used in the future for evaluating cladding characteristics or for their development.

In general, all specialized claddings are able to provide much higher mechanical properties than structural steel. Therefore, it is important to create the cladding with a predictable geometry so that minimal post-processing is required. This confirms the importance of developing mathematical expressions in order to provide predictable cladding characteristics.

Credibility of Experiment Results

There are two types of results in this work: the characteristics of cross-section of cladding and the hardness of cross-sectional profile of the cladding sample. The reliability of both results has been verified by determining the variation coefficient and standard error with the commonly used statistical calculation expressions [1], [3], [17].

The cladding characteristics have been determined in *SolidWorks* software by treating and measuring the scaled sample photograph of a macro sample cross-section. In the work, when determining the measurement error, the appropriateness and accuracy of such a measurement method has been checked. The calculation of the coefficient of variation and the standard error has been made for the characteristics of $A_{\text{c},}$ A_{b}, H_{min} and H_{max}. Table 5.3 summarises the results of 10 independent measurements of one sample.

Table 5.3

Coefficient of Variation and Standard Error of MAG Sample No. 16

	Coefficient of Variation, %	Standard Error
A_{c}	0.77	0.16 mm^2
A_{b}	0.75	0.10 mm^2
H_{min}	0.82	0.004 mm
H_{max}	0.43	0.003 mm

For the hardness measurements taken using the INNOVATEST NEXUS 4000$^{\text{TM}}$ equipment the coefficient of variation and standard error have been determined; Table 5.4. summarises 10 independent results of one measurement – imprint.

Table 5.4

Coefficient of Variation and Standard Error of Hardness Measurements

No	HV 0.2	$(n_{\text{vid}} - n)^2$	No	HV 0.2	$(n_{\text{vid}} - n)^2$
1	506.2	25.30	6	519.8	73.44
2	508.3	8.58	7	518.8	57.30
3	509.8	2.04	8	507.4	14.67
4	501.6	92.74	9	517.8	43.16
5	511.8	0.32	10	510.8	0.18
n_{vid}		**511.23**	$\sum(n_{\text{vid}} - n)^2$		**317.76**
			Standard Deviation		**5.94**
			Coefficient of Variation, %		**1.16**
			Standard Error, kg/mm^2		**1.88**

The obtained results show that the method for measuring the cladding characteristics produces results with a small coefficient of variation and standard error and that hardness measurements show good accuracy. Consequently, the result readings performed in this work are highly reliable and scientifically sound.

6. MATHEMATICAL EXPRESSIONS FOR PREDICTING CHARACTERISTICS OF LASER CLADDING

In this work, mathematical expressions for predicting MAG and laser cladding characteristics have been developed to provide predictability when using the technology.

Developing Mathematical Expressions for MAG Cladding

Mathematical Eqs. (6.1)–(6.3) for predicting the cladding characteristics were developed for the summarised results of the MAG experiment (Chapter 3). Basically, a regression polynomial has been used where the characteristic depends on the technological parameters and coefficients determined by the SYSTAT program [3], [7], [17].

$$H_{\min} = -19.39 + 2.45U - 10.54v + 0.04w + 0.14Uv + 0.15vw \\ -0.06U^2 + 3.16v^2. \tag{6.1}$$

$$D_{\mathrm{c}} = 378.41 - 54.40U + 235.90v + 32.351w - 12.94Uv \\ -1.88Uw + 8.45vw + 1.88U^2. \tag{6.2}$$

$$Q = 93.29 - 409.43v + 41.14w - 18.06Uv - 18.64vw \\ +0.51U^2 + 487.78v^2 - 0.91w^2. \tag{6.3}$$

ANOVA (analysis of variance) analysis of the generated mathematical expressions was performed to determine variation in the distribution of the values of selections (Table 6.1) [22].

Table 6.1

ANOVA (Dispersion) Data of MAG Mathematical Expressions

	$H_{\min}$	D_{c}	Q
Sum of Divergent Squares			
Regression	3.24	495.5	53 927.3
Residual	0.10	78.5	69.19
Number of Degrees of Freedom			
Regression	7	7	7
Residual	9	9	9
Dispersion			
Regression	0.46	70.79	7703.9
Residual	0.01	8.72	7.69
F Criteria	42.57	8.12	1002.07
p-value (*F*-test)	<0.0005	0.003	<0.0005
R^2 (%)	**97.1**	**86.3**	**99.9**

The smallest correlation coefficient quadratic value R^2 is 86.3%, which indicates that the formulated expressions explain the results of the experiment with high precision. The developed mathematical expressions are not comparable with the experiments of other authors because there is no coincidence in the technological parameters used.

