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Effect of high power diode laser surface alloying on wear resistance of high speed steel

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ABSTRACT

Purpose: The following paper presents the results of the influence of laser alloying on structure and properties of the surface of HS6-5-2-5 high speed steel, carried out using a high power diode laser (HPDL). WC, VC, TiC, SiC, Si_3N_4 and Al_2O_3 particles powder was used for alloying.
Design/methodology/approach: Selection of laser operating conditions is discussed, as well as beam face quality after remelting, hardness, micro hardness test, wear resistant, EDX and X-ray microanalysis results.
Findings: Selection of laser operating conditions is discussed, as well as beam face quality after remelting, hardness, micro hardness test, wear resistant, EDX and X-ray microanalysis results. Fine grained, dendritic structures occur in the remelted and alloyed zone with the crystallization direction related to the dynamical heat movement from the laser beam influence zone. The remelted zone structure is characterized by significant martensite dispersion with its laths several times shorter than of those developed during conventional quenching. The fine grained martensite structure is responsible for hardness increase of the alloyed layer. Micro-hardness changes depend up in the effects of the laser beam on the treated surface, and especially in the alloyed layer.
Practical implications: Laser technique features the especially promising tool for solving the contemporary surface engineering problems thanks to the physical properties of the laser beam, making it possible to focus precisely the delivered energy in the form of heat in the surface layer.
Originality/value: The outcome of the research provides better understanding of the structural mechanisms accompanying laser remelting and alloying.
Keywords: Heat treatment; Laser; Tool materials; Wear resistance

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1. Introduction

Laser treatment as part of the new generation techniques applied in metal surface technology is discussed in this paper. Laser treatment has been applied to the remelting of high speed steel HS6-5-2-5 with carbide and ceramic powders, especially WC, VC, TiC, SiC, Si_3N_4 and Al_2O_3 particles. Laser treatment is especially promising for solving contemporary surface engineering problems thanks to the physical properties of the laser beam, making it possible to focus precisely the delivered energy in the form of heat in the surface layer. The material behavior during the HPDL processing has been found to be different from the other high-power lasers in the following aspects: fewer cracks and more uniform melt/heating zones, smoother surface, better beam absorption for metallic materials, more consistent and repeatable. It is a well-known fact that the same laser processing parameters may not necessarily produce the same results in laser materials processing. It has already been noticed that HPDL can produce more consistent materials-processing results than Nd:YAG lasers. This feature, together with the lower maintenance costs and longer service life would make HPDL suitable for mass production applications such as the soldering of telephone connectors. Other advantages of the HPDL are: lower running cost, higher energy efficiency (up to 35% wall plug efficiency) thus the cooling requirement is low and the size of laser and cooling unit is small, flexible beam shaping by controlling the intensity of individual beams, theoretically unlimited average power, portable and longer service life (typically 4000 - 5000 up to 10000 h). This type of surface treatment is used for improvement of hardness by changing the structure, and for improvement of the abrasion wear resistance, mostly by introduction of carbide or ceramic particles to the material matrix. Rapid mixing leading to development of the surface layer from the remelted materials occurs, during the alloying process with sufficiently high laser power. Therefore, the laser melted pool is formed on the specimen surface, to which the carbide or ceramic powder is introduced. Intensive mixing in the remelted zone is due to the shear stresses developed in the remelted zone. This process is very important, as affects the type of convection motion, and therefore the final distribution of the alloying element in the remelted zone. The intensity of the convection motion, therefore velocity of liquid transition, is caused also by a large temperature gradient, which is increase with energy portion delivered in the unit time of the laser beam operation. Addition of powder is done using a conveyor directly during remelting, or the powder can be applied as paste or powder which dries on the specimen surface, before laser treatment. This makes it possible to divelop alloys with the bi- or multi-component structures, and also composites or functionally gradient material with the intermetallic phases. Due to the rapid cooling because of heat removal to the cold substrate an advantageous, fine-grained structure develops, which may also display gradient morphology. The surface layers obtained with laser alloying may have a heat-resisting and anti-corrosion properties, may also provide a high abrasion and erosion resistance. Mechanical and tribological properties of alloys obtained in this way are hard to acquire in the conventional technological processes [4,5]. Tribological tests are carried out in the laboratory or service conditions. Tests like these provide detailed information pertaining analysis of the friction physical phenomena [1]. Service tests are used less often due to their very high costs. This cost results from the number of the investigated objects, long test times, and technical difficulties. Regardless of the tribological tests types, measurement is carried out of friction force, moment of friction, wear intensity and wear value. Selection of the tribological test method is determined by: test goal, measurement accuracy, and test duration. Factors with the most significant effect on the tribological tests results may be divided into four groups:

- factors connected with the substrate, hardness and roughness,
- coating thickness (surface layer),
- motion type (slip or rolling),
- test conditions: counter-specimen material type, wear products presence in the friction zone, surrounding air humidity, slip rate, load, temperature, and the friction node vibration level [6].

These factors have a significant effect on test results and, therefore, only results of tests carried out in the same conditions can be compared. High speed steels still feature as a widely used group of tool materials, especially because of their low price and very good functional properties. Continued interest in these steels has out to investigations focused on improvement of the functional properties of these materials.

2. Investigation methodology

Investigations were carried out on test pieces from the HS6-5-2-5 high speed steel with the composition according to PN-EN ISO 4957:200 standard. Chemical composition of the steel is given in Table 1. The investigated steel was melted in a vacuum induction furnace at a pressure of about 1 Pa, and cast into ingots weighing about 250 kg, with were roughed at the temperature range 1100-900°C into the O.D. 75 mm bars, which were soft annealed. After machining, the specimens were heat treated. The specimens were austenitized in a salt bath furnace and tempered in a chamber furnace in a protective atmosphere of argon. The specimens were gradually heated to the austenitizing temperature with the isothermal arrests at 650 and 850°C for 15 min. They were austenized for 30 min at the temperature of 1210°C and then cooled in hot oil. The specimens were tempered twice after quenching, each time for 2 hours, at a temperature of 575°C and next at 560°C. Surfaces of specimens were sand blasted and machined on magnetic grinder.

Particular attention was paid to prevent development of micro-cracks that might disqualify the specimen from further examination. Sample size was 10x10x55 mm. On specimen surface two parallel grooves, deep for 0.5 mm of triangular shape (with angle of 45°) were machined. The grooves were located along sample axis and distance between them was ca. 1.0mm. Such prepared grooves were filled with WC, VC, TiC, SiC, Si_3N_4 and Al_2O_3 particles. Properties of the powders are presented in Table 2.

It was found in the preliminary investigations made using the HPDL Rofin DL 020 high power diode laser, with parameters presented in Table 3, that the maximum feed rate at which the process was stable is v=0.5 m/min.

