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LASER CLADDING AND QUALITY ASSESSMENT OF WEAR-RESISTANT Cr_3C_2 7(Ni20Cr) COATINGS

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Abstract: The study aimed to evaluate the quality and structure of test clads made by means of laser deposition of chromium carbide - nickel aluminide powder with the nominal chemistry Cr_3C_2 7(Ni 20Cr). The clads were deposited on the substrate of unalloyed mild steel S235, using different laser power parameters and assisted by two different shielding gases, inert argon and active nitrogen. As part of the research, images of the macrostructure, microstructure, and analysis of the chemical composition using SEM and EDS analysis were conducted. The next stage was to carry out hardness tests, starting from the face of the clads and ending with the base metal. The 5 Whys method, as a quality tool, was additionally applied for determining causes of imperfections and defects. The influence of laser cladding parameters and the shielding atmosphere on the quality and properties of clads was determined.
Key words: laser cladding, powder cladding, Cr_3C_2 7(Ni 20Cr), composite coatings, disk laser, wear resistance, chromium carbides, 5 Why analysis

1. INTRODUCTION

Modern material processing technologies are increasingly using advanced surface engineering methods to improve the durability and resistance of structural components. One of the most innovative techniques is laser deposition of wear-resistant layers, which allows for the precise application of coatings with high hardness and mechanical strength. This process is widely used in the aerospace, automotive, energy and tool sectors, where abrasion, corrosion, and fatigue resistance are crucial [1].
Laser deposition has a number of advantages over traditional methods, such as arc metal deposition or thermal spraying. Thanks to the precise control of the laser beam, it is possible to obtain thin, homogeneous layers with minimal impact on the substrate structure. What is more, this technique allows reducing deformation and increasing the bond of the clad layer to the base material [1,2]. Despite its many advantages, laser deposition presents challenges such as crack control in the coating and optimization of process parameters. Current researches focus on the selection of coating materials, such as high-carbon iron alloys, nickel alloys or composites with ceramic particles, which can further increase wear resistance.
The chromium carbide Cr_3C_2 is a hard ceramic phase with high wear resistance, which, when combined with a metallic matrix (usually NiCr or CoCr), forms metal-matrix-composite (MMC) composites with synergistic mechanical and chemical properties [1,2].
Laser-deposited coatings using Cr_3C_2-NiCr type powders provide an advanced solution in surface engineering to improve the wear resistance of metal components, including titanium alloys.
Cr_3C_2-NiCr powder is a metal-ceramic composite in which hard chromium carbide (Cr_3C_2) particles are embedded in a ductile matrix of a nickel-chromium (NiCr) alloy. This combination provides the coatings with high hardness, abrasion resistance, and stability at elevated temperatures [3].
The laser cladding technology allows for the precise application of Cr_3C_2-NiCr coatings on the surfaces of titanium alloys, which leads to the improvement of their functional properties. Studies have shown that these coatings significantly increase the hardness and wear resistance of different substrates, including titanium alloys, which is crucial in applications that require high durability.
The process of laser cladding consists of the deposition of powder, most often by delivery through a coaxial or

side nozzle, into the zone of operation of the laser beam, where it is partially melted.
During the laser cladding process:
- Cr_3C_2 carbide is not completely melted, but is fused into the nickel-chromium alloy matrix,
- a layer with clearly visible carbide particles embedded in a plastic NiCr matrix is formed;
- after the rapid solidification typical of laser cladding processes, a fine-grained structure is obtained, reducing the risk of cracking and ensuring a better bond quality to the substrate.
An interesting example of research is also the modification of the powder composition, e.g., by adding tungsten disulfide (WS_2), which can provide self-lubricating properties, further improving the tribological characteristics of coatings [4].
Laser cladded coatings with the addition of Cr_3C_2 achieve hardness in the range of 850-1200 $HV_{0.3}$, depending on the carbide concentration, process parameters, and powder quality.
Due to the presence of hard Cr_3C_2 particles, coatings exhibit up to 5-10 times higher wear resistance compared to the base material (e.g. tool steel or titanium alloys).
The chromium carbide Cr_3C_2 has chemical and structural stability up to a temperature of 870-980°C, which makes such coatings resistant to oxidation and thermal degradation.
Laser cladding allows obtaining coatings with very good metallurgical bond to the substrate and a dense, compact structure, with a minimum number of internal defects.
In recent years, numerous studies have been carried out on the use of chromium carbide (Cr_3C_2) in laser-deposited coatings. Many studies on the optimization of powder composition, the influence of process parameters on the microstructure, and tribological studies of coatings can be found in the literature [5,6].
The results of the research presented in the literature have shown that Cr_3C_2-NiCr coatings are characterized by a heterogeneous microstructure, in which the following can be distinguished:
- Separate Cr_3C_2 carbide particles that increase wear resistance,
- Nickel-chromium matrix (NiCr) that improves the ductility of the coating and its fracture resistance,
- Fine-grained dendritic structures whose presence depends on the cooling rate.
Recent studies emphasize the importance of minimizing porosity and microdefects in Cr_3C_2–NiCr laser-cladded coatings to improve mechanical and wear-resistant properties. Zhang et al. [7] demonstrated that proper selection of laser cladding parameters enhances the homogeneity and metallurgical bonding of the coating with the substrate. Similarly, Huirui et al. [8] analyzed the mechanisms of pore and crack formation and proposed optimization strategies, such as the adjustment of laser power, scanning speed and shielding gas parameters, to improve coating quality. These findings underline the critical role of process control in obtaining dense, well-adhered coatings with high functional performance.
In this study, the experimental powder Cr_3C_2 7(Ni 20Cr) was used to produce composite coatings by means of laser cladding with a disk laser. Two different gas atmospheres were applied during cladding. First was the typical atmosphere of argon as an inert gas used during conventional laser cladding. For comparison the nitrogen was used as the active atmosphere. The laser cladding in active gas can be considered as a hybrid process combining conventional laser cladding with a gas nitriding/alloying process.