Developing Mathematical Expressions for Laser Cladding

Analyzing the results of the laser cladding experiment it has been concluded that it is possible to introduce a new laser cladding impact parameter G (W·g/mm^3) (6.4) describing in one parameter all the technological parameters that have been used.

$$G = \frac{4P\sin\alpha}{\pi D^2} \cdot \frac{F_{\mathrm{pm}}}{v}. \tag{6.4}$$

In addition, it has been found that parameter G describes with high precision (96.7 %) the A_{c} values obtained (Fig. 6.1). Therefore, it has been concluded in this work that G is suitable for calculating cladding characteristics (6.5).

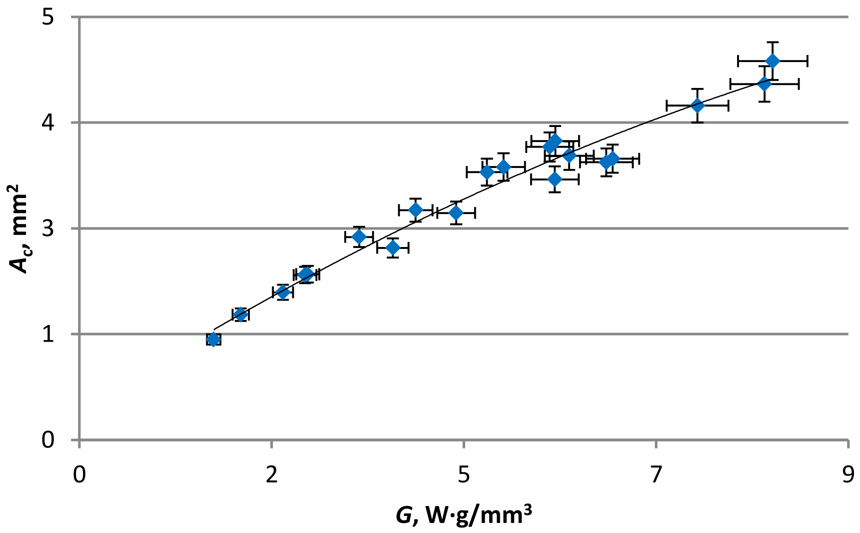

Fig. 6.1. Effect of G on A_{c}, results with 5 % error.

$$A_{\mathrm{c}} = -0.02G^2 + 0.65G + 0.33. \tag{6.5}$$

In this work, further expressions have been developed in the same way as for mathematical Eq. (6.5): Eq. (6.6) to determine H with 95.3 % accuracy; Eq. (6.7) for H_{min} prediction with 70 % accuracy; and Eq. (6.8) for D_{c} calculation with 81 % accuracy.

$$H = -0.008G^2 + 0.25G + 0.2. \tag{6.6}$$

$$H_{\mathrm{min}} = 0.025G^2 - 0.065G + 0.58. \tag{6.7}$$

$$D_{\mathrm{c}} = 0.7G^2 - 9.77G + 43.64. \tag{6.8}$$

It has been found that characteristics A_{c} and H of one cladding sample are interrelated and H can be determined with high accuracy (95.2 %) using Eq. (6.9).

$$H = 0.38A_{\mathrm{c}} + 0.08. \tag{6.9}$$

Variation (6.10) of Eq. (6.5) has been developed in this work, where the coefficients of the parameter G are expressed by the linear equation, which is described by the proportion of cladding material (ρ) and the efficiency of cladding (E_{pm}, at $\alpha = 90°$) – E_{pm}/ρ. It has been concluded (6.10) that the use of mathematical expressions is wider than (6.5) because they evaluate the variation of different materials and nozzles knowing ρ and E_{pm}values.

$$A_{\mathrm{c}} = \frac{\left(-1.7\frac{E_{\mathrm{pm}}}{\rho} + 10\right)G^2 + \left(77.83\frac{E_{\mathrm{pm}}}{\rho} + 1.11 \cdot 10^{-12}\right)G + \left(86.5\frac{E_{\mathrm{pm}}}{\rho} + 5\right)}{10\,000}. \tag{6.10}$$

Selection and Calculation of Laser Cladding Technology Parameters

The work contains developed mathematical expressions that predict the characteristics to be obtained, knowing the technological parameters used. It was shown in the previous section that in this way it is possible to determine the characteristics with high precision, but these calculations are not suitable for the development of technological process. Therefore, mathematical expressions have been developed that ensure the selection and calculation of suitable technological parameters in order to provide the desired geometric characteristics of cladding.

