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Article

Laser surface alloying of ductile cast iron with Ti + 5% W mixture

Aleksandra Kotarska[1,*]

[1] Silesian University of Technology, Poland;
* Correspondence: Aleksandra Kotarska M.Sc. Eng. Aleksandra.Kotarska@polsl.pl

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Abstract: The article presents results of the research on laser alloying of the ductile cast iron EN-GJS 350-22 substrate with the mixture of titanium powder with addition of 5 wt.% of tungsten. The aim of the process was to obtain surface layer with the in-situ composite structure. Laser alloying process was carried out using high power diode laser (HPDDL) with rectangular laser beam focus and uniform power density distribution in one axis of the beam focus (top-hat profile). The tests included determination of the influence of process parameters on the dimensions of the alloyed beads, metallographic macroscopic and microscopic observations, microhardness measurements of the laser alloyed layers and EDS chemical composition tests.

Keywords: laser surface alloying; ductile cast iron

Introduction

Ductile iron is a material widely used for various types of machinery and equipment, such as cams, pistons, cylinders. This is the result of combining many of the beneficial properties of this material. It is characterized by high mechanical and fatigue strength, with equally high plastic properties. In addition, this material exhibits very good casting properties and high machinability, which affects the relatively low manufacturing costs and ease of forming [1÷3].

However, despite many of the above advantages, ductile cast iron exhibits poor tribologic wear resistance, which is required in some applications, including crankshafts, valves, gearshifts and gearwheels. The use of surface engineering technology allows to improve the wear resistance of ductile cast iron, which results in a reduction in the production costs of this type of components in comparison with their production from an abrasion-resistant material with a significant content of alloy additives. The use of laser beam in surface engineering gives a number of advantages. First of all, it is possible to obtain unique structures caused by very high heating and cooling speeds. In addition, the laser beam gives the possibility of very precise processing of even small areas with minimal heat impact on the substrate material. Using the laser beam, various surface engineering processes can be carried out, for example surface hardening, remelting, alloying or surfacing [3÷6]. In the process of laser alloying, various components can be used, which are selected depending on the properties of the surface after machining. It can be either non-metals (e.g. coal), metals (e.g. Cr, Ni, Mo, W, Ti, Nb) and chemical compounds (e.g. carbides) [5÷9]. By adding carbides in the alloying process, it is possible to obtain a surface layer with a composite structure by ex-situ method. It is also possible to create a composite structure by adding components which in the pool of liquid metal will lead to the creation of in-situ reinforcement. An example of such an ingredient is titanium, which when combined with carbon forms TiC carbides with high hardness strengthening the metallic matrix [3,10,11].

Material and methodology of the research

The aim of the conducted research was to examine the structure and properties of a laser-welded surface layer using titanium powder with the addition of 5 wt.% tungsten, on a spheroidal iron substrate EN-GJS 350-22 with a minimum tensile strength of 350 MPa, a minimum yield strength of 220 MPa and a minimum elongation of 22%. The chemical composition of the cast iron is presented in table I. It is a cast iron with a carbon content of 3.66% with a ferrite-pearlitic structure, with ballistic graphites of approx. 65 µm diameter (Fig. 1). Titanium and tungsten as additional materials have been selected in order to create reinforcing structure in the form of carbide precipitates due to the fact that they have high affinity to carbon.

Table I. EN-GJS 350-22 ductile cast iron chemical composition

C	Si	Mn	P	S	Cu	Ti	Mg	Cr
3,66%	2,71%	0,527%	0,042%	0,001%	0,068%	0,032%	0,012%	0,124%