2. MATERIALS AND METHODS

The study aimed to evaluate the quality and structure of test clads made with self-fusing chromium carbide-nickel aluminide powder with the
nominal chemistry Cr_3C_2 7(Ni 20Cr) by laser deposition. The nominal particle size distribution is -75 +10 (μm), while the morphology of the particles is angular, blocky, and spheroidal.
The coating structure produced by the powder consists of a chromium carbide-nickel matrix and hard phases of nickel and chromium borides, carbides, and carboborides. The structure provides a combination of good resistance to wear and corrosion at elevated temperatures up to 820°C.
The test clads were made on a steel plate made of non-alloy steel S235 with dimensions of 80x80 mm and a thickness of 6 mm, Table 1.
The tests of laser deposition were carried out using a Yb: YAG TruDisk 3302 disk laser with a wavelength of 1.03μm and a maximum output power of 3.3 kW with a laser beam diameter of 200μm. However, the tests of laser deposition were carried out with a defocused laser beam by increasing the distance of the laser head by 70 mm from the surface of the steel substrate. In this configuration, the diameter of the laser beam on the surface of the steel substrate was approximately 2.5 mm.
The powder was fed into the melt pool by a nozzle with a diameter of 1 mm at a constant powder feed rate of 6.5 g/min. The powder feeding nozzle was positioned in front of the melt pool and inclined at an angle of

approximately 45° to ensure the lowest possible powder losses. The powder carrying gas was argon with a purity of 99.999% at a flow rate of 1.5-1.6 l/min. Laser metal deposition tests were carried out in an argon atmosphere as a shielding gas, which was fed by means of a nozzle with a diameter of 8 mm set at an angle of 45° (and a flow rate of 8-8.5 l/min. In addition, for comparison purposes, clads were made in a nitrogen atmosphere, with the same other cladding parameters. The test clads were made as single straight beads at different heat inputs, as a result of changing the output power of the laser beam at a constant traveling speed (speed relative to the substrate). The traveling speed was set at 300 mm/min, and it was determined on the basis of previous laser cladding tests. In turn, the output power of the laser beam in the range of the study was assumed at the level of 1000 and 2000 W, also selected on the basis of preliminary laser cladding tests (Table 2).

Before laser deposition tests, the steel substrate was sandblasted to provide repeatable surface conditions with the roughness of Rz 30÷60 µm (Ra≥12.5). The surface was additionally cleaned with alcohol.

Table 1. Chemical composition (wt.%) of the substrate of mild steel S235 (according to EN 10025-2)

C	Mn	Si	P	S	N	Cu	Fe
max. 0.17	max. 1.4	0.05	0.04	0.04	0.012	0.3	Bal.

After completing the tests of laser cladding, first the test clads were examined visually, then samples were cut perpendicularly to the longitudinal axis of clads and samples for metallographic analysis were prepared by a typical procedure including grinding, polishing ad etching, Fig. 1.

Table 2. Basic parameters of laser deposition, Fig. 1

Sample No.	Output power, W	Shielding gas	Energy input*, kJ/cm
A2	1000	Argon	2.0
A4	2000	Argon	4.0
N2	1000	Nitrogen	2.0
N4	2000	Nitrogen	4.0

Remarks: * - unlike heat input, energy input does not take into account the efficiency of heat transfer to the material, traveling speed: 300 mm/s, powder feed rate of 6.5 g/min

Macrostructure of clads was observed and analysed by the OLYMPUS SZX-9 microscope, while the microstructure was analysed by the NIKON Eclipse MA100 microscope. Additionally, the microstructure was identified by the SEM microscope Phenom Pro-X and Carl Zeiss with EDS detectors.