Technological parameters for laser cladding are P, F_{pm}, v, f, and protective gas and transport gas, as well as possible cladding position and nozzle angle α. It was found in the laser cladding experiment performed in this work and in its analysis that the most suitable cladding position is F, nozzle angle $\alpha = 90°$, and step $f = 2$ mm for a 4 mm round laser point. P and F_{pm} should be determined knowing all the technological parameters listed above, assuming that the amount of powder transport gas and protective gas supply are respectively 3 l/min and 15 l/min, like the amounts used in the laser cladding experiment.

Geometrically a new layer of cladding material should provide a certain layer height after mechanical post-treatment. In theory this height is provided by H_{min}, which is taken as the basis for further calculations. After that, it was decided to develop an expression that can be used to determine the applied P by required H_{min}. Eq. (5.1) was used and power P stated, obtaining Eq. (6.11) where the expression has reducible value of v and unknown value of F_{pm}.

$$P = I_{\mathrm{LP}}\frac{\pi D^2}{4\sin\alpha}. \tag{6.11}$$

Consequently, separate linear Eqs. (6.12)–(6.14) were derived from the results of the laser cladding experiment and the analysis of the results. Linear equations were obtained after the establishment of regression equations.

$$I_{\mathrm{LP}} = 37.475H + 67.54. \tag{6.12}$$

$$H = 0.187G + 0.252. \tag{6.13}$$

$$G = 4.81H_{\mathrm{min}} - 0.073. \tag{6.14}$$

To determine power P (W), Eq. (6.11) was used and by inserting Eqs. (6.12)–(6.14) a simple calculation of P (6.15) was obtained according to the required cladding height H_{min}.

$$P = 8.42\pi D^2(H_{\mathrm{min}} + 2.27). \tag{6.15}$$

When P was known, Eq. (6.4) was used and F_{pm} determined, obtaining Eq. (6.16).

$$F_{\mathrm{pm}} = \frac{Gv}{I_{\mathrm{LP}}} = \frac{Gv\pi D^2}{P\sin\alpha}. \tag{6.16}$$

Using Eqs. (6.16) and (6.14), it is possible to get Eq. (6.17) in order to determine F_{pm} (g/min).

$$F_{\mathrm{pm}} = \frac{72.165\pi D^2 v(H_{\mathrm{min}} - 0.0015)}{P}. \tag{6.17}$$

Eqs. (6.15) and (6.17) of theoretical calculation can be applied in laser cladding at nozzle angle $\alpha = 90°$, cladding position F, step f = 2 mm, laser point 4 mm, transport gas supply 3 l/min, and shielding gas supply 15 l/min. The expressions facilitate the development of technological process and the choice of technological parameters, because technological parameters P and F_{pm} can be determined by calculations, knowing value of H_{min} to be provided in the cladding process.

Correction of Technological Parameters for Laser Cladding During Processing

Analysing the results of the cladding experiment it has been established that it is necessary to control technological processes during the process to ensure smooth cladding and reduce the amount of mechanical treatment. The industry uses *E-MAqS* system, which adjusts the laser power based on the cladding conditions by analyzing the melt pool temperature distribution and T_{A} characteristic. Thus, the *E-MAqS* system provides stable cladding conditions, but does not provide direct information on cladding characteristics. The linking of *E-MAqS* system to real cladding characteristics can only be obtained through systematic empirical experiments. Therefore, empirical expressions have been developed in this work that provide the correction of cladding height H during the process, changing the technological parameters when necessary.

The most suitable laser cladding technological parameters for correction during the cladding process are P or v. The most technologically simple way is to adjust P, this is already done in practice with *E-MAqS* system and changes can be made instantly as soon as necessary. Only the rate of change of parameter P must be performed without compromising the quality of cladding, therefore the P correction step and/or the minimum and maximum P values must be set. The correction of cladding speed v is technically possible immediately, so it should be possible to determine the correction step or acceleration or the minimum, maximum rate values when the rate correction is made.

Using Eq. (6.4) a calculation was made to express P_{izm} and v_{izm} and subsequently to develop Eqs. (6.18) and (6.19) in order to determine P_{izm} and v_{izm}, which is the real change in the parameter values.

$$P_{\mathrm{izm}} = \frac{v\pi D^2(9.62H_{\mathrm{min}} - 5.35H_{\mathrm{kontr}} + 1.2)}{4F_{\mathrm{pm}}\sin\alpha} - P. \tag{6.18}$$

$$v_{\mathrm{izm}} = \frac{4PF_{\mathrm{pm}}\sin\alpha}{\pi D^2(9.62H_{\mathrm{min}} - 5.35H_{\mathrm{kontr}} + 1.2)} - v. \tag{6.19}$$

The developed laser cladding parameter correction expressions are theoretical expressions accuracy of which has not been tested in the work. But Eqs. (6.18) and (6.19) give information about the way in which the correction of online technological parameters is possible if reliable information about H_{kontr} values is provided.