Table 1.
Chemical composition of the HS6-5-2-5 high speed steel

Average mass concentration of elements, %								
Steel type	C	Cr	W	Mo	V	Si	P	S
HS6-5-2-5	0.91	4.2	6.3	5.0	1.9	1.09	0.015	0.010

Table 2.
Selected properties of powders

Powder	Average grain size, μm	Melting point, °C	Density g/cm^3	Hardness, HV
Tungsten carbide WC	5	2770	15.6	2600
Vanadium carbide VC	1.5	2830	5.36	2850
Titanium carbide TiC	3	3140	4.25	2800
Silicon carbide SiC	7	2700	3.21	2100
Silicon nitride Si_3N_4	5	1900	3,44	1600
Alumina oxide Al_2O_3	5	2047	3.90	2300

Table 3.
Specification of the HPDL ROFIN DL 020 diode laser

Wavelength of the laser radiation, nm	808 ± 5
Maximum output power of the laser beam (continuous wave), W	2300
Power range, W	100-2300
Focal length of the laser beam, mm	82 / 32
Laser spot size, mm	1.8 × 6.8
Power density range in the laser beam focal plane, kW/cm^2	0.8-36.5

Therefore all experiments were made varying the laser beam power in the range from 0.7 to 2.1 kW. At low laser power values, i.e., 0.4 to 0.7 kW, no remelting was observed for powders mentioned above.

It was established experimentally that argon purging with flow rate of 20 l/min through a 12 mm circular nozzle oppositely directed in respect to the remelting direction provided full remelting zone protection.

The cross sections' surfaces were ground on diamond wheels and next polished using diamond buffing compounds on Struers equipment. Etching of specimens was carried out 10 ml HNO_3 + 30 ml HCl, at room temperature. Suitable etching time was selecting experimentally for each specimen.

Metallographic examination of the material structures after surface laser alloying were made on a Zeiss LEICA MEF4A light microscope with magnifications from 50 to 500x. A Leica-Qwin computer image analysis system was used for thickness examination of the particular zones of the surface layer. Structure of the developed coatings were examined with SUPRA 25 scanning electron microscope (SEM) equipped with X-ray energy dispersive spectrometer (EDS).

The phase composition of the laser alloyed zone was determined on a Panalytical X'Pert PRO diffractometer, using filtered radiation from a cobalt anode lamp, powered with 40 kV voltage, at 20 mA heater current. The measurements were made in the angle range 30º-110º.

Hardness tests were made using Rockwell method in C scale on specimens subjected to the standard heat treatment and alloyed using the high power diode laser at various parameters, making 10 measurements for each condition and calculating their average value. Test results were analysed statistically. Hardness was measured on the ground and bead face of specimens. Coating microhardness was tested on the FM-700 microhardness tester. The tests were carried out at 0.01 N load, making the necessary number of indents on the section of each examined specimen, correspondingly to the structural changes depth in the material surface layer. The microhardness tests were made along the lines perpendicular to specimens' surfaces, along the run face axis.

Abrasion wear resistance tests of the surface layers were carried out in the metal-ceramic material arrangement according to the ASTM standard. The ceramic material - quartz sand with the granularity of 212-300 μm - is delivered by the nozzle with the flow rate of about 350 g/min during the test. The nozzle is between the examined test piece and the rubber wheel with the diameter of 229 mm. The test piece is loaded with the constant force of 130 N and is pressed down to the rotating rubber wheel. This wheel, rotating at the constant speed of 200 rpm, makes 6000 rotations during the test. The test pieces before and after the grindability examinations were weighed on the analytical balance to check the mass loss, depending on the used particles and laser power. The HS6-5-2-5 conventionally heat treated steel was used as reference material. The test piece was examined on which two remelting or alloying paths were made for each of the surface layers. Preparation of the test pieces for examinations consists in grinding the surface with the 1200 grit abrasive papers, to remove the remains of the non-remelted powder. Particular attention was paid to prevent removal of the remelted zone.

3. Investigation results

The investigated steel displays in the softened state a ferritic structure with carbides distributed uniformly in the matrix. A lath martensite structure is obtained after quenching, which is saturated with alloying elements, which is confirmed by the EDX chemical composition analysis, and with carbon. The anticipated hardenability of these steels was attained at an austenitizing time long enough, to ensure solubility of most alloy carbides in the austenite.

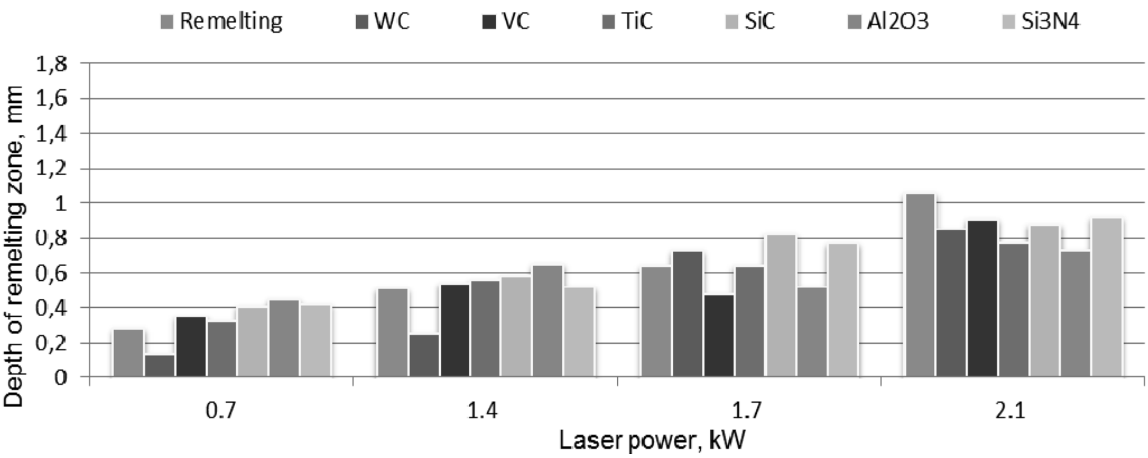

Fig. 1. Influence of the laser power on the remelted zone thickness of the high speed steel HS6-5-2-5 after laser alloying with the WC, VC, TiC, SiC, Si_3N_4 and Al_2O_3 powder

Structural examinations compared the effect of parameters of heat treatment and remelting of the high speed steel with the diode laser on the run face shape and remelting depth.

The initial experiments indicated the clear influence of the laser power of 0.7, 1.7, 2.1kW respectively on the run face shape and its depth. It was observed that the remelting depth increased with the laser power increase, as illustrated by Fig. 1

It was found, that thickness of the analysed layers, evaluated supported on the computer image analysis made on pictures from the light microscope and confirmed by examinations on the scanning electron microscope, falls within the broad range and is a function of laser beam power.

