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STUDY OF LASER CLADDING OF COMPOSITE COATINGS

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Abstract: Laser cladding is often used for manufacturing of protective coatings due to limited heat input. The thermal conditions are decisive for the microstructure and thus the properties. In this study Ni-based powder with addition of WC particles was used laser cladding with the TruDisk 3302 laser. Tests were conducted at different energy input (heat transfer efficiency not considered). Powder was fed directly into the melt pool by a single coaxial nozzle set in front of the melt pool. The influence of basic laser cladding parameters on the geometry, microstructure and hardness was determined. The heat input of laser cladding has significant effect on chemical and phase composition, as well as microstructure. The obtained coatings have typical composite structure with NiCr metallic matrix and WC carbides. The lower energy input of laser cladding is beneficial providing limited penetration depth, dilution, and preferable distribution and high share of tungsten carbides. However, too low energy input at the chosen technological conditions will lead to the lack of fusion. The share of carbides on cross section of the coatings produced at minimum heat input is over 50%, while for the maximum heat input the share is below 20%.

Key word: laser cladding, heat input, Ni-based powder, composite coatings, disk laser generator

1. INTRODUCTION

The problem of wear of tools and moving parts is well known and continues to be a major industrial and economic challenge. The progressive wear of working surfaces and working edges of components or tools is the natural phenomenon under normal operation conditions. Due to excessive wear of the working surfaces, usually the characteristic of the component or even entire device or machine deteriorate. Finally, the component must be replaced. Therefore, for technical and economic reasons it is usually beneficial to ensure the highest possible durability of parts, components, or tools. It is costly to manufacture the entire element from a highly wear-resistant material [1, 2]. Therefore, different methods and technologies are used for making protective coatings or for shaping the surface layer properties, providing increased service time. Laser cladding is one of the modern and advanced coating technologies which can be considered as attractive due to some advantages. The most important advantages that can be pointed are high flexibility ease of robotization and automation, high power density, localized and precise heating and melting, high scanning speed, low heat input, low penetration depth and low dilution. It is worth to mention that the low heat input and related high cooling rate can provide some beneficial effects and high quality coatings can be produced, characterized by good metallurgical bonding, fine-grained and refined microstructure. Such factors are decisive for properties of surface layers and coatings, especially for tribological characteristics, abrasive or erosion wear resistance or corrosion and fatigue resistance [3,4]. The laser cladding process has been studied extensively for a long time by many researchers and it is already well known. Hence, many results presented in various studies indicate that usually the surface layers, clads, and coatings produced by laser cladding expose better properties compared to coatings produced by plasma transferred arc (PTA) or conventional arc cladding processes, even if the coatings are made by the same materials. Explanation of this phenomenon is related with intense grain refinement resulted by rapid cooling at the solidification stage. The quantitative results presented in the literature indicate that the cooling under laser processing is approx. an order of magnitude higher than under plasma arc cladding. Since the refinement of the microstructure is advantageous, different techniques of accelerated cooling are also being developed and described in the literature [5].

The multitude of different materials and coatings is due to the fact that the type and intensity of wear depend on the type and intensity of load, environmental factors such as corrosive liquid or gaseous agents, temperature (high or low) [6]. Therefore, each coating should be individually designed and customized considering the wear conditions, environment characteristics and operating conditions [7].

Laser cladding is usually used for manufacturing wear-resistant coatings based on metallic or composite materials. The most popular metallic materials used for protective coatings and considered as providing good wear resistance in various conditions, there are alloys based on Ni, Co, and Fe.

Another type of coatings often produced by laser claddings are metal matrix composite MMC (ex-situ or in-situ) [4,5]. The metal matrix composites are composed of metallic matrix (relatively soft) reinforced by hard particles. The reinforcing particles are usually oxides, nitrides, borides, or carbides. Such composite materials provide superior protection against wear under abrasive type load at low or medium impact.

One group of metal matrix composites used commonly for protective coatings are coatings based on nickel matrix and reinforced by tungsten carbides (WC). Such composites are characterized by good wear resistance, corrosion resistance and satisfactory dynamic load resistance [6]. Therefore, in this study the process of laser cladding with the TruDisk 3302 laser of composite coatings based on nickel matrix with addition of reinforcing particles of WC was undertaken.