The chapter develops mathematical expressions for the calculation of cladding characteristics using laser cladding impact parameter G, which summarizes all technological parameters. Also, the calculation expressions of laser cladding technological parameters P and F_{pm} are introduced in the work, knowing the required cladding height H_{min}. Also, theoretical expressions have been introduced, which are intended for correction of laser cladding technological parameters P and v during the cladding process, evaluating the obtained H_{kontr} value. These calculations provide a significant improvement in the development of technological process, making it easier. Furthermore, the developed cladding height control expressions may potentially reduce the amount of post-processing required.

The laser cladding mathematical expressions for predicting characteristics using technological parameters are tested in the following section. Examination of expressions was performed using the results of independent experiments.

7. EXAMINATION OF LASER CLADDING MATHEMATICAL EXPRESSIONS AND EXPERIMENT RESULTS

The purpose of this chapter is to compare the calculations of mathematical expressions developed with results from experiments that are not related to the development of expressions.

The examination of accuracy of A_c, H, and D_c – Eqs. (6.5), (6.6), and (6.8) – has been performed in this work by using the square value of correlation coefficient (R^2) calculated with Eq. (7.1) where A_c is the value delivered in the experiment, but A_cMod is the calculated value. R^2 indicates the percentage of cases when the introduced expression with laser cladding impact parameter G explains the results of the experiment [3], [21].

$$R^2 = \left(\frac{\sum A_\mathrm{c} \cdot A_\mathrm{cMod} - \dfrac{\sum A_\mathrm{c} \cdot \sum A_\mathrm{cMod}}{n}}{\sqrt{\sum A_\mathrm{c}^2 - \dfrac{(\sum A_\mathrm{c})^2}{n}} \cdot \sqrt{\sum A_\mathrm{cMod}^2 - \dfrac{(\sum A_\mathrm{cMod})^2}{n}}} \right)^2 . \tag{7.1}$$

Experimental results found in the comparison experiment and literature sources [4], [11], [15], [23], [25], [28] have been used to test the laser cladding expressions developed in the Doctoral Thesis. For example, A_c results have been summarised in Figure 7.1 where A_c values are simulated with the red curve, but the results of the comparative experiment are marked with blue points (indicated by 5 % error) and the blue curve is the approximation of experimental results.

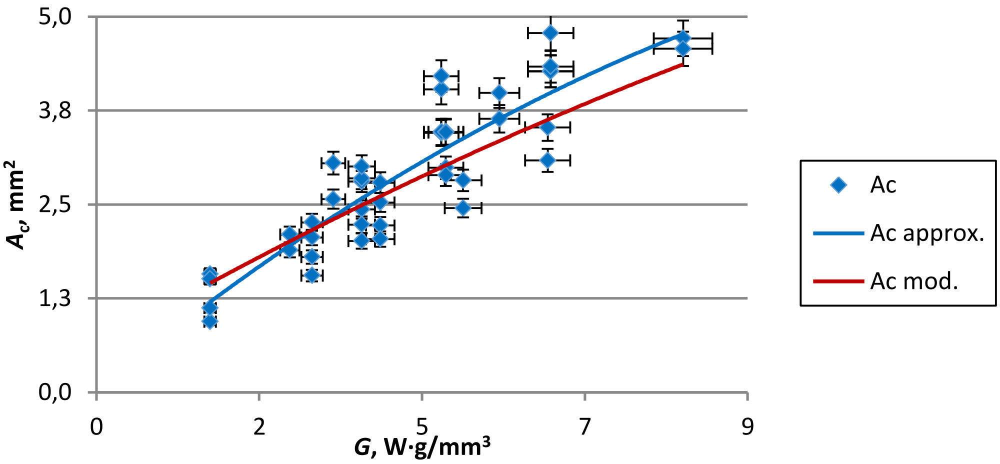

Fig. 7.1. Effect of parameter G on the surface of cladding square A_c.

It has been determined that calculation A_c estimates 82 % to 87 % of the results, calculation H – 92 % and calculation D_c – 38 % of all results, but 62 % of the results of technology comparison experiment. The mathematical expressions developed in the work are practically applicable for obtaining a highly precise prediction of laser cladding characteristics using simple calculation. In this way, by refining and accelerating the technological process of cladding and renewal, operation time is reduced thus also reducing the price.