Microhardness distribution was measured on metallographic samples, starting from the under top surface region to the base metal, as illustrated in Fig. 2. The measurements were carried out by means of the hardness tester WILSON WOLPERT 401 MVD was used for the measurements. The load of 50 N and dwell time of 10 s was set during measurements. The distance between subsequent points was 0.1 mm, Fig. 2.

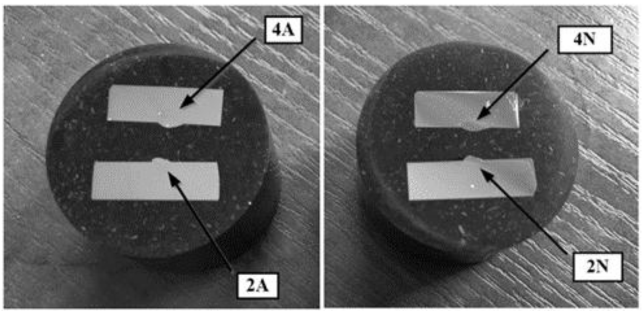


Fig. 1. View of clad samples prepared for metallographic testing, Table 2

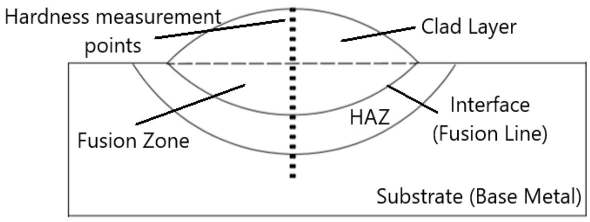


Fig. 2. Scheme of microhardness measurements

3. RESULTS AND DISCUSSION

Observations of test clads showed that the beads made at low heat input are asymmetrical, which was most likely caused by the non-axial orientation of the powder feeding nozzle. In the case of clads made at higher heat input, the asymmetry of the clad face was much smaller, which is the result of the larger volume and larger width of the melt pool. Under these conditions, the powder fed through the nozzle into the melt pool is melted and distributed more evenly.

Macro and microscopic observations confirmed that the fusion line of the clads made at lower heat input is also asymmetrical. On the other hand, the penetration depth of clads made at a higher power of 2000 W is greater, with the highest penetration depth being held by the clad made in an active nitrogen atmosphere. In this case, the penetration depth is three times higher compared to the clad made at a lower laser power of 1000 W, Fig. 3, Table 3. In addition, the dilution by the base metal of the clad made in an active nitrogen gas atmosphere is significantly higher (56.6%) than the clad made at the same parameters, but in a neutral argon atmosphere (50.5%).

Table 3. Dimensions of the clads, Fig. 3

Sample No.	Penetration depth, [mm]	Width, [mm]	Reinforcement, [mm]	Dilution, [%]
A2	0.6	4.7	1.1	25.2
A4	1.3	6.6	1.3	50.5
N2	0.5	4.8	1.2	24.3
N4	1.6	6.9	1.2	56.6