2. MATERIALS AND METHODOLOGY

The aim of the study was to investigate the influence of basic laser cladding parameters, especially energy input on the geometry, properties, and microstructure of composite clads. The tests of cladding were conducted on fully automated stand equipped with a disk laser generator TruDisk 3302. The maximum output power of the applied laser was 3.3 kW. The wavelength of the laser beam was 1030 nm. The laser head was coupled with the generator by a fiberglass with a core diameter 200 µm and mounted on a vertical drive (axis “z”) of the 3D positioning system controlled by a PC computer. The powder was delivered into the melt pool by a cylindrical nozzle 1.2 mm in diameter and constant feeding rate of 8.0 g/min. The powder delivering nozzle was set in front of the melt pool at an angle approx. 40°, providing maximum powder efficiency (minimalized powder loss). The carrying gas was high purity argon set at 2.0 l/min. The shielding gas was also high purity argon delivered to the melt pool region by cylindrical nozzles 10 mm in diameter. The gas flow took place several seconds before the laser beam, and was kept constant at approx. 8.0 l/min.

Since the laser beam spot at the applied optics was just 200 µm in diameter, the laser beam was defocused by lifting the laser head 35 mm over the top surface of the steel plate substrate. Under such set the laser beam diameter on the substrate was approx. 1.5 mm.

The substrate for laser cladding was mild steel S235 (EN 10025-2) with thickness 6.0 mm, Table 1, Fig. 1. The dimensions of the coupons were 80x80 mm. Prior to cladding tests, the steel substrate was sandblasted, providing repeatable surface conditions with the roughness of Ra 30÷60 µm. Additionally, the surface was cleaned and degreased by acetone. The powder used in the study was commercially available (DURMAT 352) NiCr-WC composite powder (Cr 16÷18wt.%, WC 60wt.%, and Ni balance). The particle size of the powder was ranged 53÷150 µm, Fig. 2, 3, Table 2.

The test clads were produced as single stringer beads at different energy input. The scanning speed and laser output power were changed. Each test stringer bead was 50 mm long. The scanning speed was 200 mm/min and 300 mm/min, while the laser output power was ranged from 1.0 kW to 2.0 kW.

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

C	Mn	Si	P	S	N	Cu	Al	Fe
0.05–0.14	0.2–0.8	0.1	0.025	0.015	0.01	0.2	0.015–0.08	Bal.

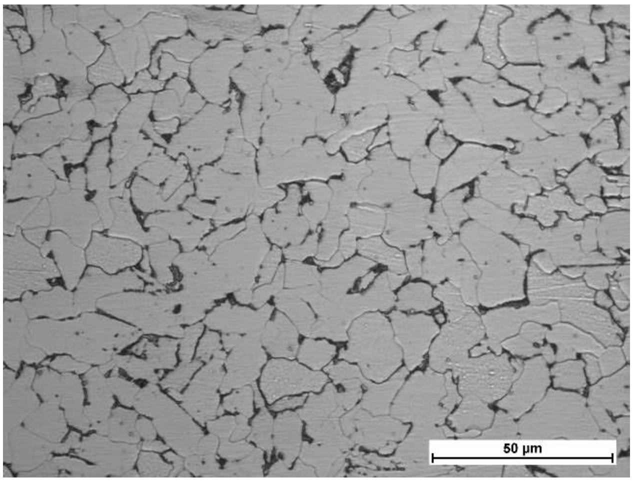


Fig. 1. Microstructure of the substrate of mild steel S235 (EN 10025-2)

After completing the tests of laser cladding, first the stringer beads were examined by visual inspection. Next the test samples were cut perpendicularly to the stringer beds axis, and samples for metallographic analysis and observations were prepared. Macrostructure and microstructure of the surface layers was analysed by OM and SEM microscope Phenom Pro-X and Cark Zeiss with EDS detectors.