CONCLUSIONS

In the dissertation, the set goal of the research “to find out the influence of laser cladding and MAG cladding technological parameters on cladding characteristics, to compare these technologies, and to develop a mathematical expression for predicting characteristics” has been entirely achieved and the initial tasks have been fulfilled.

1. A comprehensive analysis of available material surface cladding technologies has been performed.
2. Analysis of cladding experiments and results was performed, determining the dependence of laser cladding characteristics on the technological parameters, cladding position and nozzle angle. The results of MAG cladding and laser cladding experiments were compared.
3. The hardness of cladding was tested and the factors, which have the most influence on hardness of laser cladding, were determined;
4. Mathematical expressions of the laser cladding and MAG cladding technologies for predicting cladding characteristics were determined and compared with experimental results.
5. Recommendations for practical application of cladding technologies have been provided.

The following conclusions have been made.

Analysis of the technology

1. It was concluded that at the horizontal bore position the cladding position must be changed between the floor (F), vertical up (VU), overhead (OH), and vertical down (VD) positions.
2. The ranges of technological parameters used in the experimental part of laser cladding were clarified in the literature review. In the analysis of the laser cladding literature, it emerged that the only position used to perform laser cladding experiments was the floor (F) position with a $\alpha = 90°$ cladding nozzle angle in relation to the workpiece. In addition, no information was found in the literature on studies of bore cladding or use of the overhead (OH) position cladding.

Analysis of cladding experiments and results

3. In the experimental part, it was found that cladding height H mainly depends on the amount of material fed in the cladding zone, which in turn is influenced by material feed and cladding speed. This corresponds in MAG technology to the ratio of wire feed and speed w/v, and in laser cladding the powder feed rate and speed F_{pm}/v ratio.
4. In the technology comparison experiment, it was confirmed that MAG cladding technology is not suitable for small, local cladding because it provides high values of D_{c} and H_{min}. But MAG cladding technology can be used more efficiently at high cladding heights where there is no need for a special layer. In addition, it was

concluded that in laser cladding the amount of material cladded is smaller than for MAG technology when using similar technological parameters. This is due to lower laser cladding efficiency.

5. It has been found that the variation of angle α of the laser cladding nozzle has a significant effect on melt characteristics, because changing of α affects the intensity of the laser and the powder flow in the cladding zone. In the experiment, it was concluded that the most suitable position of the cladding nozzle is F and nozzle angle $\alpha = 90°$ because then the smallest material losses are observed, thus cladding efficiency E_{pm} is the highest. In addition, the cladding obtained at $\alpha = 90°$ is symmetrical, which promotes the formation of smooth area cladding.
6. It is concluded that the cladding position of the nozzle significantly affects the values of cladding characteristics H, A_{c}, and D_{c} that are expressed in coefficients K_{pos}. The introduced coefficients indicate the difference between the values of cladding characteristics and provide an opportunity to predict the value of the respective cladding position (VU, OH, or VD) if the result at position F is known. The analysis of the performed experimental results shows that with laser cladding technology it is possible to provide cladding in all necessary cladding positions with the necessary cladding characteristics.

Factors that influence hardness in laser cladding

7. Comparing the results of cross-sectional hardness of the laser cladding sample and MAG cladding sample, it was found that laser cladding samples have higher hardness values, which suggests that the abrasion resistance is also much higher for laser cladding samples. It was found that the MAG cladding samples using a welding wire G3Si1 provide HV 250 kg/mm^2 that has 1.25 times higher hardness than base material S355J2 HV 200 kg/mm^2. Laser cladding with STELLITE® 6 powder provides HV 550 kg/mm^2 – 2.8 times higher hardness than the base material. In addition, STELLITE® 6 is a specialised cladding powder, although other cladding materials can be used.
8. It was concluded that the cladding nozzle angle, cladding position and the shape of the laser point affect the cladding hardness values. To provide smooth hardness values (HV), the laser cladding profile requires the cladding to be carried out with nozzle angle $\alpha = 90°$. Accordingly, if the nozzle angle is not positioned perpendicular to the workpiece, the powder flow is not symmetrical and consequently the horizontal hardness values of cladding profile will be asymmetric.
9. It was found that the temperature distribution of the cladding melt pool can be described with T_{A}. It has been proved that D_{c} is directly influenced by the T_{A} value, which in turn inversely affects HV, since the increase in the D_{c} value indicates a higher blend of the cladding material with the base material.
10. It has been found that T_{A} values are numerically able to give indications of cladding conditions that affect the values of cladding characteristics. Potentially in the future, *E-MAqS* system data such as T_{A} can be used to evaluate or purposefully develop

cladding characteristics. By monitoring, analysis and adaptation of online technological parameters of the cladding process it is aimed to develop the desired mechanical properties.