The average remelted layer thickness was proportional to the laser power increase. It was found that the remelted layer thickness changes from 0.26 mm, with the 0.7 kW laser beam, to about 1.07 mm, with the 2.1 kW laser beam power. The remelted zone thickness also increases in proportion to the laser power in the case of alloying the steel with carbides and ceramic particles such that the average alloyed layer thickness varied from 0.13 mm (laser beam power 0.7 kW), to about 0.93 mm (laser beam power 2.1 kW). Roughness of the surface layers obtained by remelting the steel with the laser beam with power ranging from 0.7 to 2.1 kW is within the range of R_a = 0.39-0.79 µm and incised in proportion to the laser beam power (Figs 2-7). The surface layer obtained by alloying with carbides and ceramic particles did not demonstrate proportional dependence of the surface roughness with the laser beam power. The maximum surface roughness of R_a = 21.4 µm occurs at the surface of the layer obtained with the laser beam with the power of 1.7 kW; whereas, the minimum surface roughness of R_a = 5.9 µm was obtained on the surface layer developed of 2.1 kW. No dependence of surface roughness with laser beam power in the case of alloying with the carbides and ceramic particles is caused by the mechanism of the hard particles powder inundation into the surface layer of steel. At low laser beam power some of the carbide grains remain at the surface, causing high roughness; whereas, at the higher laser beam power the steel surface is formed in a very characteristic shape, resulting from the fast crystallization in the heat transfer direction and from interaction with the flow of protective gas (Figs. 8-13).

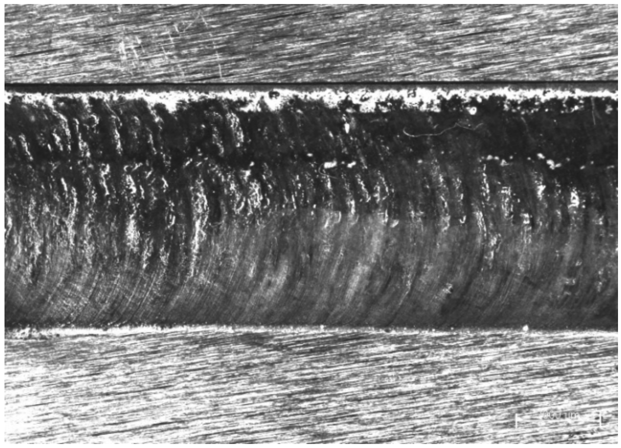

Fig. 2. Part shape of bead face of the high speed steel HS6-5-2-5 surface alloyed with the WC, laser power 1.7 kW

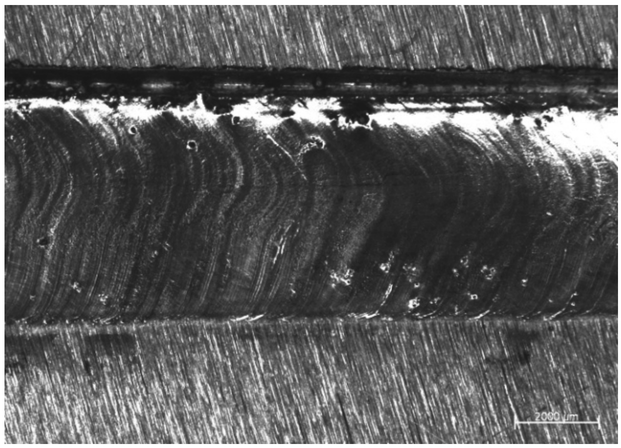

Fig. 3. Part shape of bead face of the high speed steel HS6-5-2-5 surface alloyed with the VC, laser power 1.7 kW

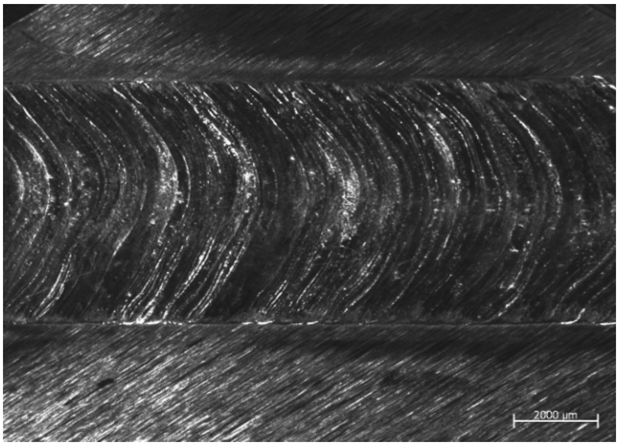

Fig. 4. Part shape of bead face of the high speed steel HS6-5-2-5 surface alloyed with the TiC, laser power 1.7 kW

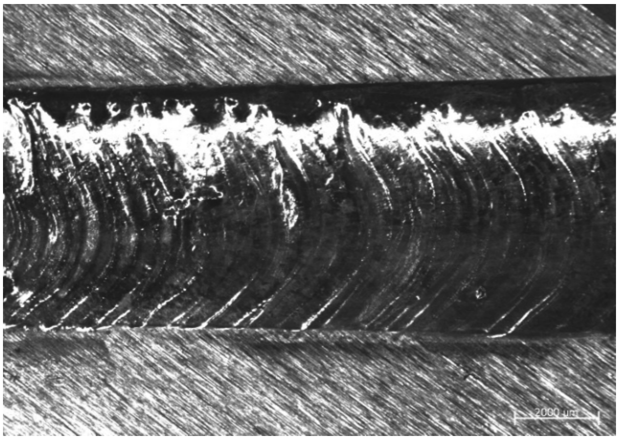

Fig. 5. Part shape of bead face of the high speed steel HS6-5-2-5 surface alloyed with the SiC, laser power 1.7 kW

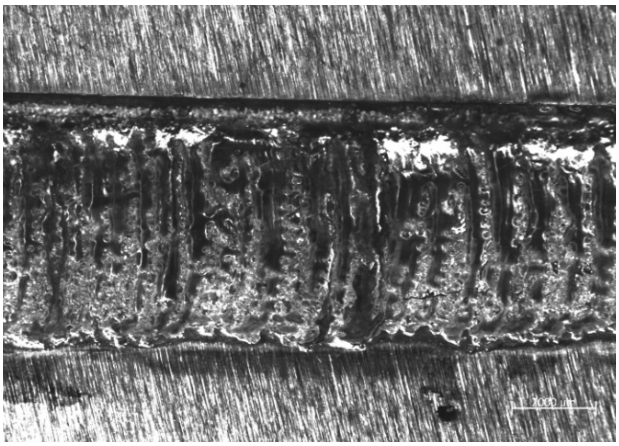

Fig. 6. Part shape of bead face of the high speed steel HS6-5-2-5 surface alloyed with the Al_2O_3, laser power 1.7 kW