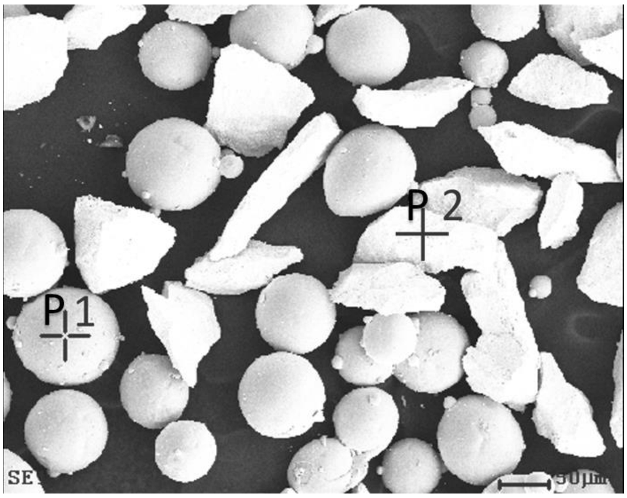
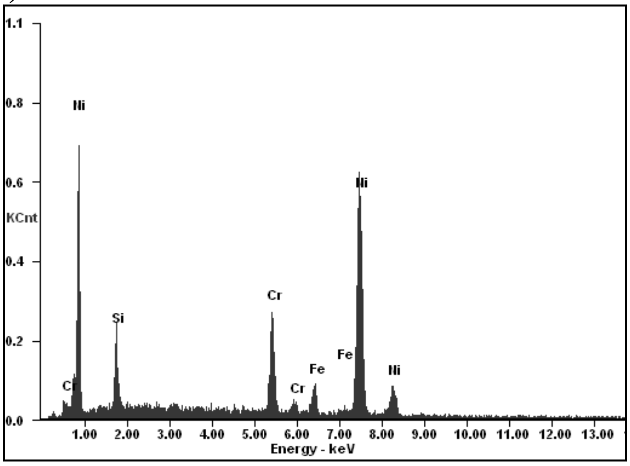


Fig. 2. Morphology of the composite NiCr-WC powder; irregular fused WC particles (P2) and spherical metallic NiCr particles (P1)

a)



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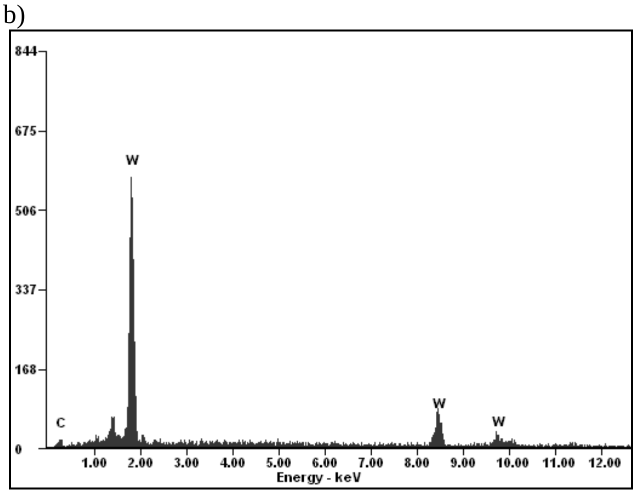


Fig. 3. EDS spectra of the composite NiCr-WC powder taken from the; a) spherical metallic particle (P1, Fig. 2), b) irregular WC particle (P2, Fig. 2)

Table 2. EDS analysis of the composite NiCr-WC powder

Point	Elements. Wt.%					
	Ni	Cr	Si	Fe	W	C
P1	75.2	13.4	6.2	5.2	-	-
P2	-	-	-	-	91.9	8.1

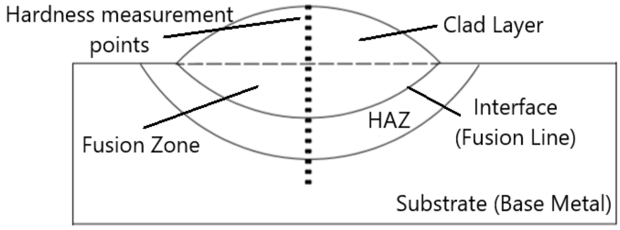


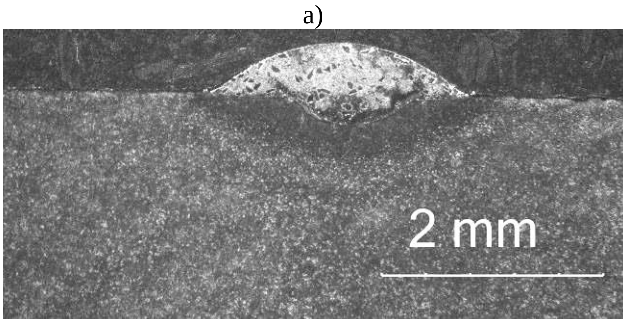
Fig. 4. Scheme of microhardness measurements