11. Cross-sectional hardness analysis of laser cladding samples showed that laser cladding provides adequate cladding quality, ensuring uniform cladding, with small changes in hardness values in the cross-sectional profile.

Mathematical expressions of laser cladding and MAG cladding technologies

12. Mathematical expressions have been empirically developed for determining (predicting) MAG and laser cladding characteristics. This was achieved using the technological parameters of cladding technology. *SYSTAT* data processing programme was used to determine the mathematical expressions used in MAG cladding technology. In turn, *Excel* programme was used for creating the laser cladding mathematical expressions where laser cladding impact parameter G is introduced that describes the parameters used for the laser cladding technology. Parameter G has been used as the basis for the formulation of mathematical expressions.
13. The adequacy of the developed mathematical expressions was verified using the square of correlation coefficient (R^2). It was concluded that the developed mathematical expressions show a high degree of precision. Mathematical expressions for MAG cladding D_c, H_min, and Q explain respectively 86.3 %, 97.1 %, and 99.9 % of the experiment result. For the laser cladding for a single cladding sample, A_c explains 87 % to 96.3 % of the result, H – 84 % to 95.3 %, D_c – 57 % to 83.5 %, and H_min – 70 % of the result. Here, the adequacy indicators of mathematical expression are combined for the results of mathematical development and the author's experiment that was not related to the development of mathematical expressions and for the results of experiments of other authors.
14. This work presents the calculation expressions for laser cladding technological parameters P and F_pm, which provide an opportunity to calculate the aforementioned technological parameters, knowing the required cladding height. In addition, theoretical expressions have been introduced to correct the technological parameters of laser cladding during the process, evaluating the obtained technological parameters and ensuring that they are constant throughout the cladding process.
15. The mathematical expressions for predicting cladding characteristics developed in this work show high precision and can be applied in real production contexts in order to specify the results to be obtained. In turn, technological parameter calculation expressions and control methods facilitate the development of the cladding technological process, shortening the duration of the cladding operation and reducing the required post-treatment.

Recommendations for practical application

16. Technological recommendations have been advanced for the cladding of external and internal surfaces. In order to minimise post-treatment following the cladding technology, as smooth a profile as possible should be created that can be achieved with MAG technology at w/v = 8.5 to 11.0 and laser cladding technology at F_{pm}/v = 28 g/m to 65 g/m. The aforementioned technological parameters w/v and F_{pm}/v describe the supply of material in the cladding zone, the most significant factor affecting the cladding geometry characteristics H and A_{c}.
17. For laser cladding with a coaxial nozzle, the ideal position is F, while the most suitable nozzle angle is $\alpha = 90°$. An angle other than $\alpha = 90°$ should only be used if the reachability of the cladding surface can be achieved by reducing α, as well as in the situation where it is necessary to clad in OH position, but $\alpha = 36°$ must be used for OH, which has been tested experimentally.
18. In order to provide constant mechanical properties, it is recommended to monitor the system process (using, for example, *E-MAqS* system) and to adjust power during the process – active process control. This ensures constant cladding conditions.
19. It has been determined that it is possible to develop cladding equipment, which would improve the cladding of both external and internal surfaces, including the cladding of internal cylindrical surfaces, by performing cladding in F–VU–OH–VD positions. In the cladding zone, the cladding equipment nozzle should provide the powder and laser beam feed with mutually scattered axes – separate axes where the laser beam is applied to the cladding zone below the narrow angle, but the powder supply is perpendicular to the base material with a symmetrical laser eclipse. These improvements would ensure safe operation of the equipment, higher cladding quality and lower dependence of cladding characteristics on the cladding position. This is feasible because the laser optic elements would be further away from the cladding zone and the cladding profile would be symmetrical in all cladding positions.

The hypothesis proposed in this work has been fully confirmed: laser cladding with powder can be successfully implemented in floor (F) and overhead (OH) positions, and the results obtained are predictable and meaningful. Also, it was found that OH position cladding should be performed at $\alpha = 36°$, to reduce the risk of damaging the equipment.

The research and **conclusions in this work offer an important novelty in mechanical engineering science** and production technology. The scientific novelty of this work relates to laser cladding technology where it has been experimentally established that cladding can be achieved in all of the cladding positions with predictable characteristics, and the effect of the cladding nozzle angle on the cladding characteristics has been determined. The mathematical expressions developed in this work can be used in production in order to reduce the operation time.