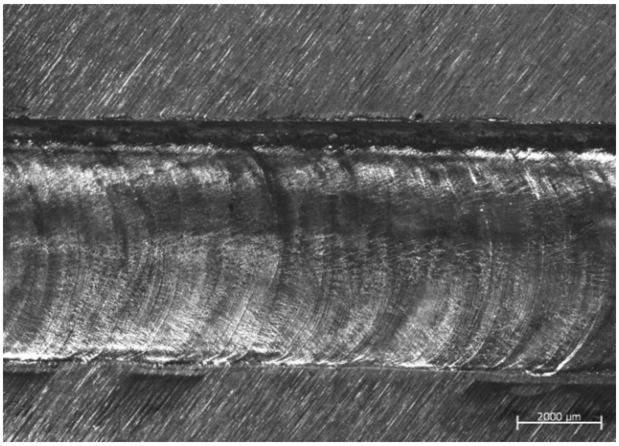

Fig. 7. Part shape of bead face of the high speed steel HS6-5-2-5 surface alloyed with the Si_3N_4, laser power 1.7 kW

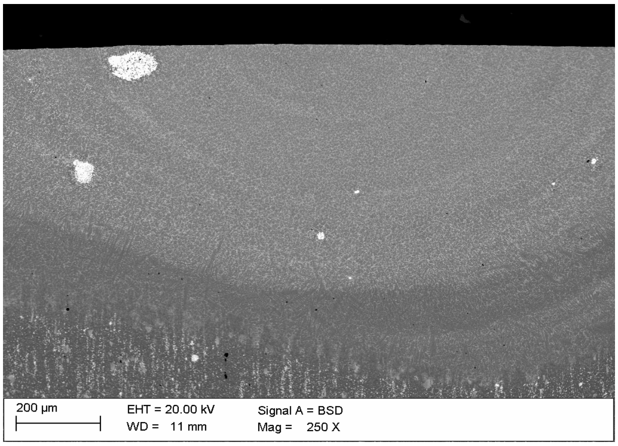

Fig. 8. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the WC particles with laser power value 2.1 kW

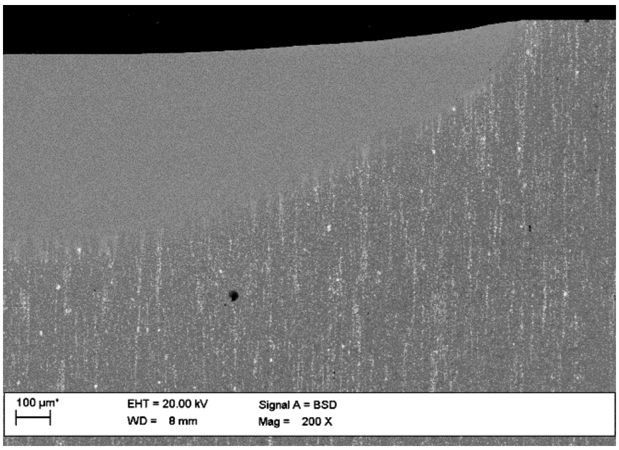

Fig. 9. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the VC particles with laser power value 2.1 kW

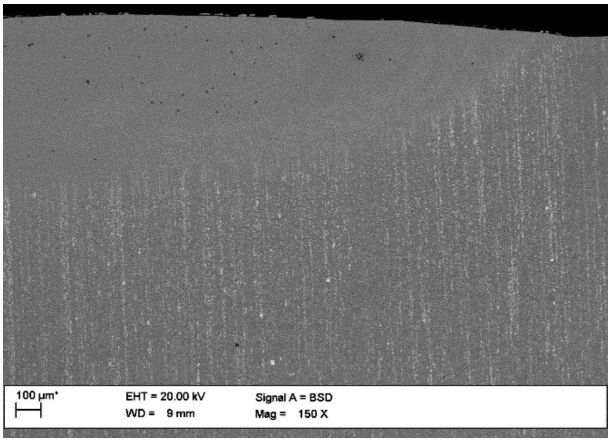

Fig. 10. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the TiC particles with laser power value 2.1 kW

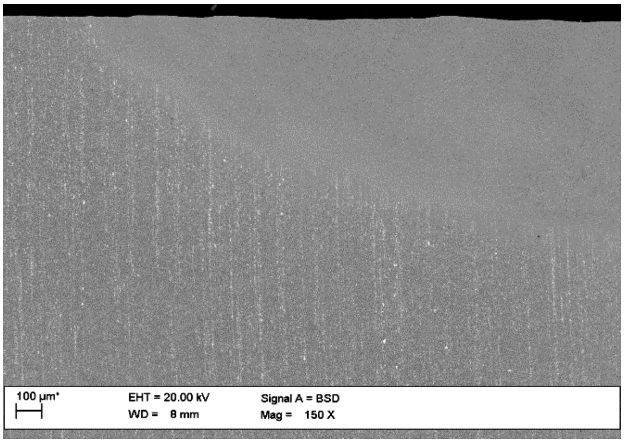

Fig. 11. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the SiC particles with laser power value 2.1 kW

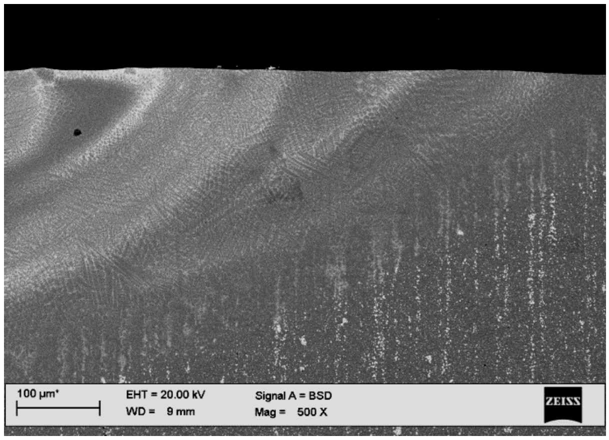

Fig. 12. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the Al_2O_3 particles with laser power value 2.1 kW

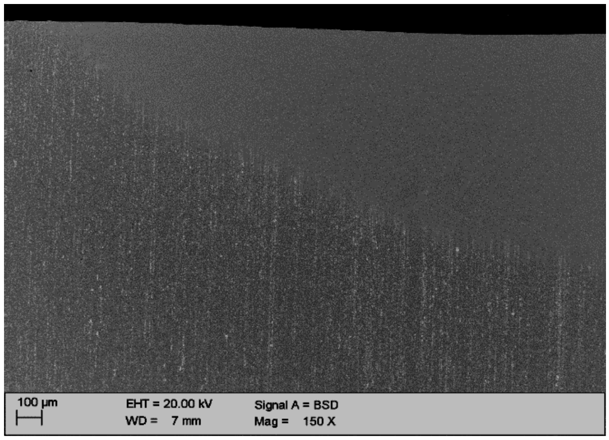

Fig. 13. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the Si_3N_4 particles with laser power value 2.5 kW