Microhardness distributions were determined on cross-sections as shown in Fig. 4. The measurements were carried out by means of the hardness tester WILSON WOLPERT 401 MVD at the load of 10 N and the dwell time of 10 s. The distance between the subsequent points was 0.2 mm.

3. RESULTS AND DISCUSSION

The visual testing VT of the single stringer clads showed that the surface of the clads is smooth and even. No shape imperfections were found at this stage of investigations. Therefore, all the clads were intended to cut and prepare metallographic samples. The macrographs analysis showed that all the clads meet the criterion of complete penetration of the substrate, Fig. 5. However, it is obvious that the shape, especially the width, reinforcement, and penetration depth depend on the parameters, mainly heat input.

a)



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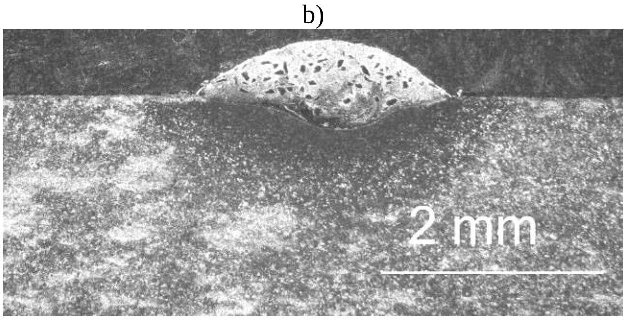
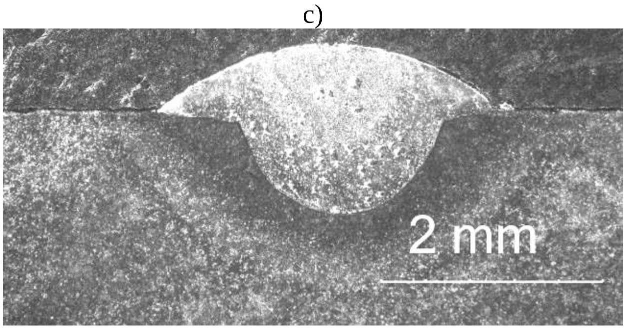


c)



d)

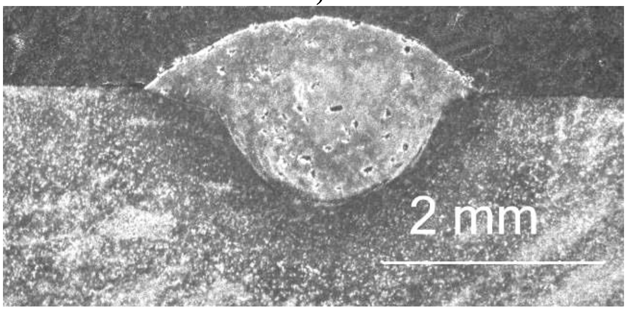
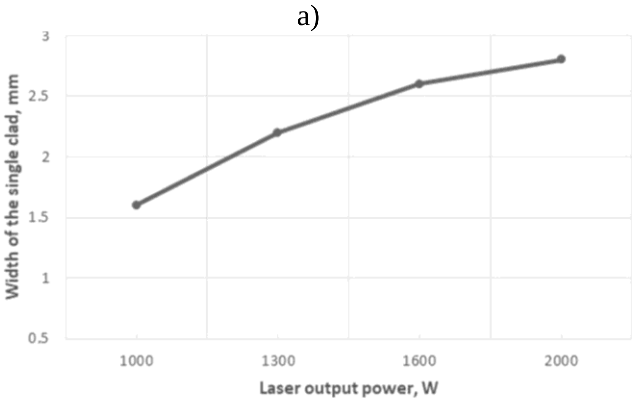


