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# THE INVESTIGATION OF PROPERTIES OF HIGH-SPEED STEEL AFTER LASER SURFACE TREATMENT

The aim of this research paper is to present laser surface treatment technologies, investigation of properties of the HS6-5-3-8 high-speed steel \ alloying with ceramic particles using High Power Diode Laser. Selection of laser operating conditions is discussed, as well as beam face quality after remelting, hardness, micro hardness test, wear resistant. Remelting of the steel with introducing into liquid molten pool the alloying additions in the form of ceramic powders, causes significant increase of properties of surface layer of investigated steel in comparison to its analogical properties obtained through conventional heat treatment, depending on the laser beam power implemented for remelting. The increase of hardness of surface layer obtained throughout remelting and alloying with carbides by high power diode laser is accompanied by increase of tribological properties, when comparing to the steel processed with conventional heat treatment.

*Keywords:* Laser, surface, treatment, alloying, tool, steel, tribology

## 1. Introduction

Tool materials decide many a time the efficiency of the technological processes of metals and other materials, and also reliability of the entire processing lines [1]. Therefore, improvement of the surface layer of the tool steels has to take fully into account the anticipated tool service conditions. Laser surface treatment is a new technology altering the properties of a surface layer of materials without significantly changing the properties of their core [2,3]. Lasers have a number of interesting applications in materials manufacturing and treatment processes such as machining, welding, glazing, alloying or coating deposition. A laser, by adjusting process parameters such as laser power, beam diameter or a scanning rate, can perform multiple functions. The materials used for laser treatment include steels and other ferroalloys (including casting alloys), non-ferrous metals and their alloys, paper, cardboard, ceramics, wood and plastics [4-6]. The primary aim of the laser remelting of material surface layers is to modify the structure and associated properties. Enhanced wear resistance and thermal fatigue resistance is achieved by creating a chemically homogenous, fine-crystalline surface layer without altering the chemical composition of the material. Even more advantageous effects, such as improved functional properties, are achievable by alloying a material surface layer with the particles of hard phases of carbides, oxides or nitrides [7-8]. Studies in the field of laser remelting, alloying and hardfacing conducted at home and abroad are focussed on the treatment of high-speed steels and machine steels by means of continuous and pulsed $CO_2$ gas lasers and solid-state lasers. High power diode lasers, allowing to further develop and considerably expand the use of surface engineering technologies, have been introduced in industry due to the sharp advancement of laser techniques and devices [4,7]. The investigation results obtained may be used for the further research on optimization of the surface layer properties of the tool steels, targeted at obtaining tools with the possibly high mechanical and service properties. The goal of this work is studying the selected properties of the surface layers obtained by the high power diode laser treatment of the tool steel.

## 2. Experimental procedure

The experiments were made on specimens made from the high-speed steel HS6-5-3-8. Surfaces of specimens were sand blasted and machined on magnetic grinder. 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. 1.0 mm. Such prepared grooves were filled with WC, VC, TiC, SiC, $Si_3N_4$ and $Al_2O_3$ particles. Surface of specimens of the HS6-5-3-8 steel fixed in a turntable was remelted with the Rofin DL 020 high power diode laser beam with parameters specified in Table 1. Remelting and alloying of surface layers were made using the HPDL Rofin DL 020 in the laser power range of 0.7÷2.3 kW. Remelting and alloying was carried out perpendicularly to the

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longer side of the focused beam with the multimode energy distribution, which makes it possible to obtain the wide surface. Abrasion wear resistance tests of the surface layers were carried out in the metal-ceramic material arrangement according to the ASTM D4060 standard. The surface layer obtained consists of four adjacent welding remelted or alloyed. Two test pieces of each type of the investigated surface coatings were examined according to the requirements of the standard. The test conditions are specified by the requirements of the ASTM G65standard. 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 with the accuracy of 0.0001 g to check the mass loss, depending on the used particles and laser power. The test of dry wear resistance with the pin-on-disk method were made on the computer controlled CSEM High Temperature Tribometer. Friction force between the ball and the disk was measured during the test run. Basing on the preliminary experiments the following test conditions were assumed: the smallest scatter of results and stable tribological characteristics were obtained for the counter-specimen in the form of the 6 mm diameter ball from the aluminium oxide $Al_2O_3$ and steel ball with 8.7 mm diameter. In this test the stationary ball was pressed against the disk rotating in the horizontal plane with the force of 10 N. The rubbing speed was 0.5 m/sec, friction radius was from 11 to 22 mm, and the optimum friction distance was determined as 1000 m. The temperature of the environment was assumed as 23°C, and the relative air humidity as 50%. Measurement of the specimens mass loss was made on the Mettler AT 201 electronic weigher, cleaning the specimens form the wear products in the friction zone with the air jet. Metallographic examination of the material structures after surface laser alloying were made on a Zeiss LEICA MEF4A light microscope with magnifications from 50 to 200×. 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). 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.