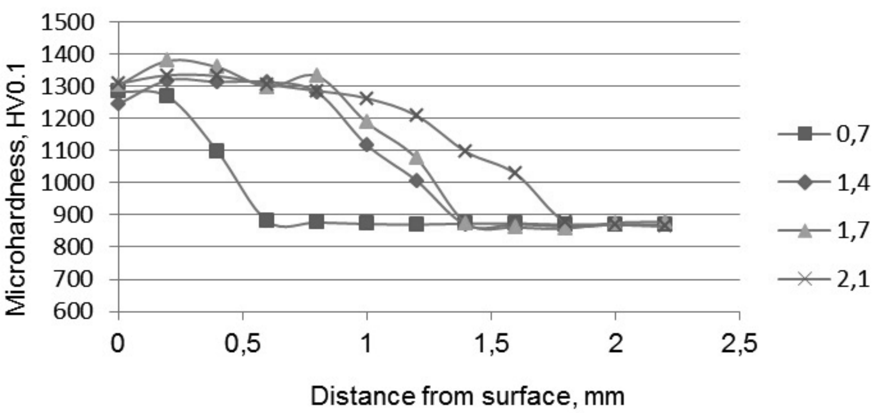

Fig. 14. Change in microhardness of the high speed steel HS6-5-2-5 surface layer after alloying with TiC carbide

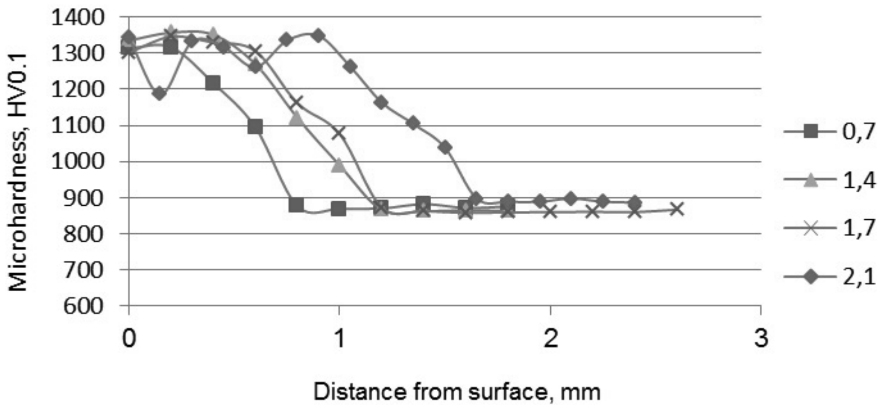

Fig. 15. Change in microhardness of the high speed steel HS6-5-2-5 surface layer after alloying with Si_3N_4 particle

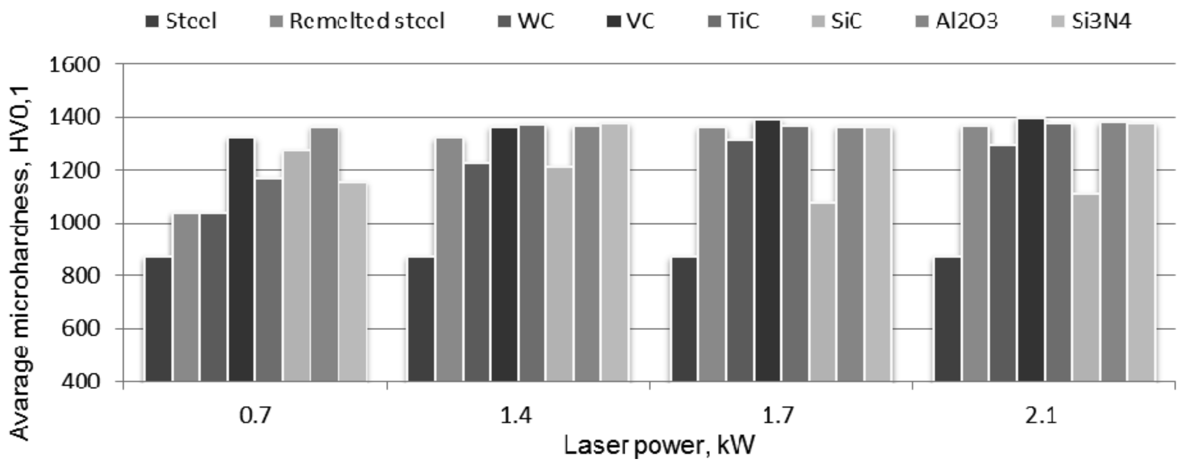

Fig. 16. Avarage microhardness for the high speed steel HS6-5-2-5 remelted and alloyed with the WC, VC, TiC, SiC, Si_3N_4 and Al_2O_3 particles with the scanning rate of 0.5 m/min and laser beam power of 0.7, 1.4, 1.7 and 2.1 kW

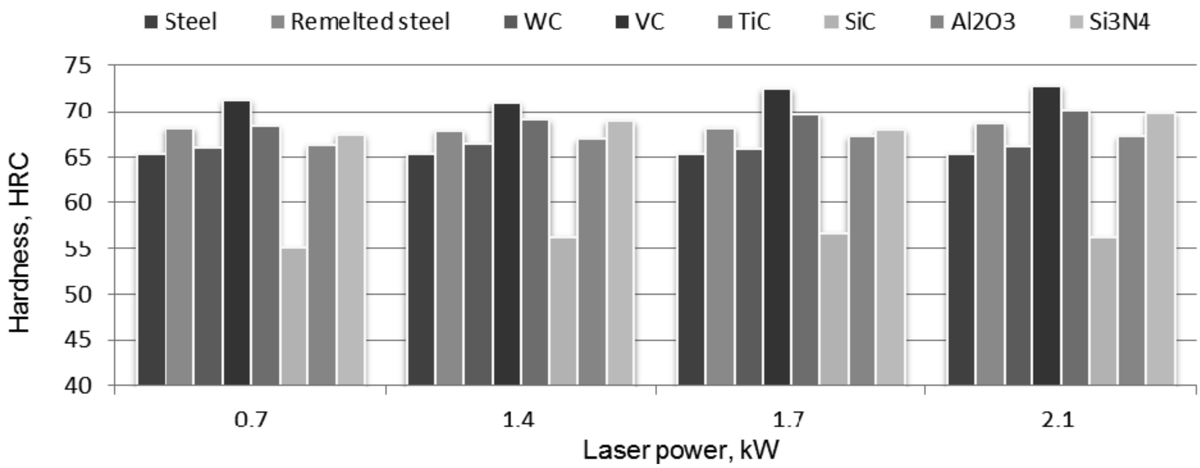

Fig. 17. Avarage hardness for the high speed steel HS6-5-2-5 remelted and alloyed with the WC, VC, TiC, SiC, Si_3N_4 and Al_2O_3 particles with the scanning rate of 0.5 m/min and laser beam power of 0.7, 1.4, 1.7 and 2.1 kW.