Fig. 5. Macrostructure of the single stringer beads produced by laser cladding of composite NiCr-WC powder at constant scanning speed 300 mm/min, powder feeding rate 8.0 g/min and different laser output power: a) 1000 W, b) 1300W, c) 1600W, d) 2000 W

Moreover, the observations od macrographs proved high quality of the clads, because no internal imperfections were found, such cracks or porosity.

a)



b)

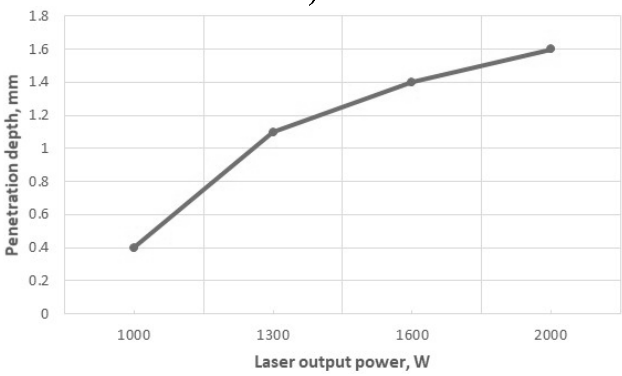


Fig. 6. Influence of the energy (heat transfer efficiency not considered) input on the width (a) and penetration depth (b) of the stringer beads, Fig. 5

All the test clads show composite structure with WC carbide particles embedded in the matrix. However, even at this stage it can be seen that the number and distribution of carbides is different and depend on the processing parameters. The width of the clads in the investigated range of parameters is from 1.6 to 2.7 mm, Fig. 6a. In turn, the penetration depth at the minimum energy input (200 J/mm) and minimum laser output power of 1000 W is approx. 0.4 mm. The penetration depth increases up to 2.5 mm at the maximum energy input (400 J/mm) and the laser output power of 2000 W, Fig. 6b. The width of the heat affected zone can be clearly seen at the micrographs, and it is ranged between 0.8 to 1.5 mm, Fig. 5. Both the face of the clads and the fusion zones are even and elliptical. Next the microhardness profiles were determined and analysed. As can be seen in Fig. 7 the microhardness in the region of the clads is from 600 to 800$HV_{0.2}$. The microhardness of the clad produced at lowest heat input show the highest values at 800$HV_{0.2}$.

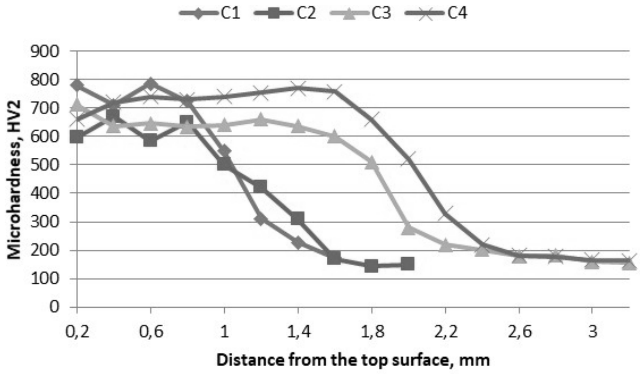
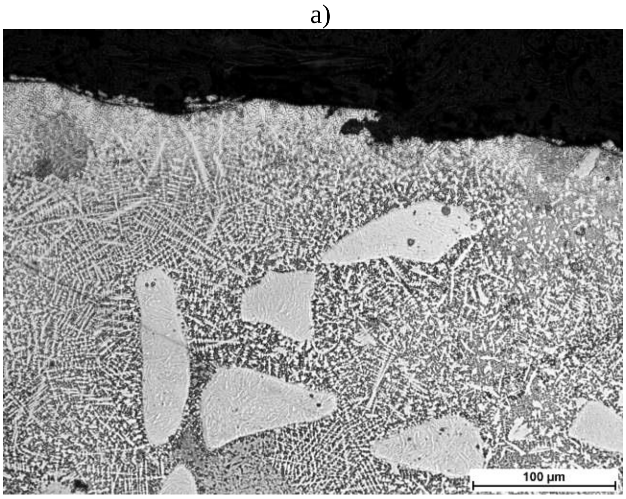