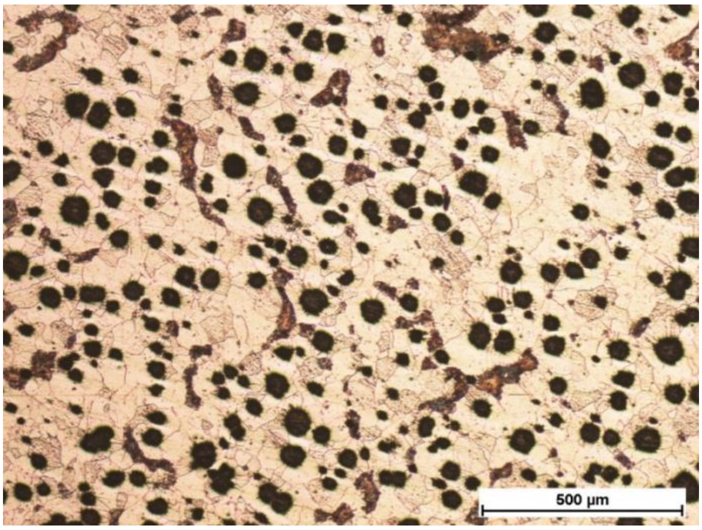


Fig. 1. EN-GJS 350-22 ductile cast iron microstructure

The alloying process was carried out on a test bench equipped with a diode laser with direct beam transmission to the HPDDL Rofin Sinar DL 020 surface, numerically controlled positioning system of the laser head and the substrate to be treated, and a gravitational powder feeder with a vibrator. The laser parameters are presented in the table II. The powder was fed into the melted metal pool at an angle of 45°. The beam was focused on the surface of the material being melted. The beads were made at a constant laser beam power of 1500 W and a stopping rate of 1.25 mm/s and a variable powder flow rate. Process parameters are presented in table III. The linear energy was 1200 J/mm. Argon with a flow rate of 15 l/min was used as a protective gas.

In order to examine the created surface layers, macroscopic observations and the analysis of the impact of parameters on the bead geometry, microstructure of the produced surface layers and analysis of the chemical composition of EDS were made and the average proportion of carbides on the surface of the alloy layer was determined. In order to test the mechanical properties of the surface layer, Vickers microhardness HV0.2 measurements were carried out, in accordance with the PN-EN ISO 6507-1 standard, on the cross-section of beads at distances of 0.1 mm.

Table II. Technical parameters of diode laser HPDDL DL 020, Rofin Sinar

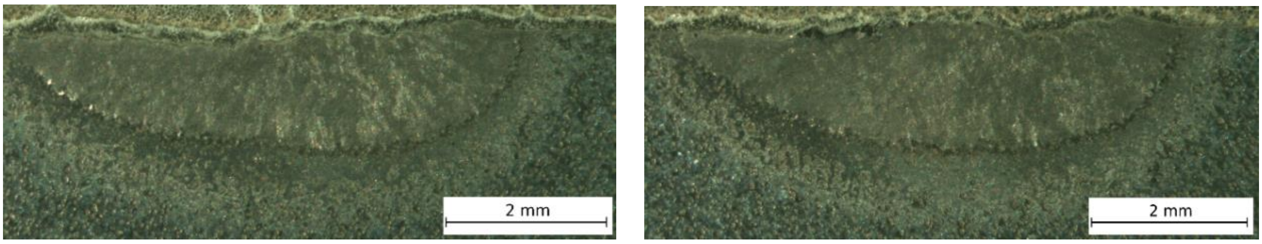
Parameter	Value
Rated output power (continuous radiation) [W]	2200
Output power regulation [W]	100÷2200
The wavelength of radiation [nm]	808÷950
Dimensions of the laser beam focus [mm]	1.8 x 6.8 / 1.8 x 3.8
Focal length of the laser beam [mm]	82 / 32
Power density range in the plane of the laser beam focus [kW/cm^2]	0.8÷32.3