Microhardness growth was revealed, based on microhardness tests on the transverse section of laser runs versus distance from the surface of the examined steel test pieces showed hardness increases (Figs. 14-15).

The high average microhardness (Fig. 16) increase in the remelted zone surface layer was observed for laser beam power of 2.1 kW. In the case of alloying, the highest microhardness was obtained for the steel surface layer alloyed with the VC particles, for which the average microhardness increase is 1398 $HV_{0,1}$, when the laser power used for alloying was 2.1 kW.

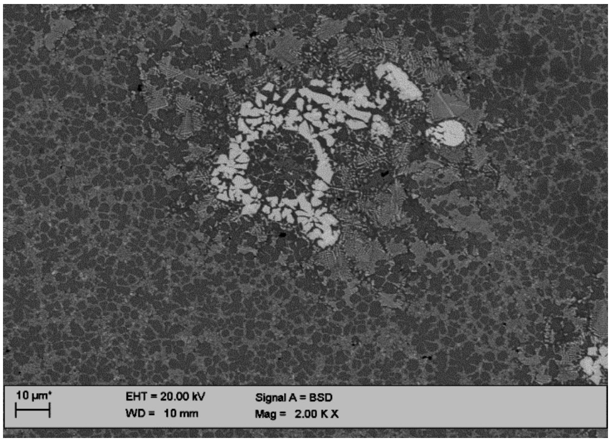

Fig. 18. Surface layer of the high speed steel HS6-5-2-5 steel after laser remelting with the WC particles with the scanning rate of 0.5 m/min and laser beam power of 1.7 kW, remelted zone - visible particles of tungsten carbide in the surface layer

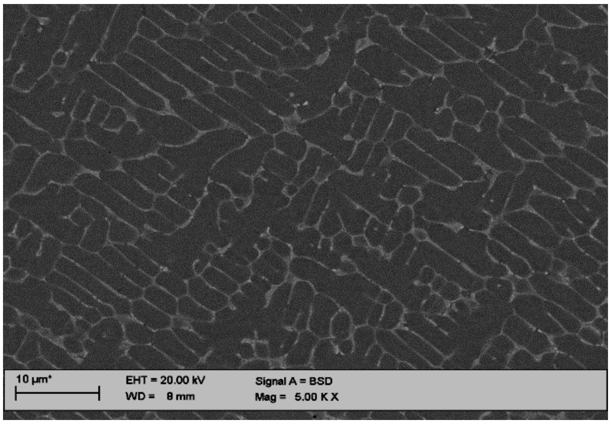

Fig. 19. Surface layer of the high speed steel HS6-5-2-5 steel after laser remelting with the VC particles with the scanning rate of 0.5 m/min and laser beam power of 1.7 kW, remelted zone

Figure 17 presents the HRC hardness tests results of the surface layer after remelting with the HPDL high power diode laser using the carbide and ceramic particles. It was observed that increase of the laser power causes inundation of a larger amount of the carbide and ceramic particles; and therefore, increased the surface layer hardness, which was confirmed by examination on the light microscope with the Leica-Qwin computer image analysis system, and also by observations on the scanning microscope. Hardness for the native material after heat treatment is about 65 HRC, whereas after alloying with vanadium carbide it is about 73 HRC.

Metallographic examination confirmed that the structure of the material solidifying after laser remelting is different, which is dependent on the solidification rate of the investigated steel. Occurrence of structure with dendrites was revealed in areas on the boundary between the remelted and heat affected zone (Figs. 18-21).

Examination of the chemical composition (Figs. 22-25) with the surface and pointwise methods reveal occurrences of the inundated particles in conglomerates (Fig. 22). Moreover, using the X-ray microanalysis it was found out also that titanium occurs not only in the form of conglomerated but also the remelted layer (Fig. 24).

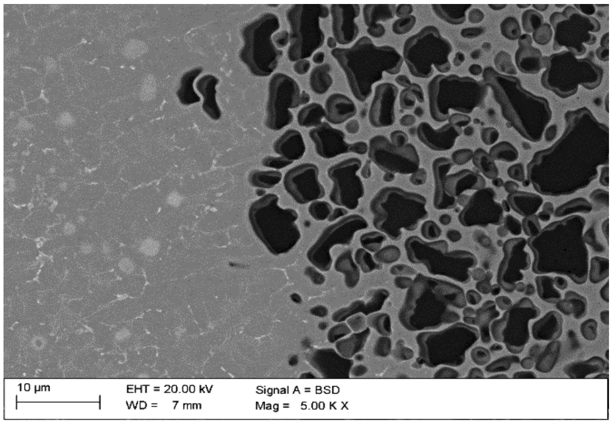

Fig. 20. Surface layer of the high speed steel HS6-5-2-5 steel after laser remelting with the TiC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW, transition between the remelted zone and the heat affected zone

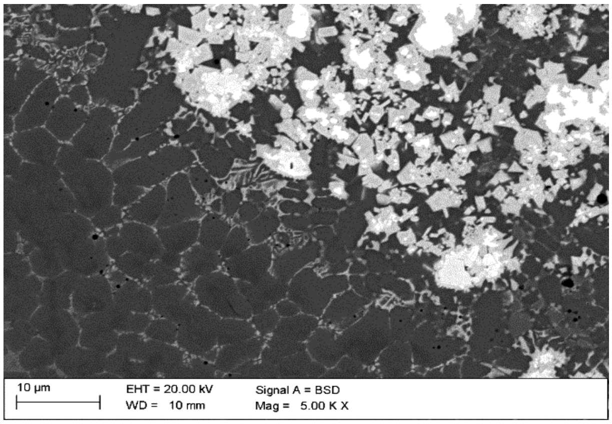

Fig. 21. Surface layer of the high speed steel HS6-5-2-5 steel alloyed after laser remelting with the Al_2O_3 particles with the scanning rate of 0.5 m/min and laser beam power of 1.7 kW, transition between the remelted zone and the heat affected zone

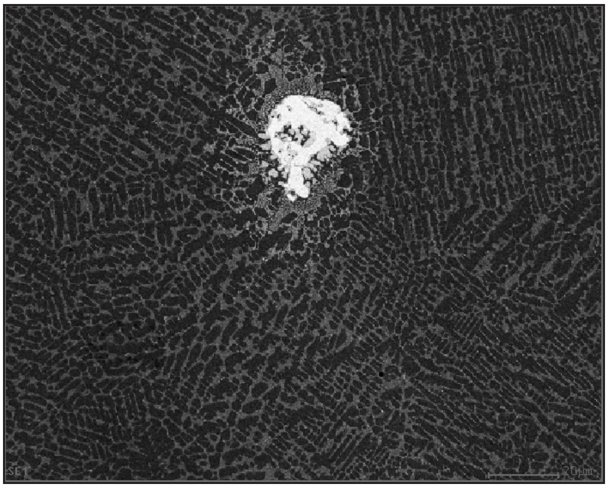

Fig. 22. Surface layer of the high speed steel HS6-5-2-5 alloyed with the WC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW - remelted zone