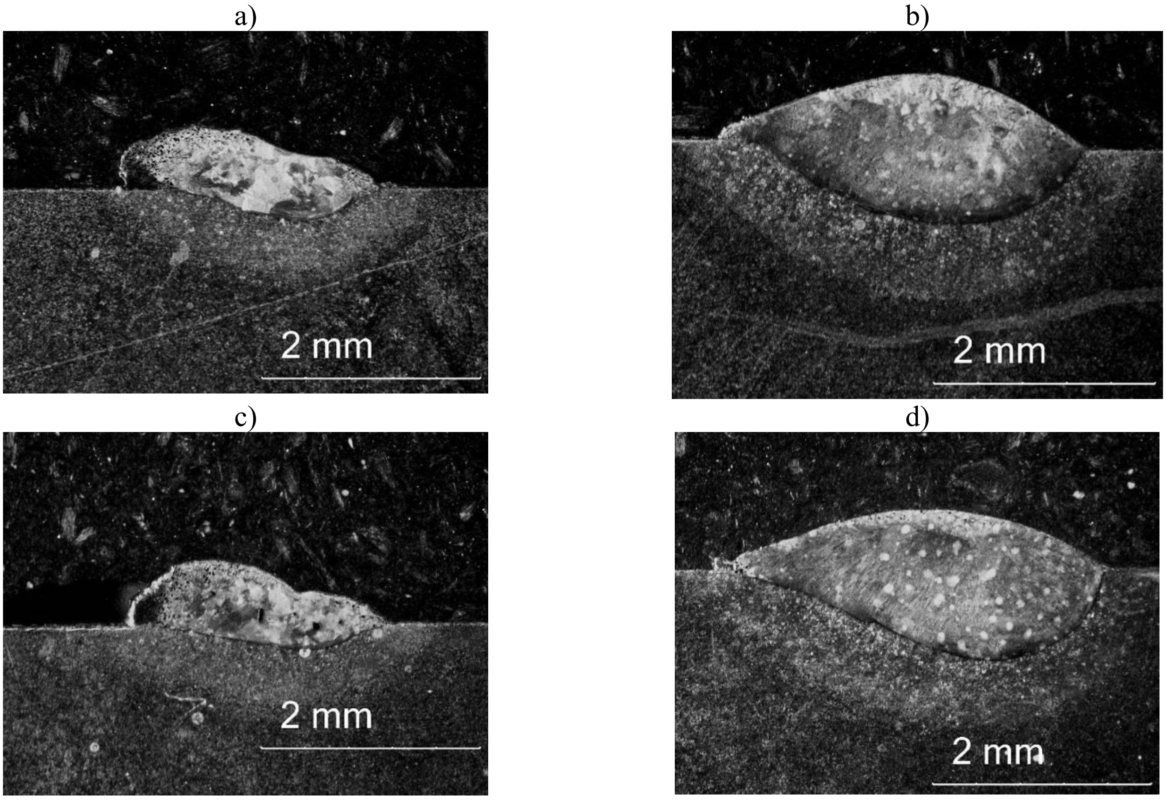


Fig. 3. Macrostructure of the single beads produced by laser cladding of composite Cr_3C_2 7(Ni 20Cr) powder at scanning speed 300 mm/min, powder feeding rate 6.5 g/min in Argon: a) sample A2, 1000 W, b) sample A4, 2000W, and in Nitrogen atmosphere: c) sample N2, 1000W, d) sample N4, 2000 W

Microscopic observations showed that the clads have a composite structure composed of carbides embedded in the matrix. The reinforcing carbides Cr_2C_3 in matrix of clads are characterized by different sizes, irregular shape and uneven distribution on the cross-section of clads. These carbides come from composite powder, but they were partially melted during laser cladding and their share in the clad strongly depends on the dilution by base metal. For this reason, it is advantageous to ensure the lowest possible dilution of base metal.

Microscopic observations revealed also a crack in the cross-section of the A2 clad. Massive carbides that are partially melted enrich the melt pool with alloying elements (mainly Cr and C) what causes precipitation of

carbides during the cooling of the melt pool. These carbides have an acicular shape and are located perpendicular to the surface of irregularly shaped massive particles (Cr_2C_3 carbides), Fig. 4-8.
Microstructures of the clad cross-sections are shown in Fig. 4-5. Figures 4 and 5 present the microstructure of the coating at 1000 W laser power using argon (A2) and nitrogen (N2) shielding gases. In both cases, partially melted Cr_3C_2 particles are visible. However, the coating formed in nitrogen appears denser and more homogeneous. The fusion line in N2 (Fig. 5b) is smoother, indicating more stable metallurgical bonding. Similar effects of gas atmosphere on structure compactness were reported by [2, 4].

a) b)

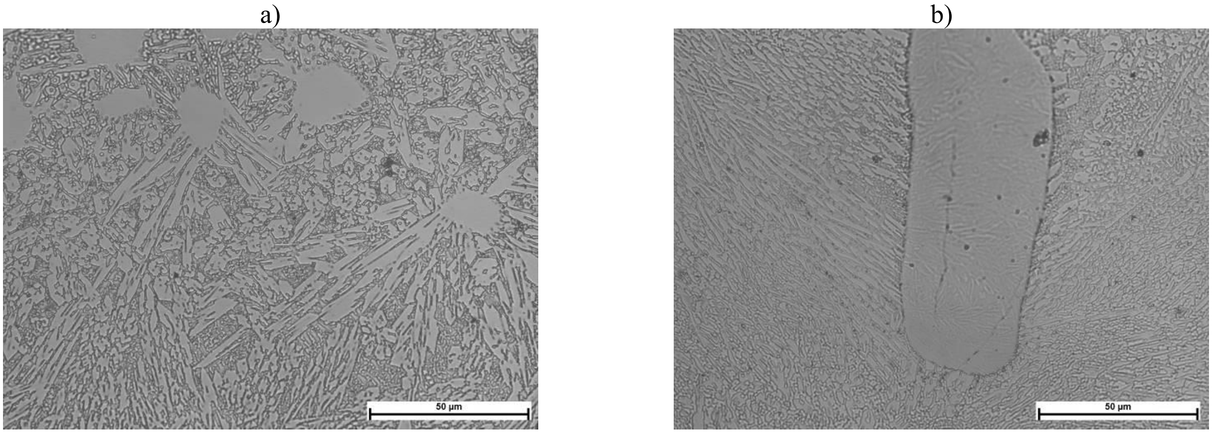


Fig. 4. Microstructure under surface of clads produced at laser power 1000 W in: a) argon atmosphere, A2, b) nitrogen atmosphere, N2, table 3

a) b)