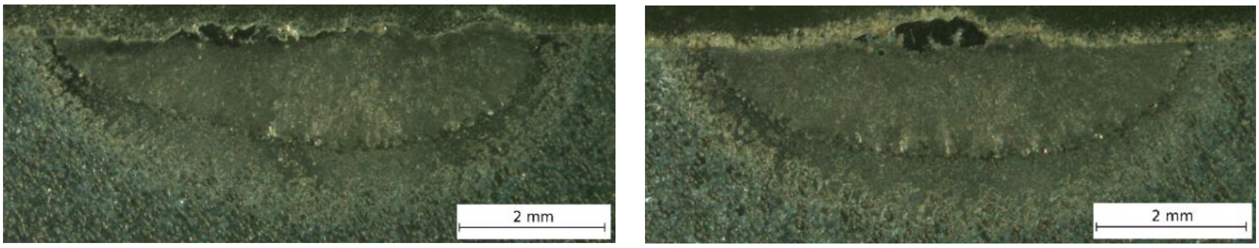
Table III. EN-GJS 350-22 ductile cast iron laser surface alloying with the Ti + 5 wt.% W mixture parameters

Power of the beam [W]	Alloying speed [mm/s]	Intensity of the powder feed [g/min]	Intensity of the powder feed per unit of bead's length [mg/mm]
1500	1.25	0.3	4
		0.6	8
		0.9	12
		1.2	16
		1.5	20

Results of the research

Macroscopic examinations showed the correctness of performed beads, except for the layer produced with the highest powder feed rate equal to 1.5 g/min, where there was no widespread decomposition of the alloying material, which resulted in a heterogeneous surface layer (Fig. 2 bead no. 5). Based on the macroscopic observations (Fig. 2), characteristic geometrical parameters of beads were measured, i.e. bead width and penetration depth (Table IV). The change in the powder delivery rate parameter did not significantly affect the depth and width of the beads (Fig. 3).


Bead no.1 **Bead no. 2**


Bead no. 3 **Bead no. 4**


Bead no. 5

Fig. 2. Macrostructure of laser-alloyed layers cross-section

Table IV. Geometrical parameters of laser surface alloyed layers

Number of the bead	1	2	3	4	5
Width of the bead [mm]	6.3	6.5	6.8	6.5	6.8
Depth of penetration [mm]	1.46	1.55	1.6	1.52	1.63

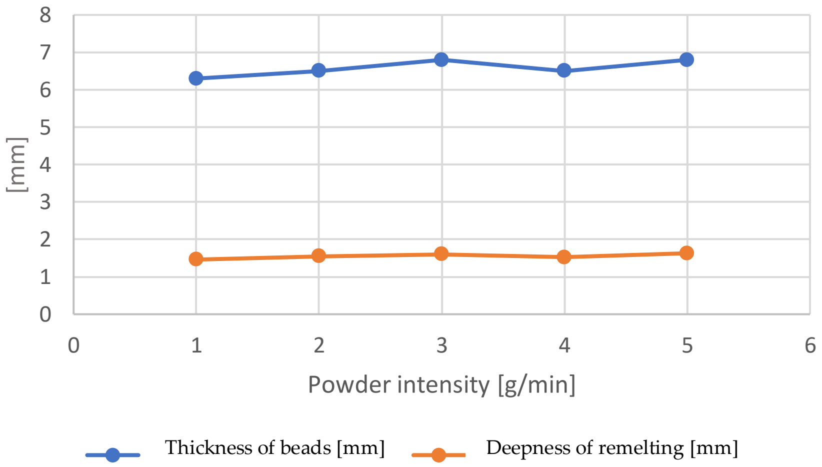


Fig. 3. Dependence of penetration depth and beads width on the powder flow rate in the laser surface alloying process