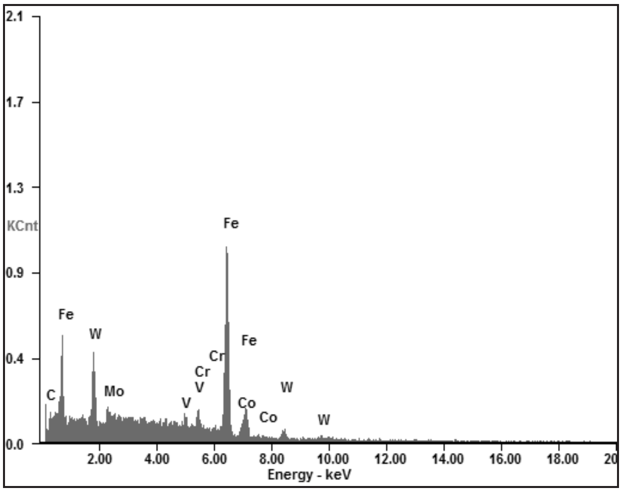

Fig. 23. Surface layer of the high speed steel HS6-5-2-5 alloyed with the WC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW. - spectrum of the pointwise chemical composition analysis

X-ray diffraction were also made of the remelted steels and alloyed with the ceramic carbides. According to the assumptions, on surface of the investigated test pieces alloyed with the NbC, TaC, VC, WC and TiC powders, occurrences of the NbC, TaC, Ta_2C VC, WC and TiC carbides were observed using the X-ray qualitative phase analysis methods. X-ray diffractions of the remelted steel and alloyed with the WC. According to the assumptions, on surface of the investigated test pieces alloyed with the WC powders, occurrences of the WC carbides were observed using the X-ray qualitative phase analysis methods (Fig. 26).

The hardness changes of the surface layers obtained by remelting and alloying with carbides using the high power diode laser (Fig. 10) are accompanied by the improved tribological properties in comparison with the conventionally heat treated steel (Fig. 27).

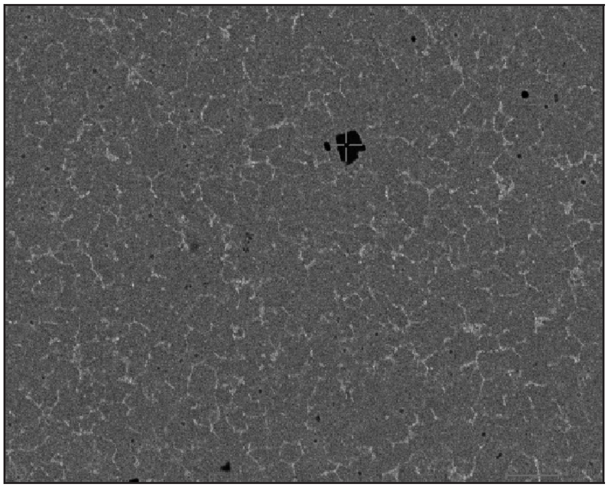

Fig. 24. Surface layer of the high speed steel HS6-5-2-5 alloyed with the TiC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW - remelted zone

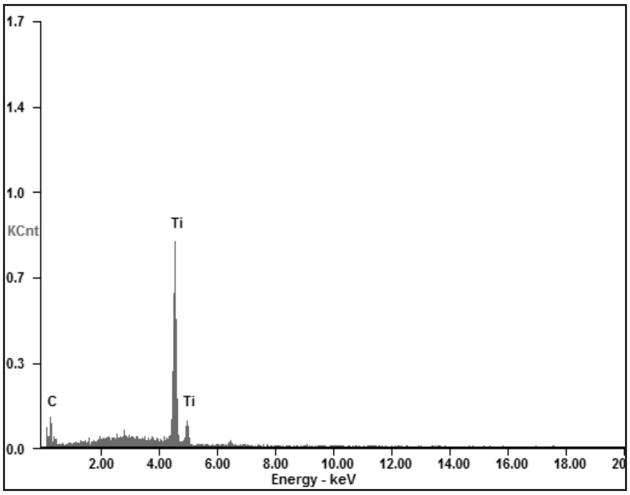

Fig. 25. Surface layer of the high speed steel HS6-5-2-5 alloyed with the TiC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW. - spectrum of the pointwise chemical composition analysis

To determine the abrasion wear resistance the surface layers of steel obtained with laser treatment were subjected to the abrasion wear resistance test according to the American ASTM standard. Figure 27 shows the relationship of the mass loss of the test pieces versus laser power and phases used for alloying. The mass loss increase was revealed along with the laser beam power increase in case of steel test pieces subjected to laser remelting.