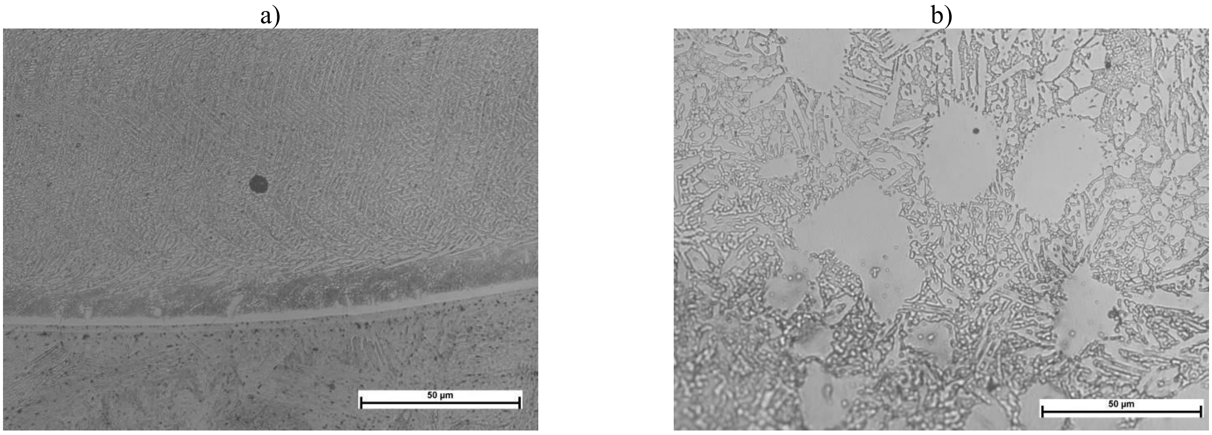
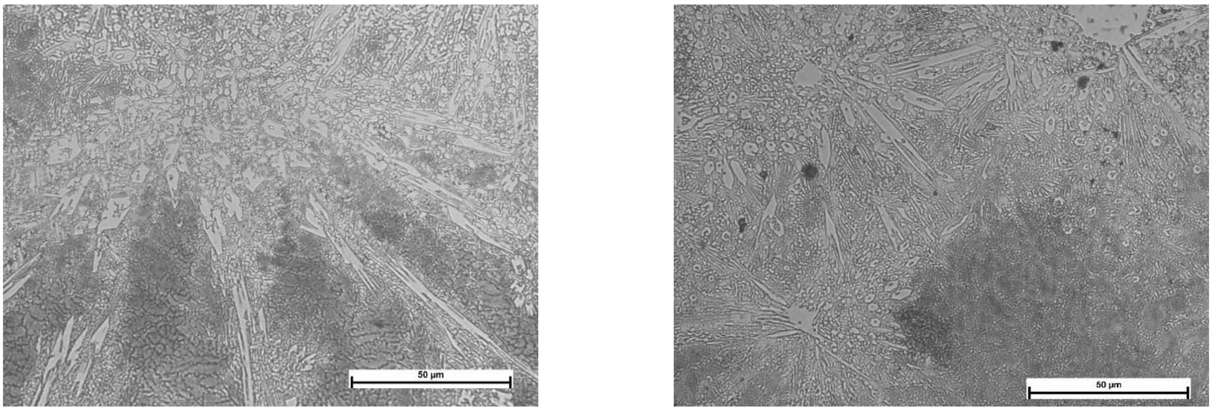


Fig. 5. Microstructure near the fusion line of clads produced at laser power 1000 W in: a) argon atmosphere, A2, b) nitrogen atmosphere, N2, Table 2

Figures 6 and 7 show microstructures of clads produced at 2000 W. The coating formed in nitrogen (N4) again exhibits better cohesion and deeper penetration than in argon (A4). The structure is less porous and more regular, confirming the positive effect of nitrogen as an active gas, consistent with findings in [5, 6].
Studies of the chemical composition on the cross-section of the clads confirmed that the massive particles in the structure are chromium carbides (containing chromium Cr), and the matrix contains mainly by nickel Ni, aluminium Al and additionally cobalt Co was identified, Fig. 8,9. Figure 8 illustrates a more compact structure in the N2 sample, with smaller carbide particles and less porosity. This agrees with [4], who observed a similar refinement with nitrogen shielding. Figure 9 confirms the expected distribution of Cr in carbides and Ni, Al, Co in the matrix, as consistent with previous work on Cr_3C_2-NiCr composites [1, 3].



a) b)

Fig. 6. Microstructure under the surface of clads produced at laser power 2000 W in: a) argon atmosphere, A4, b) nitrogen atmosphere, N4, Table 2

a) b)