TABLE 1

Specifications for the HDPL, Rofin DL 020

| | |
|---|---|
| Wavelength of the laser radiation, nm | 808 ±5 |
| Maximum output power of the laser beam (continuous wave), W | 2100 |
| 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 |

## 3. Results and discussion

The investigations of surface layers fabricated by remelting and/or alloying with WC, VC, TiC, NbC and SiC carbides, $Al_2O_3$ oxides and $Si_3N_4$ nitrides of the high-speed steel: HS6-5-3-8 clearly show the effect of remelting and alloying process parameters, in particular laser beam power and the type of ceramic particles used, on the structure and thickness of surface layers. Laser treatment within the laser power range of 0.7-2.1 kW ensures a regular and flat bead shape without remelting with relatively high smoothness. Few indents and surface irregularities caused by intensive heating exist on the tracks created during laser alloying of a surface. The main factor decisive for the formation of alloyed layers is transport of material in the liquid metal, caused by surface tension forces. A high surface tension gradient is formed on the liquid surface if a material is heated unevenly by the interacting laser beam. The force directed from the centre of the beam, where temperature is highest, causes the melted material to move towards the edges of the remelting track and the deposition of the alloying material in the axis and on the edges of the remelting track. Surface roughness is rising if power is increased of the laser used for the laser remelting of a hot-work tool steel surface layer at a constant laser beam travel speed. In case of alloying with the studied particles, including carbides, oxides and nitrides, the beam power does not have decisive impact on steel surface roughness. This phenomenon is associated with the growing absorption of laser radiation by the specimen surface owing to a higher particles absorption factor as compared to a steel surface absorption factor. Increased absorption is heightening the intensity of the steel surface layer remelting process. The achieved varied thickness of the alloyed zones is associated with a phenomenon of laser radiation absorption by the surface of specimens covered with powder consisting of carbides, oxides or nitrides. An important role in a remelting and alloying process is also played by a stream of shielding gas acting on the surface of the liquid steel flowing in the place where a surface layer is formed and securing steel in the liquid state against contact with air and removing inorganic binder decomposition products used as a powder binding material and also taking part in the formation of the crystallising bead face and in transporting the alloying material remaining on the remelted surface of the alloying material. The initial experiments consisting in alloying the HS6-5-3-8 steel indicate the clear influence of the laser power of 0.7, 1.4, 1.7, and 2.1 kW respectively on the surface shape and its depth (Fig. 1). It was observed that the remelting depth grows with the laser power increase (Fig. 2). It was found out, that thickness of the analysed layers, carried out 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 two variables: laser beam power, and the alloying material thickness in the form of carbides. The average remelted layer thickness in the steel specimens subjected to remelting, grows proportionally with the laser power increase. In the case of alloying with the following carbides, NbC, VC, TiC and WC, whose melting point is much higher than the melting point of steel, the unsolved carbide powder grains are cladded into the remelted steel substrate. The melted metal is then strongly circulated, and rapid solidification occurs once the laser beam passes. Fast crystallisation leads to differentiation in the structure of the remelted zone. The material is mixed according to different mechanisms, depending on the treatment parameters applied. With a low energy of laser-to-material impact, capillary lines are not connected, and the remelting structure is relatively homogenous. As laser power is rising, capillary lines are whirling and