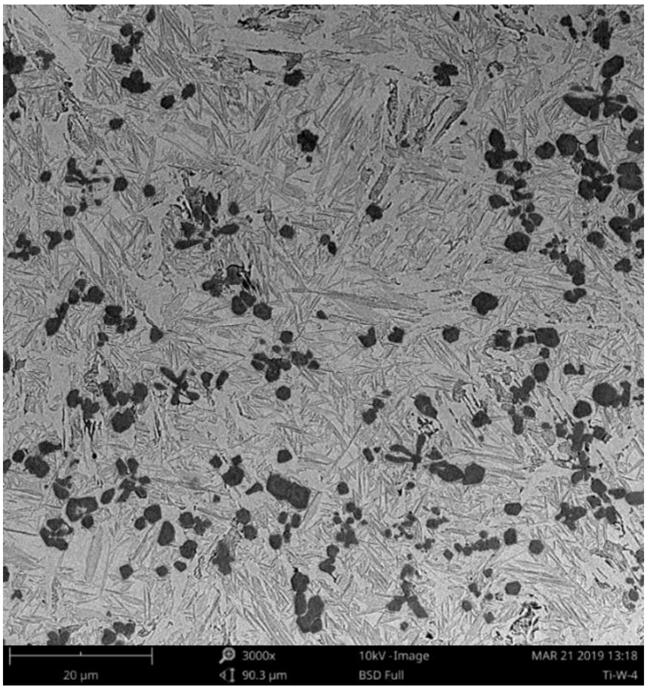


Fig. 4. Microstructure of laser alloyed surface layer with mixture of Ti + 5 wt.% W

Observations of the microstructure were performed on an electron scanning microscope. The microstructure of the obtained surface layers (Fig. 4) is a composite structure obtained using in-situ method during the laser alloying process and is composed of a reinforcing phase and a matrix. The matrix in the structure of the surface layers are dendrites of primary austenite, which have undergone martensitic transformation to a large extent, while in interdendritic areas there are eutectic precipitates of cementite and austenite. The reinforcing phase is the fine separation of TiC carbides, in which the tungsten atoms have partially dissolved, as demonstrated by the analysis of the chemical composition of EDS.

In order to determine the chemical composition of the precipitates formed in the surface layers, a point, linear and surface EDS chemical composition analysis was carried out. These tests showed the presence of TiC and (Ti,W)C precipitates. The surface analysis carried out at 5000x magnification showed an increasing average titanium content in the surface layers when increasing the rate of feeding of the alloying powder (Fig. 5). This analysis, however, did not allow unambiguous determination of tungsten content in the surface layers. Thanks to the point analysis, which did not show the participation of titanium and tungsten in the matrix of the surface layers, it can be concluded that all the alloying material introduced in the process was used to create reinforcing phases. In the structure of the surface layers, secretions with a characteristic gradient structure were observed (Fig. 6). The surface EDS analysis used showed that the lighter area inside the carbide is rich in tungsten, while the darker region found in the core and outside the precipitate is richer in titanium.

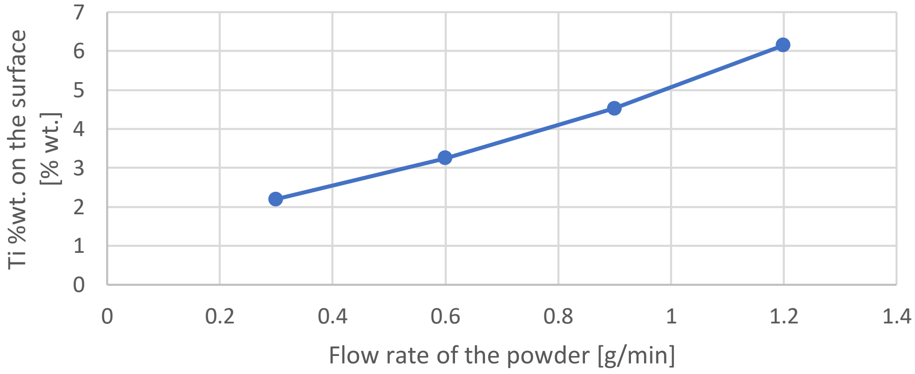


Fig. 5. The impact of the powder flow rate one the titanium weight fraction in the surface layer