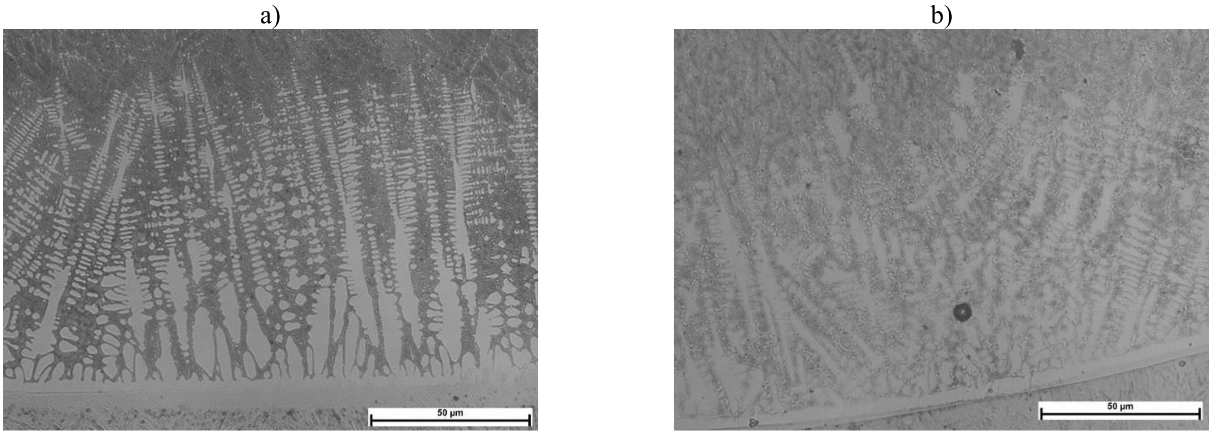


Fig. 7. Microstructure near the fusion line of clads produced at laser power 2000 W in: a) argon atmosphere, A4, b) nitrogen atmosphere, N4, table 2

a) b)

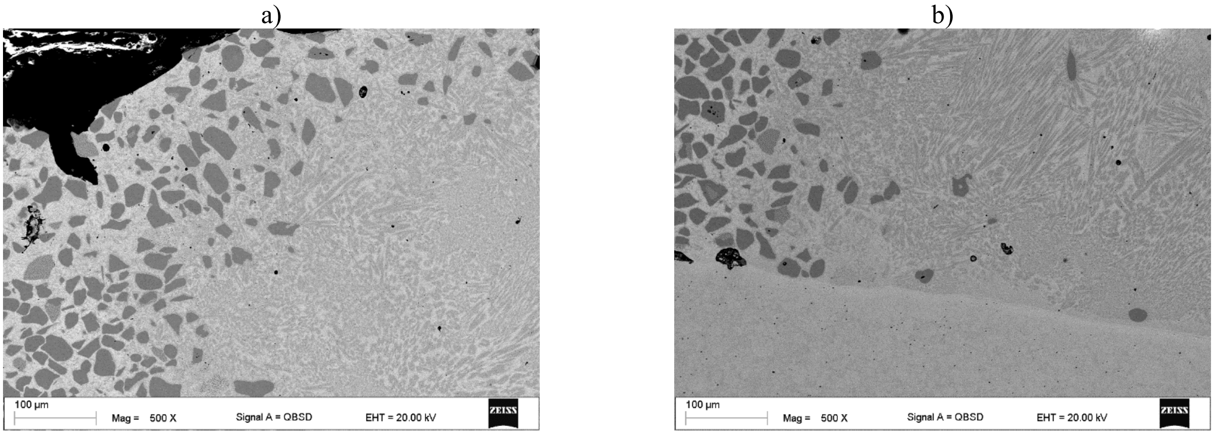


Fig. 8. SEM micrographs of clads produced at the lowest heat input and laser power 1000 W; a) sample A2 produced in argon atmosphere, b) sample N2 produced in nitrogen atmosphere

The hardness results showed that the hardness of clads made in an active nitrogen gas atmosphere showed higher values, which is particularly evident in the case of clads made at low heat input with a laser beam power of 1000 W, Fig. 10,11. Figure 10 shows that the coating produced in nitrogen (N2) has higher and more stable hardness values (~800 $HV_{0.5}$) compared to argon atmosphere (A2; maximum hardness about 690 $HV_{0.5}$, but a visible drop in the HAZ), which shows greater fluctuation. These results support findings in [1, 6], where coatings using active gas shielding exhibited better mechanical performance.