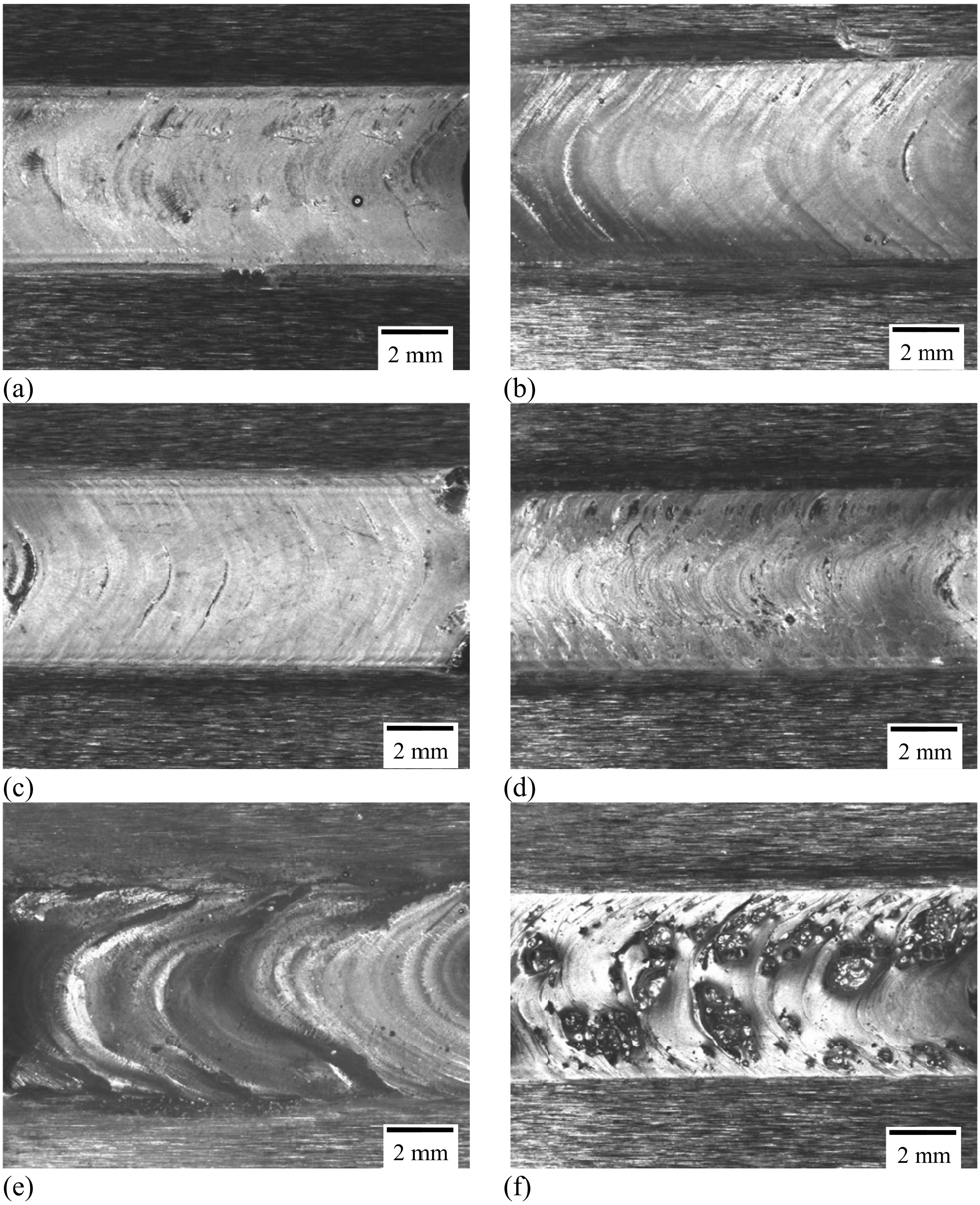


Fig. 1. Part shape of bead face of the high speed steel HS6-5-3-8 alloyed with: (a) WC, (b) VC, (c) TiC, (d) SiC, (e) $Si_3N_4$ and (f) $Al_2O_3$ particles, laser beam power of 2.1 kW