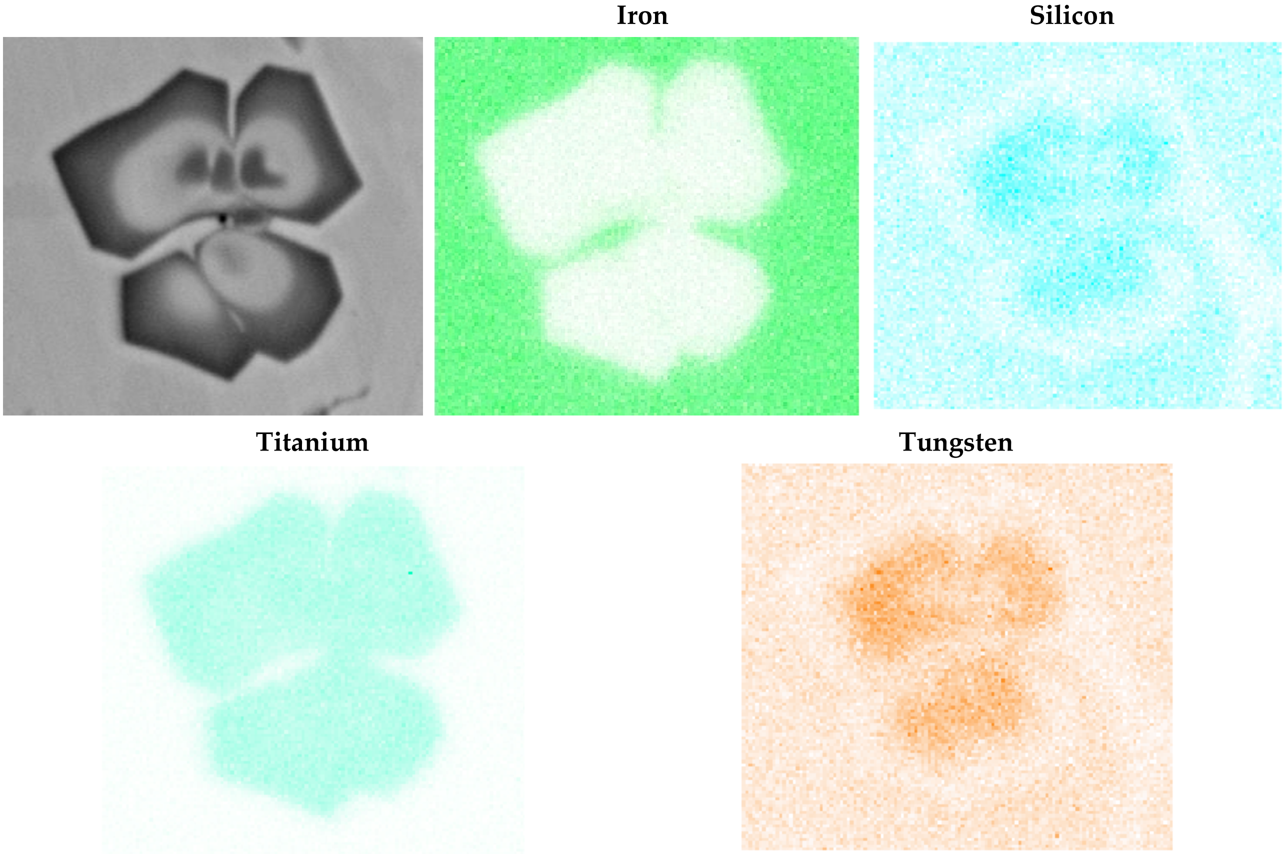


Fig. 6. The result of EDS surface analysis of the carbide produced in the surface layer after laser alloying with a Ti + 5 wt.% W mixture

In order to assess the proportion of carbides in the matrix (Table V), the observations were carried out on samples not produced in BSE mode, thanks to which a good contrast in the precipitation of the precipitates relative to the matrix was obtained. The share was determined for each of the samples except for the sample produced at a powder feed rate of 1.5 g/min due to the lack of uniform dissolution of the powder and separation of carbides in the structure. For each of the examined layers, the share was determined on the surface at a magnification of 1000x and on four surfaces at a magnification of 5000x, of which the average was taken. The obtained results (Fig. 7) showed an even increase in the average proportion of carbides in the structure along with the increase in the parameter of the powder feed rate during the laser alloying process. The growth trend is almost linear, with a coefficient R2 equal to 0.9989. The share of carbide precipitates in the case of the layer produced with the smallest powder feed rate (0.3 g/min) was on average 3.05%, and in the melted layer at the highest powder flow rate among the tested (1.2 g/min), the average content was 9.31% of precipitations.