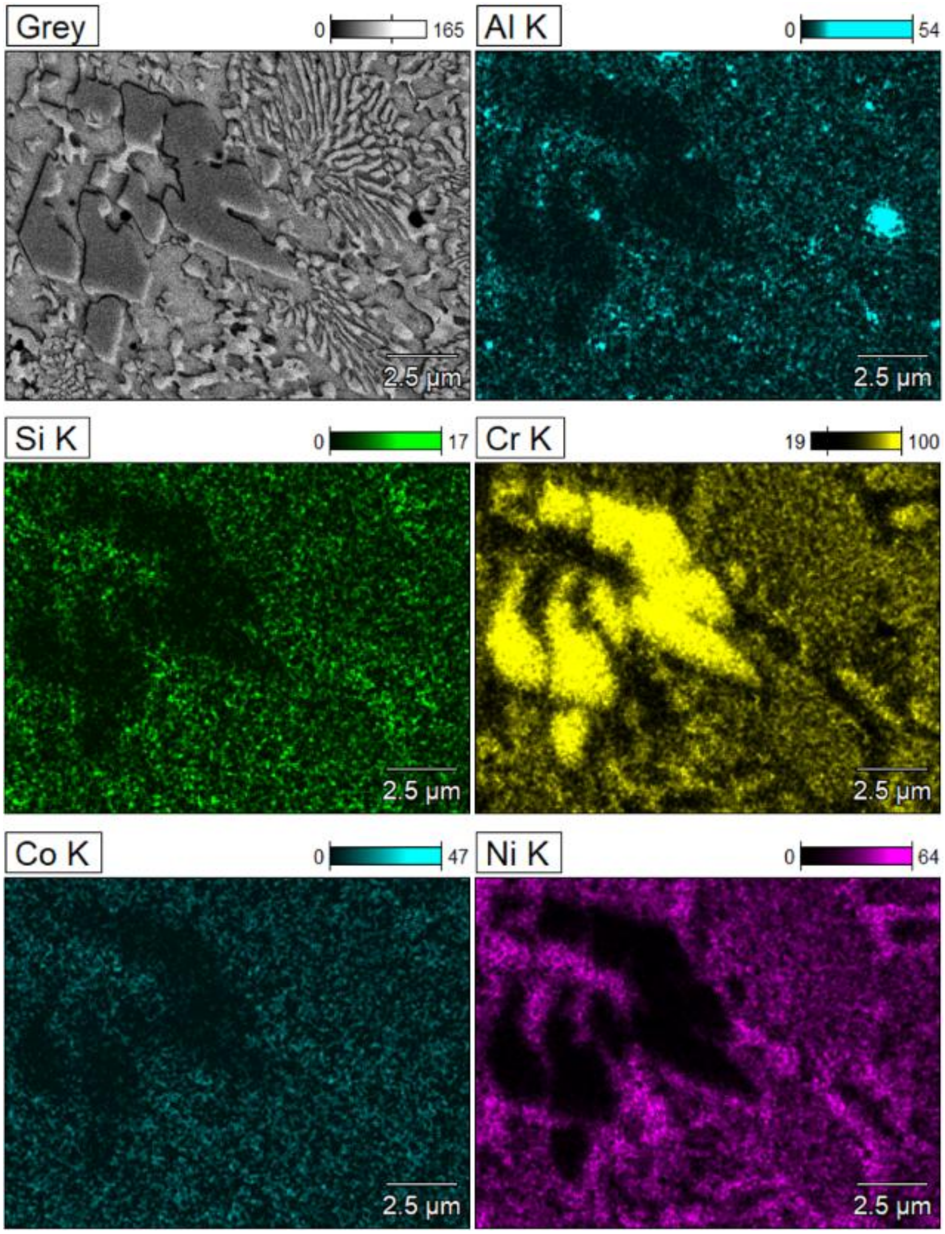


Fig. 9. Representative SEM micrograph of the clad N2 produced at laser power 1000 W in an active atmosphere of nitrogen (Grey) and maps of the elements distribution

a) b)

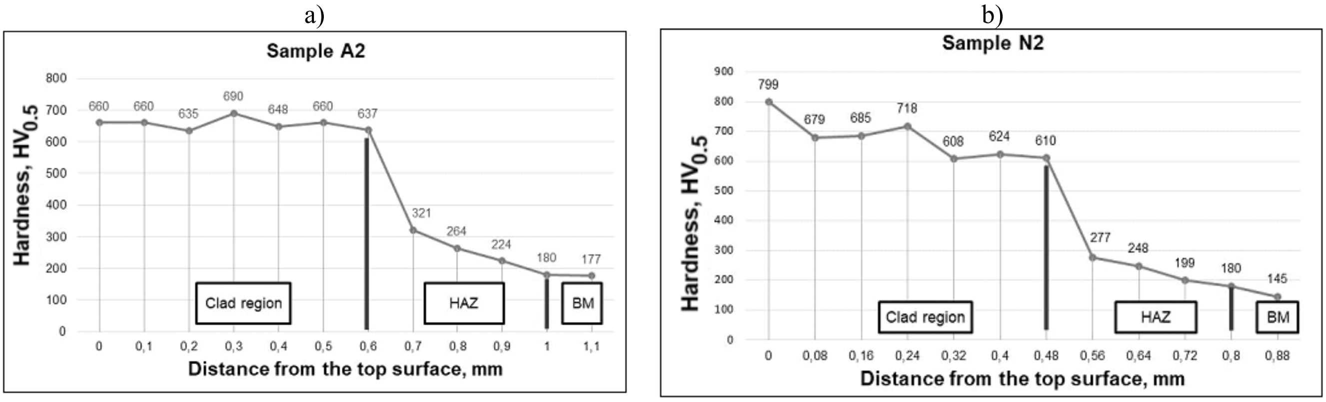


Fig. 10. Microhardness distribution on cross-sections of the test clads produced at laser power 1000 W: a) A2, argon atmosphere, b) N2, nitrogen atmosphere