Fig. 7. Microhardness distribution on cross-sections of the stringer beads; C1 – produced at 1000 W, C2 – produced at 1300 W, C3 – produced at 1600 W, C4 – produced at 2000 W

However, the distribution of the microhardness is characterized by high dispersion, similarly like in the case of the clad produced at the output power 1300 W. On the other hand, the microhardness distributions of the clads produced at higher heat inputs (1600 and 2000 W) the curve is much more even in the region of clads. The explanation can be found in the Figures presenting microstructure of the clads, Fig. 8 to 10.

a)



b)

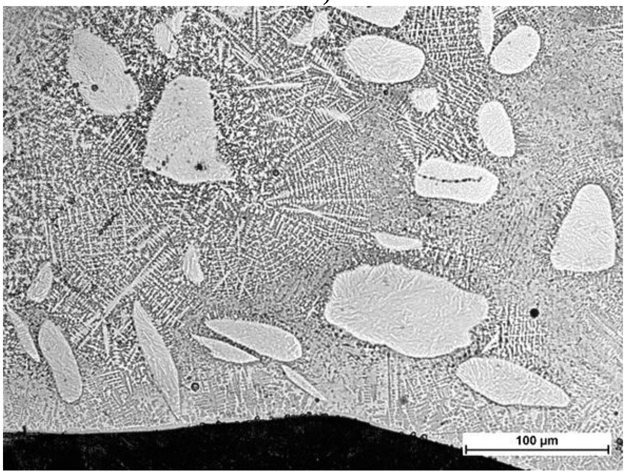


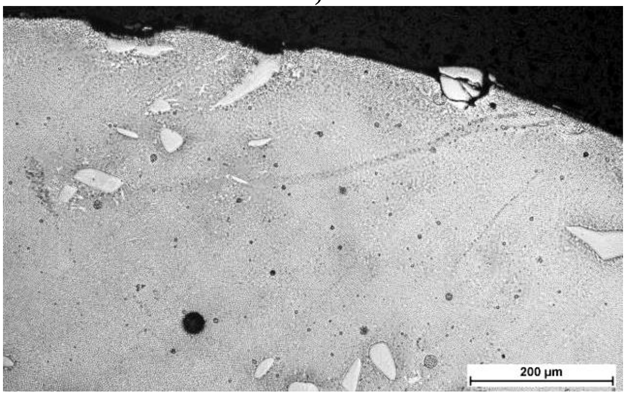
Fig. 8. Microstructure of the clad produced at lowest heat input and laser power 1000 W; a) under the top surface, b) near fusion line at the bottom

The microscopic images confirm what was shown on the macrographs. The share and distribution of massive carbides is different in the tested clads. The microstructure of the clad produced at the lowest heat input and laser power 1000 W is composed of densely packed massive carbides in the matrix. The share of massive carbides in this case is clearly higher than in the clad produced at the highest heat input and laser power 2000 W. By means of the planimetric method the share of carbides was estimated at least 50% for the clad produced at lowest heat input. In the case of such composite coating the microhardness measurements conducted at low area usually show high dispersion of results, because the material is not uniform (hard carbides and relatively soft matrix).

In turn, the clad produced at the highest heat input and laser power of 2000 W show also composite structure, but the share and size of massive carbides is clearly lower. Due to extensive heat and higher temperature of the melt pool, larger number of carbides were dissolved. As the result of WC carbides dissolving, the solid solution is enriched by the elements such C and W. The EDS analysis conducted on the NiCr-WC powder particles showed that beside the typical irregular particles of fused and crushed WC carbides, the spherical particles are composed of approx. 75.2% of nickel, 13.4% of chromium, but also approx. 6.2% of silicon, and 5.2% of iron, Fig. 2, 3, Table 2. For this reason, the microstructure is more uniform and also the microhardness distribution is uniform. In general, the values range of microhardness determined for the tested clads is similar, Fig. 7.