Table V. Volume fraction of TiC reinforcement phase in the surface layers

	The proportion of carbides on the surface (magnification 1000x) [% vol]	**Average proportion of carbides on the surface (magnification 5000x) [% vol]**
Bead 1	3.64	3.05
Bead 2	5.02	5.15
Bead 3	6.93	7.04
Bead 4	8.79	9.31

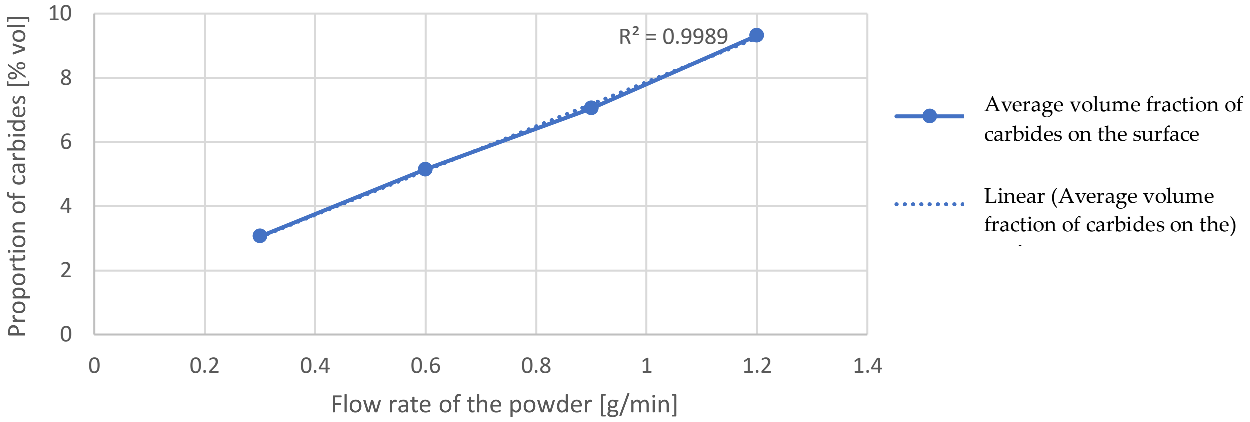


Fig. 7. Dependence of the carbides percentage on the surface in a function of the powder flow rate

The results of Vickers microhardness measurements on the cross section of the alloy layers showed a positive effect of the process on the growth of microhardness of the surface layer (Fig. 9). Compared to the average hardness of the substrate material of 235.9 HV0.2, the hardness of the surface layer, after the laser alloying process using a mixture of titanium powder with the addition of 5 wt.% tungsten, increased by approx. 250%. The highest average hardness was obtained for the sample with the lowest impact of the alloying material, while the lowest for the sample with the highest content of the alloying material (Fig. 8). The lowest average hardness of this layer is caused not only by the amount of powder introduced, but also the lack of uniform dissolution in the liquid (Fig. 2 bead 5), which resulted in areas with a higher proportion of powder (rich in separations) and areas with a much lower share of the alloying material and thus hardness slightly higher than the base material. The decrease in the hardness of the surface layer with the increase of the powder addition is caused by the depletion of the matrix's carbon, which together with the increase in the content of additives with high affinity to it, forms carbide precipitations, simultaneously causing a decrease in hardness in the matrix.