The next steps required for the advancement of scientific laser cladding technology are further development of mathematical calculations initiated in this Doctoral Thesis and validation of the results with a wider range of laser cladding experiments. It is necessary to develop flexible nozzles suitable for bore cladding, following the recommendations of this work. It is necessary to perform an analysis of the cladding's microstructure to compare the structure of the material of individual cladding zones and to determine the dependence of structure on the powder flow – laser shading and its effect on the cladding's mechanical properties. This would generally develop and make laser cladding technology more accessible.

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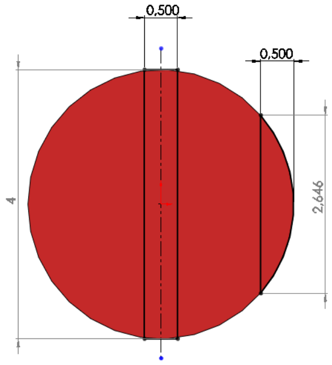
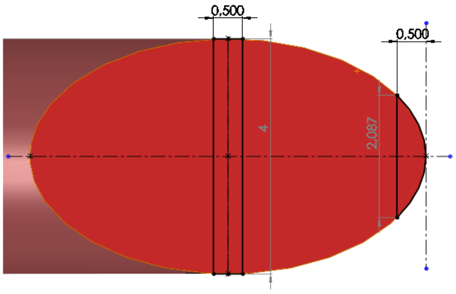
APPENDICES

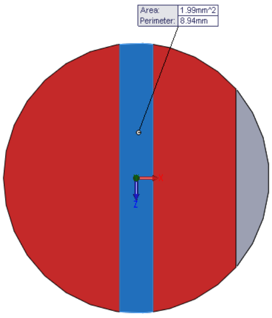
Samples With the Best Cladding Efficiency and Most Even Cladding

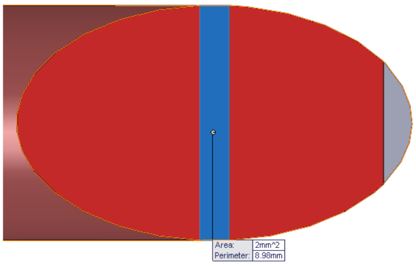
Sample No.	U, V	v, m/min	w, m/min	w/v	C_v, %	$\lvert p_{\mathrm{diff}} \rvert$
5	19	0.50	7.0	14.0	71.9	0.35
7	22	0.50	7.5	15.0	70.0	0.19
14	19	0.65	7.0	10.8	78.8	0.29
16	22	0.65	7.5	11.5	76.1	0.13
23	19	0.80	7.0	8.8	85.3	0.20
25	22	0.80	7.5	9.4	70.3	0.35

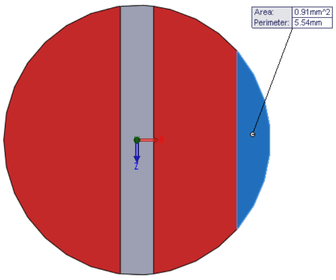
Laser Point Segments at $\alpha = 90°$ and $\alpha = 36°$