they start to connect with each other. The remelting bottom is still flat, and a small waving appears on the surface. The biggest surface layer remelting thickness is achieved by using the maximum laser energy, however the remelting bottom is subjected to waving as strong liquid movements take place. As laser power is rising and thus the beam impact on the material, the remelting zone depth is increasing. It was confirmed that a remelted zone and a heat-affected zone exist in the surface layer of the examined steel, whose thickness is dependent on the applied laser treatment parameters and the type of ceramic particles. Laser remelting and alloying using all the particles applied has an effect on structure refinement within the entire studied range of laser power. Grains with varied sizes occur in the particular zones of the surface layer after laser remelting and alloying (Fig. 3). For instance, an average size of grains in a remelting zone for HS6-5-3-8 steels is between 32.75 to 36.47 μm$^2$. The smallest average size of grain for all the steels was found for alloying with vanadium, titanium or silicon carbides ranging between 3.95 to 13.73 μm$^2$. After alloying HS6-5-3-8 steel with aluminium oxide, the average size of grains in the remelting zone spans between 28.13 to 42.65 μm$^2$, and between 254.39 to 270.67 μm$^2$ in the native material. After alloying with silicon nitride, the average size of grains in the remelting zone spans between 30.44 to 40.01 μm$^2$, and between 232.10 to 260.82 μm$^2$ in the virgin material. Elongated and decreased grains, which in laser treatment undergo partial remelting and recrystallisation, exist only on the boundary of the crystallisation front, between a remelted area and a heat-affected zone. Similar changes in grain size exist in all the studied high-speed steels. Structure refinement provokes advantageous alterations in mechanical and usable properties of the final product. As the surface layer temperature is rising due to higher laser beam power, strong convective currents occur in liquid steel. A mechanism of rapid crystallisation linked to the impact of a strong stream of shielding gas causes a proportional increase in roughness along with the growing laser beam power. The smallest value of the parameter $R_a$ is exhibited by a steel surface subjected to laser remelting with the laser beam power of 0.7 kW (Fig. 4). A surface layer obtained by alloying with carbides, oxides and nitrides does not exhibit a proportional dependency between surface roughness and laser beam power. The lack of dependency between surface roughness and laser beam power in alloying with carbides, oxides and nitrides is caused by a cladding mechanism of powders into a steel surface layer, resulting from the following factors: a high absorption factor, rapid crystallisation towards the heat evacuation direction and the impact of shielding gas blow. The maximum average microhardness of approx. 1403 HV0,01 for all the high-speed steel specimens undergoing laser treatment is ensured after alloying with WC carbide with the laser power of 0.7 kW.

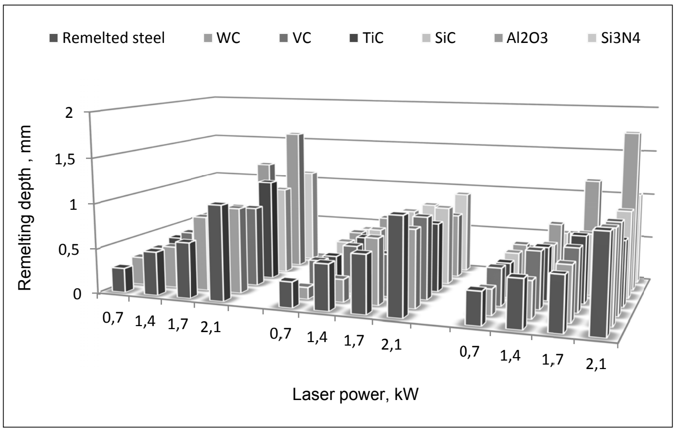


Fig. 2. Influence of the laser power on the remelted zone thickness respectively RZ, heat affected zone HAZ, and surface layer SL of the HS6-5-3-8 steel after laser alloying

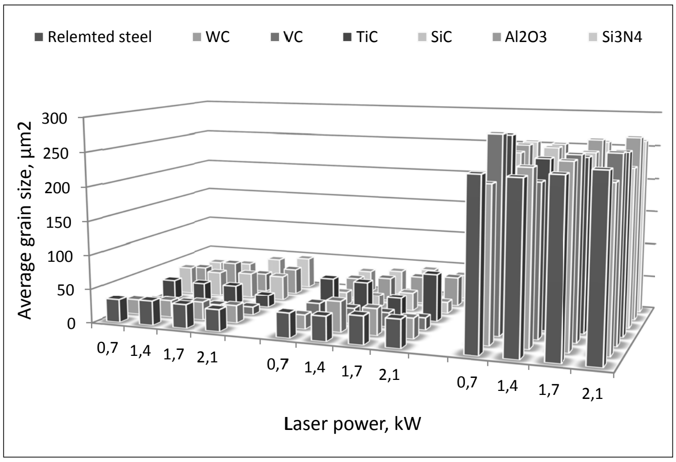


Fig. 3. The average grain size in the surface layer of the high speed steel HS6-5-3-8 alloyed with the WC, VC, TiC, SiC, $Si_3N_4$ and $Al_2O_3$ particles with the scanning rate of 0.5 m/min and laser beam power of 0.7, 1.4, 1.7 and 2.1 kW