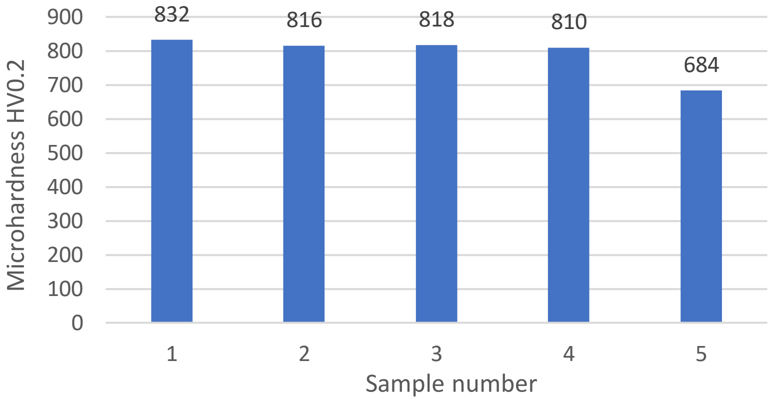


Fig. 8. Average microhardness of the laser surface alloyed layers with Ti + 5 wt.% W powder

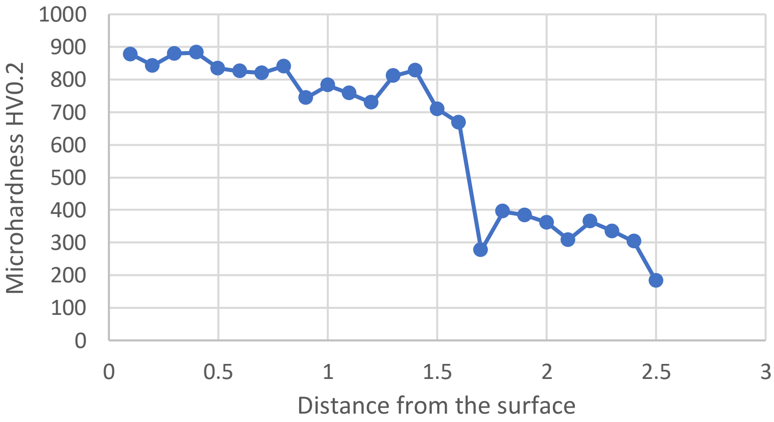


Fig. 9. The result of microhardness measurements on the cross-section of layer no. 3 on a distance from the surface

Summary

The process of alloying the laser surface of EN-GJS 350-22 ductile cast iron with the use of titanium powder with the addition of 5% wt.% tungsten allowed the formation of a composite structure in the surface layer by an in-situ method composed of a matrix and a reinforcing phase. The matrix is dendrite of primary austenite to a large extent after martensitic transformation and eutectic secretion of cementite and austenite in interdendritic spaces. The reinforcing phase is the fine separation of TiC and (Ti, W) C carbides. Microscopic observations and EDS analysis showed a characteristic, gradient structure of titanium carbide with dissolved tungsten, in which the core is titanium, then tungsten is dissolved inside, and the external part is also made of titanium. This analysis also showed the absence of alloying material in the matrix, which means that titanium and tungsten added in the process produced carbides throughout the content. Surface analysis also showed an even increase in the titanium content in the surface layers with an increase in the flow rate parameter of the alloying powder. This has contributed to the increase in the proportion of carbides in the matrix, which in relation to the flow rate of the powder increases almost linearly. Surface analysis of EDS did not allow unambiguous determination of the tungsten content in the surface layers. With the 1500 W laser beam power parameters and an alloying rate of 1.25 mm/s, the maximum powder flow rate at which uniform powder fusion was achieved was 1.2 g/min. The change in the powder feed rate parameter did not significantly affect the bead's geometry. The alloying process also had a positive effect on the increase in the hardness of the surface layer as compared to the substrate material by up to 250%. As the impact of the alloying material increases, the average hardness of the surface layer decreases, which results from the formation of more carbide precipitates and a reduction in the carbon fraction in the matrix.

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