However, high hardness is maintained throughout the depth of the clads, which is proportional to the conditions of cladding, mainly heat input. Analysis of the micrographs revelled some slight imperfections. In the Fig. 8a a transverse transcrystalline crack can be found.

a)



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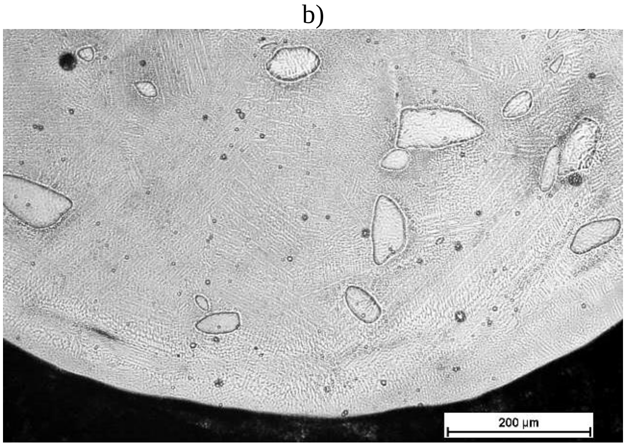
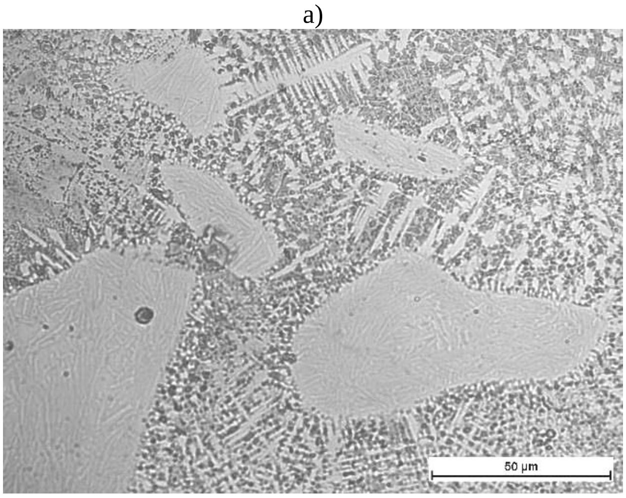


Fig. 9. Microstructure of the clad produced at highest heat input and laser power 2000 W; a) under the top surface, b) near fusion line at the bottom

The clads produced at higher heat input were free of such cracks. Moreover, some single pores can be found on every micrograph. However, the diameter of single pores in the case of the clad produced at the lowest heat input is up to several microns, while in the case of the clad produced at the highest heat input the diameter is significantly higher up to 50 microns, Fig. 8 and 9. Thus, the size, and intensity of the susceptibility for porosity is related with the heat input of the laser cladding process.

a)



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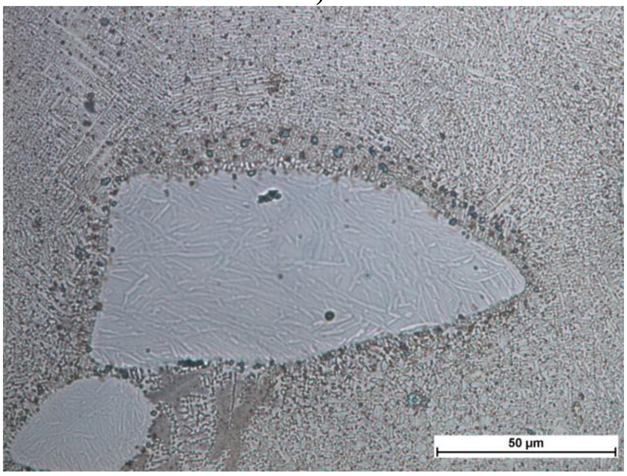