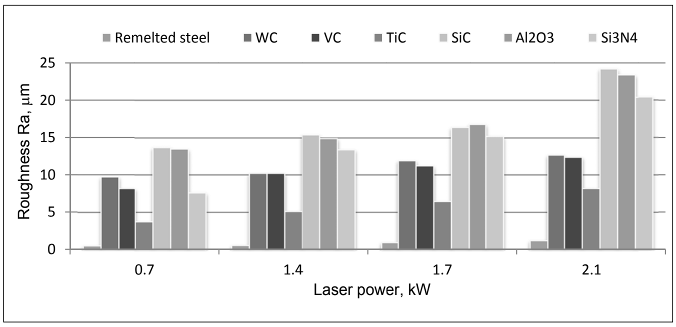


Fig. 4. Influence of the laser power beam for roughness of surface layer of the high speed steel HS6-5-3-8 alloyed with the WC, VC, TiC, SiC, $Si_3N_4$ and $Al_2O_3$ particles with the scanning rate of 0.5 m/min and laser beam power of 0.7, 1.4, 1.7 and 2.1 kW

Microhardness growth was revealed, basing on microhardness tests on the transverse section of laser runs versus distance from the surface of the examined steel test pieces, in case of remelting and alloying with all used particles (Fig. 5). This phenomenon is achieved by the presence of phase transitions closely linked to a heat evacuation rate from the remelted zone. The factor which is mainly decisive for a cooling rate is the thickness of the remelted layer dependent on the absorbed energy of radiation and the time for which a laser beam is acting on the steel surface. For constant remelting velocity, laser power has only influence on the energy supplied to the surface layer. Remelting depth for low laser beam power is small, hence the heat evacuation rate is highest. A high rate of cooling leads to the existence of superfast phase transitions, for this reason a fine-crystalline martensite structure responsible for hardness growth exists in the material. Variations in the hardness of surface layers achieved by remelting and alloying with carbides using the a high power diode laser are accompanied by improved tribological properties as compared to conventionally steels. A loss in specimen mass is dependent upon laser energy for all the tested laser treatment methods of a surface layer. The smallest mass loss, thus the highest wear resistance in all the cases, was exhibited by steel alloyed with vanadium carbide VC and titanium carbide TiC powder (Figs 6,7). Dependencies can also be identified between the laser power used for alloying and wear resistance; it has been observed that in the majority of powders the highest wear resistance was attained after remelting with the laser power of 1.4 kW and 1.7 kW. The steel subjected to alloying with silicon carbide showed smallest wear resistance for all the specimens. The highest mass loss for steels alloyed with carbides is usually seen, despite large disparities in the outcomes obtained, for surface layers fabricated with the laser power of 0.7 and 2.1 kW. This derives from the fact that for the laser power of 0.7 kW, small surface layer remelting occurs, hence the surface layer achieved is subject to faster wear, while for the maximum laser power used, i.e. 2.1 kW, a surface layer often exhibits small microcracks which may cause a higher mass loss of the analysed layers. The tests with the gravimetric method were carried out weighing each specimen three times before the experiment and after the test and their results were statistically analysed. Test results of the average specimens mass loss due to friction in the ball – disk pair for the surface layer obtained at various laser beam power values are presented in figure 6. It turns out from the analysis of the mass loss of specimens, depending on the laser beam power used for alloying of the surface layer that the mass wear of the alloyed VC alloyed specimens was about 50% smaller and was from 0.38 mg to 0.45 mg in comparison with the material after laser remelting, for which this value was 0.81 mg. The laser beam power does not have any clear effect on the mass wear of the investigated specimens. Increase in the counter-specimen wear land area was observed (0.43 to 0.88 $mm^2$) in the contact with the laser alloyed surface layer. The counter-specimen land wear after the contact with the HS6-5-3-8 steel after laser remelting is about three times smaller (about 0.29 $mm^2$). The laser beam power during melting does not have a meaningful influence on the wear land of the counter-specimen from $Al_2O_3$. For the tribological assessment of the examined surface layer the linear wear was measured using the wear profiles. The influence of laser alloying was found out on the depth of the transverse section of the wear path, which for the remelted material was about 4 μm, whereas for the surface layer alloyed by TiC carbides with the laser beam with the 1.7 kW power it achieved value of 2,0 μm. It was revealed as a result of the investigations performed that if surface layers are fabricated by remelting and alloying high-speed tool steels with carbides, oxides and nitrides using a high power diode laser, functional properties are improved as compared to the properties of the conventionally hot worked steel (Figs 8,9). Such layers may be essential for the enhancement of functional properties of tools made of such steels by improving hardness and abrasive wear resistance. The surface layers fabricated with a high performance diode laser should be used for producing tools employed mainly for hot plastic working, as well as in other mechanical forming processes, including, among others, for machining certain materials, and for alloying the worn working surfaces of tools made of such steels. These layers are characteristic of the best tribological properties among all the used particles. Both observations of the steel counter-specimen wear and the surface layers' wear profiles confirm the best tribological properties compared to the conventionally heat treated steel.