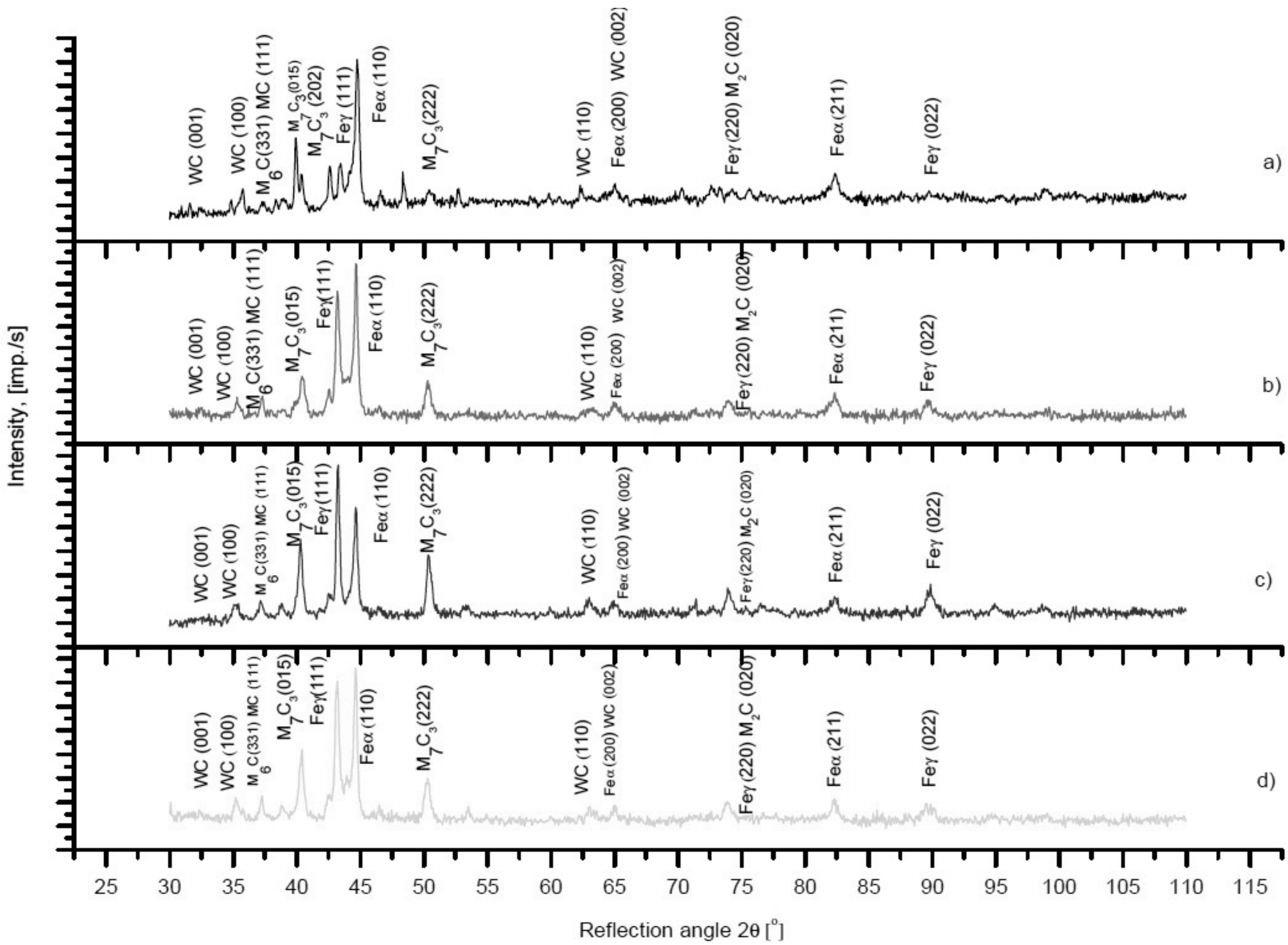

Fig. 26. X-ray diffraction pattern of the high speed steel HS6-5-2-5 alloyed with the WC ceramic powder with the scanning rate of 0.5 m/min and laser beam power a) 0.7 kW, b) 1.4 kW, c) 1.7 kW, d) 2.1 kW

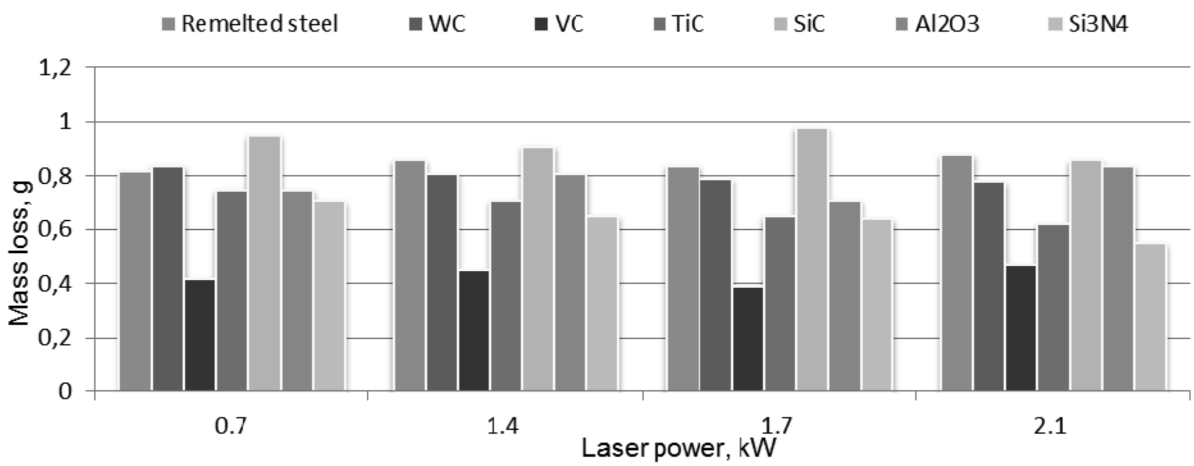

Fig. 27. Mass loss versus particle used, in the HS6-5-2-5 steel surface layer after alloying with the WC, VC, TiC, SiC, Al_2O_3 i Si_3N_4 particles using the variable power laser

However, in case of alloying the mass loss decrease was observed in proportion to the laser power increase (Fig. 27), the smallest mass loss occurs in case of the surface layers subjected to alloying with vanadium carbide, among which the minimum mass loss is 0.391 g for laser power of 2.0 kW (Fig. 27).
Whereas the biggest mass loss of about 0.927 g was observed, among all particles used, in the surface laser of steel alloyed with SiC at laser beam power of 1.7 kW (Fig. 27).

4. Conclusions

The investigations carried out made it possible to state that due to the heat treatment and remelting of the HS6-5-2-5 tool steel with the ceramic powders it is possible to obtain the high quality of the surface layer with no cracks and defects and with hardness significantly higher than the substrate metal. Remelting experiments made it possible to demonstrate the effect of the HPDL high power diode laser alloying parameters on properties and structure of the tool steels. Remelting depth grows along with the laser power increase and the remelted surface is more regular, less rough and more flat along with the laser power increase.

Due to the martensitic transformation of the HS6-5-2-5 high speed steel subjected to remelting and alloying with carbides steel hardness growth occurs usually compared to hardness of about 65.1 HRC after the conventional heat treatment. The maximum hardness of 73.2 HRC the investigated steel achieves in case of alloying with the vanadium carbide with the laser power of 2.3 kW. The average micro-hardness of the surface layers subjected to laser treatment is up to about 80% higher in case of the tantalum carbide than in case of the native material.

The hardness changes of the surface layers obtained by remelting and alloying with carbides using the high power diode laser are accompanied with the improved tribological properties compared to the conventionally heat treated steel. The highest abrasion wear resistance, more than 1.5 times higher than that of the native material, was revealed in case the steel alloyed with vanadium carbide.

A very fast process of the heat abstraction from the remelted zone through the core of a material with a multiply bigger heat capacity decides about the martensite transformation of the austenite arisen as a result of crystallization, and the partially twined lath martensite, formed this way, is characterized by big lathes' dispersion with their length several times shorter in comparison to martensite lathes after a conventional heat treatment.

Metallographic examinations on the scanning microscope with the EDX attachment and also with the X-ray qualitative phase analysis method confirm the occurrence of the NbC, TaC, VC, WC and TiC carbides in the surface layer of the investigated steel. It was found out that the vanadium and titanium occurs in the remelted layers mainly in the form of conglomerates.

The research results indicate to the feasibility and purposefulness of the practical use of remelting and alloying with ceramic carbides using the high power diode laser for manufacturing and regeneration of various tools from the HS6-5-2-5 high speed tool steel.

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