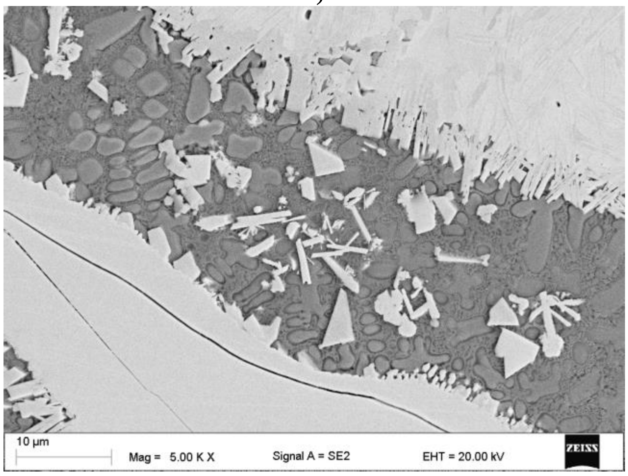
Fig. 10. Comparison of the microstructure in the space between the massive WC carbides: clad produced at lowest heat input and laser power 1000 W, b) the clad produced at highest heat input and laser power 2000 W

As can be seen the dendrites on the cross-section of the clad produced at lowest heat input are larger and clear, comparing to the microstructure of the clad produced at highest heat input, Fig. 9. However, the number of dendritic precipitations is lower. In turn, the microstructure of the clad produced at highest heat input is different. The dendrites are much smaller, but their number is clearly greater. Due to high extent of WC carbides dissolution, the melt pool is highly enriched by the W and C elements. Therefore, the precipitations of complex dendritic carbides are more intensive, and the large number of dendrites block each other during solidification. As a result, the number of dendritic precipitations is larger but they are smaller, Fig. 10.

Observations of the misstructure revealed that beside the massive WC carbides, there are significant amounts of dendritic precipitations in the case of the clad produced at the lowest heat input, Fig. 10, 11. Since even at the lowest heat input the partial decomposition of the WC carbides takes place, the liquid solution of melt pool is enriched by tungsten and carbon. Therefore, under solidification complex carbides containing W and Cr precipitate also. In the SEM micrograph of the clad produced at the lowest heat input the region between two massive WC carbides is shown, Fig. 11.

As can be seen, there are many small triangular, rectangular, and needle-like particles od size lower than 5 microns, Fig. 11a. Closer observations reveal traces of partial resolidification of the particles at edges, Fig. 11b. Such particles come from decomposition of the massive WC carbides due to exposition to high temperature of the melt pool or rather due to direct exposition to the laser beam interaction.

a)



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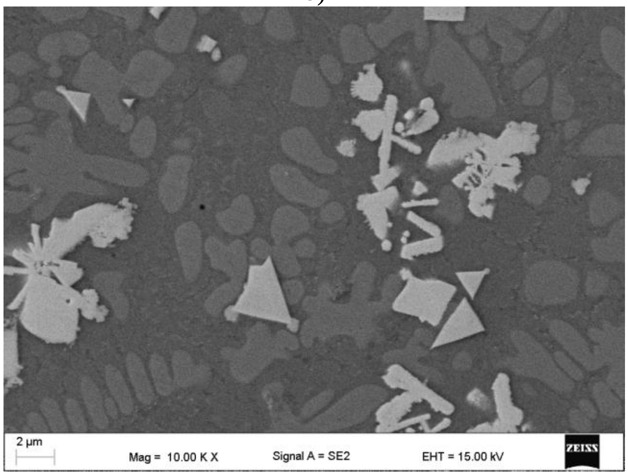

Fig. 11. SEM micrographs of the clad produced at lowest heat input and laser power 1000 W; a) region between two massive WC carbides with dendritic precipitations, b) small regularly shaped particles between dendrites' arms

Acknowledgements

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4. CONCLUSIONS

Based on the study of laser cladding of composite coatings by Ni-Cr-WC powder on steel some conclusions have been drown.

It was proved that the produced coatings have typical composite structure composed of NiCr metal matrix with massive carbides WC dispersed evenly on cross-section of the coting. However, the share and distribution of massive WC carbides depends clearly on the heat input of laser cladding. Moreover, the heat input of laser cladding has significant effect on chemical and phase composition, microstructure, and properties of the coatings. Lower heat input of laser cladding is beneficial due to lowering tendency for decomposition and dissolving the carbides in the melt pool. Additionally, the share of carbides on cross section of the coatings produced at minimum heat input is over 50%, while in the case of the coating produced at maximum heat input the share of massive WC carbides was below 20%.

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