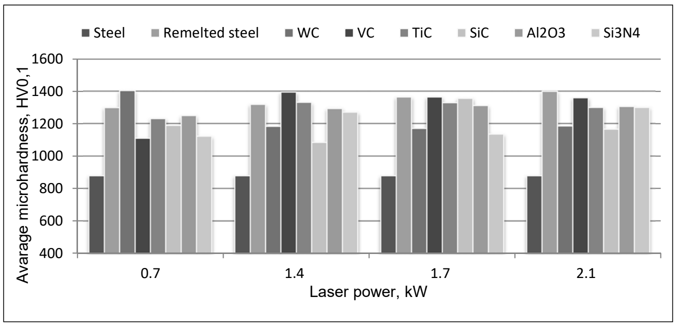


Fig. 5. Avarage microhardness for the high speed steel HS6-5-3-8 remelted and alloyed with the WC, VC, TiC, SiC, $Si_3N_4$ and $Al_2O_3$ particles with the scanning rate of 0.5 m/min and laser beam power of 0.7, 1.4, 1.7 and 2.1 kW

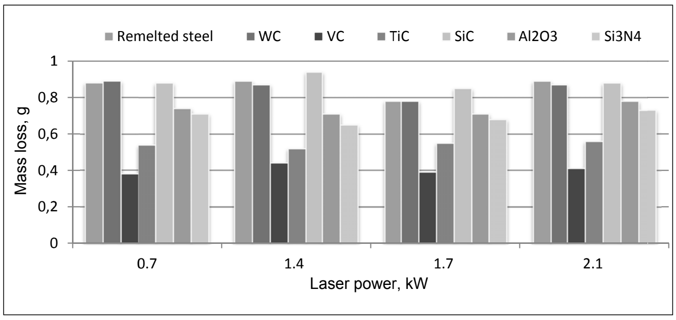


Fig. 6. Measurement results of the average specimen mass loss depending on the laser beam power and alloying particles

## 4. Conclusion

The investigations carried out made it possible to state that due to the heat treatment and remelting of the HS6-5-3-8 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 hot work tool steel