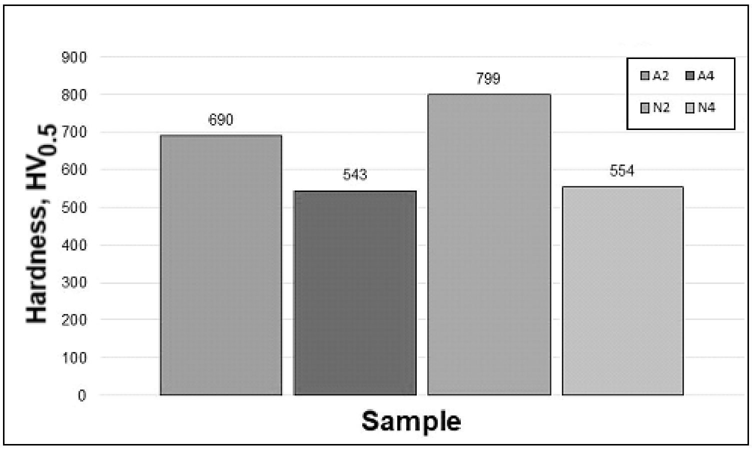


Fig.11. Comparison of the highest values of microhardness measured for test clads, Table 2

A qualitative tool in the form of the 5Whys method was used to identify the causes of imperfections and defects in the tested clads (Table 4). Based on the results of the study and the analysis of 5 Whys, it was concluded that precise control of process parameters and technological conditions is necessary to ensure reproducible laser cladding conditions, and further testing and research are needed to optimize process parameters.

Table 4. 5Whys method for test clads that do not meet the quality requirements

Problem	Coating does not meet quality requirements
1. Why does Laser-cladded coating not meet quality requirements?	Several critical defects of clads were found: asymmetry, cracks, uneven distribution of carbides, too low carbide share.
2. What can be the cause of these defects?	Asymmetrical positioning of the powder nozzle, excessive penetration, and unfavorable distribution of internal stresses.
3. Why was the powder nozzle positioned incorrectly? What caused excessive penetration depth and stress in the overlay?	The reason for improper setting of the nozzle could be accidental shifting, careless preparation of the cladding process. The reason for the unfavorable stresses could be the asymmetrical shape of the clad, and the reason for the excessive penetration depth could be the wrong setting of the powder stream (incorrect nozzle setting) and/or improperly selected surfacing parameters.
4. Why could the powder nozzle have been accidentally moved, and why could the cladding parameters have been incorrectly selected?	Accidental nozzle movement could have been caused by insufficient process control, too fast and careless execution of cladding tests.
5. Why is the process insufficiently controlled? How to improve the shape of the clads, reduce the risk of cracks, and limit the depth of penetration?	It is necessary to perform further surfacing tests to optimize the parameters and ensure fully repeatable conditions of the surfacing process and control of all parameters and technological conditions.

4. CONCLUSIONS

The study evaluated the quality, microstructure, and hardness distribution of laser-deposited coatings produced by Cr_3C_2-7(Ni20Cr) powder on S235 mild steel substrates. The study focused on the effects of laser power (1000 W and 2000 W) and shielding gas (argon vs. nitrogen) on the properties of coatings. Based on observations of the microstructure and quality of the coatings, it was found that coatings produced in the nitrogen atmosphere showed denser, more homogeneous structure with fewer defects compared to those made in argon. SEM and EDS analysis confirmed the uniform distribution of Cr_3C_2 carbides embedded in the NiCr matrix, especially in N2 and N4 samples. Nitrogen shielding improved metallurgical bonding, as evidenced by smoother fusion lines and deeper penetration. In addition, higher hardness values (~800 $HV_{0.5}$) were obtained in nitrogen-shielded coatings (N2, N4) compared to argon-shielded coatings (A2, A4; max. 690 $HV_{0.5}$), suggesting increased wear resistance due to active gas interaction. Asymmetry and cracks in the low-power (A2) cladding were found to be related to nozzle misalignment and insufficient heat input. The 5 Whys analysis highlighted the need for precise parameter control to minimize defects. Higher laser power (2000 W) reduced asymmetry and improved carbide distribution, but increased dilution (56.6% for N4 vs. 50.5% for A4).

Further optimization of laser power, scanning speed, and gas flow is required to balance dilution and carbide retention. Nitrogen shielding shows promise for industrial applications due to its positive effects on coating cohesion and hardness. In summary, this study demonstrates that laser cladding parameters and shielding gas selection critically impact coating quality.

Author Contributions: Conceptualization, A.L.; methodology, A.L., investigation, W.P.; validation, A.K-L.; data curation, A.L.; writing - original draft preparation, A.L. and A.K-L.; writing - review and editing, A.L. and A.K-L.; All authors have read and agreed to the published version of the manuscript.
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