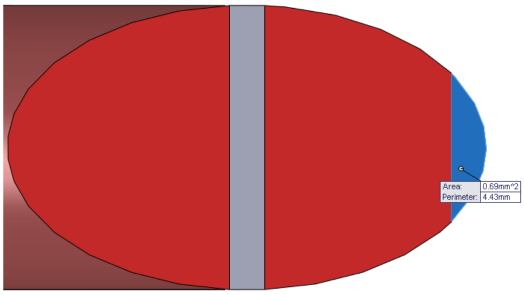




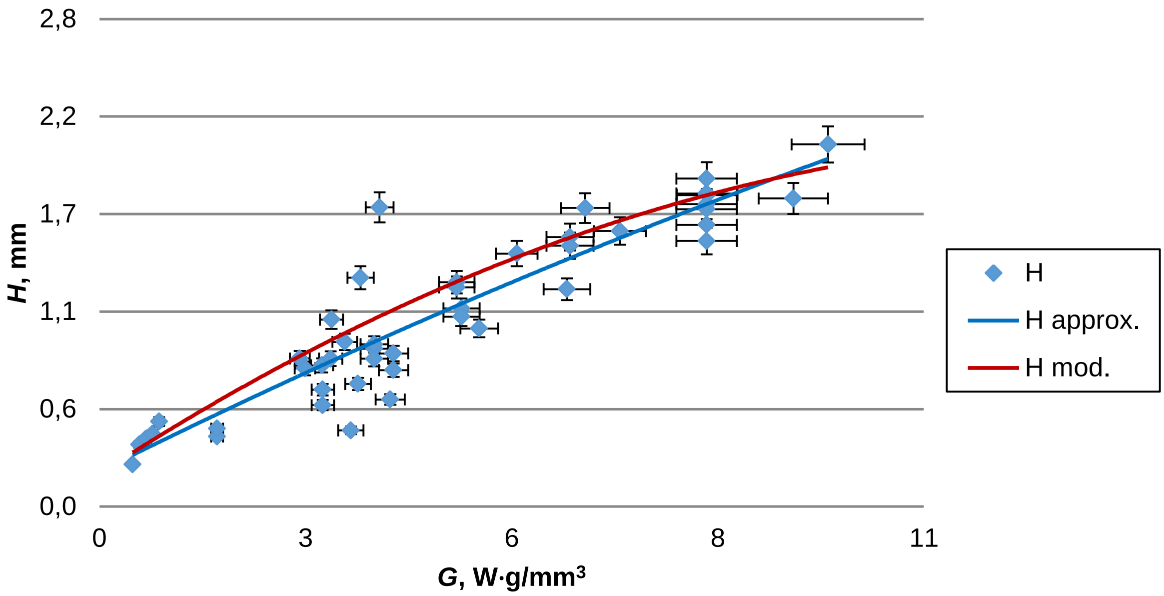




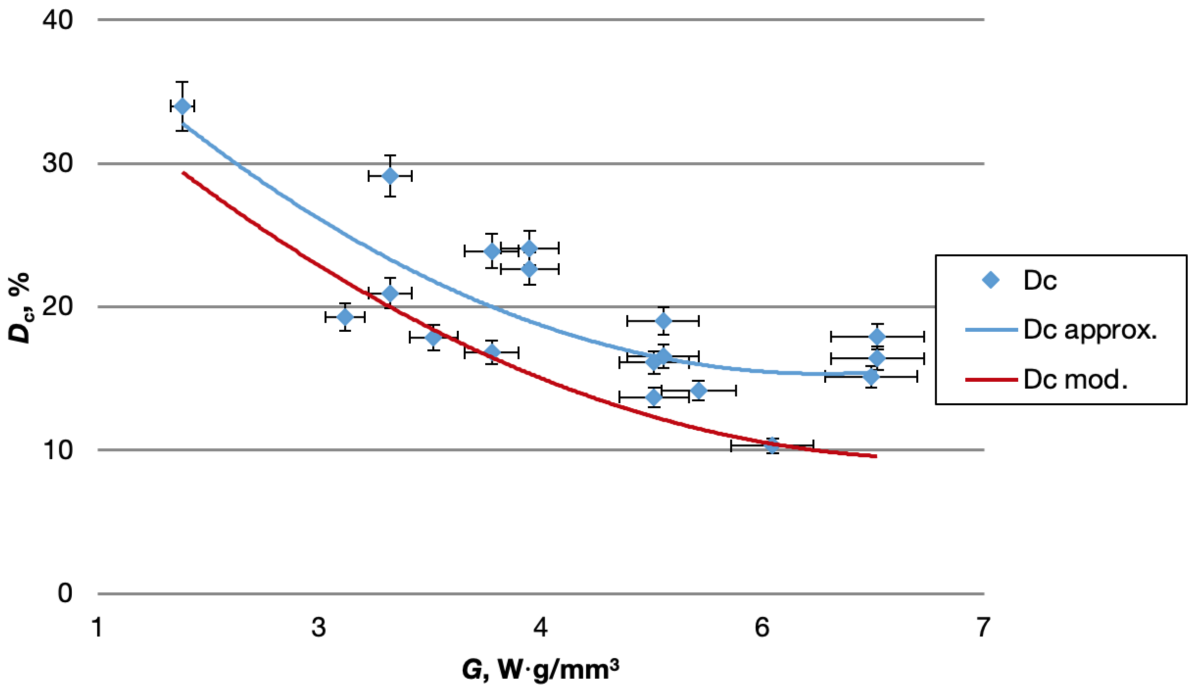




Laser point segment	Middle	Edge	Edge
α, °	90	90	36
v, mm/s	8.33	8.33	8.33
L on 0.5 mm segment, mm	4	2.646	2.087
t, s	0.48	0.32	0.25
% shorter t than 90 middle, %	0	–34	–48



H results and calculation with parameter G, results with 5 % error bars.



D_c results and calculation with parameter G, results with 5 % error bars.