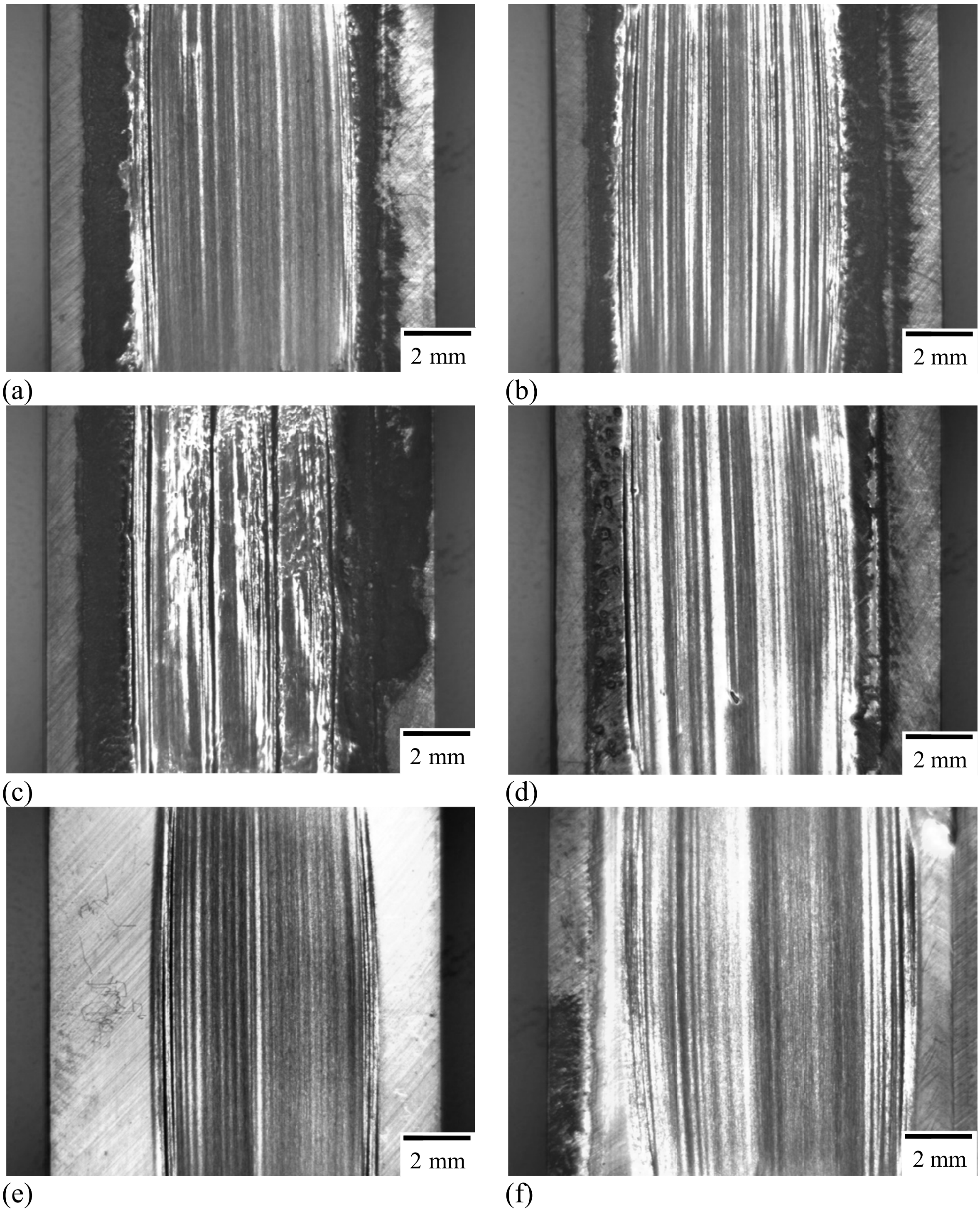


Fig. 7. Trace of wear after abrasion wear resistance tests in the metal-ceramic material arrangement according to the ASTM D65 standard of the surface layer of steel HS6-5-3-8, (a) WC, (b) VC, (c) TiC, (d) SiC, (e) $Si_3N_4$ and (f) $Al_2O_3$ alloying with the 2.1 kW laser beam

subjected to remelting and alloying with carbides steel hardness growth occurs usually compared to hardness after the conventional heat treatment. The maximum hardness of 74.2 HRC the investigated steel achieves in case of alloying with the titanium carbide with the laser power of 1.7 kW. The average microhardness of the surface layers subjected to laser treatment is up to about 80% higher in case of the vanadium 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 2.5 times higher than that of the native material, was revealed in case the steel alloyed with titanium carbide. 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 HS6-5-3-8 tool steel.

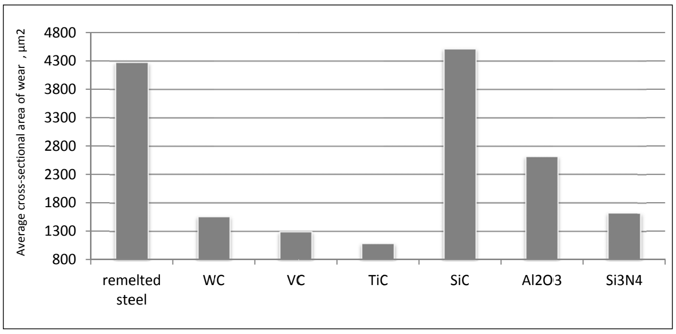


Fig. 8. The average cross-sectional area of wear during the investigation of tribological properties for the high speed steel HS6-5-3-8 remelted and alloyed with the WC, VC, TiC, SiC, $Si_3N_4$ and $Al_2O_3$ particles

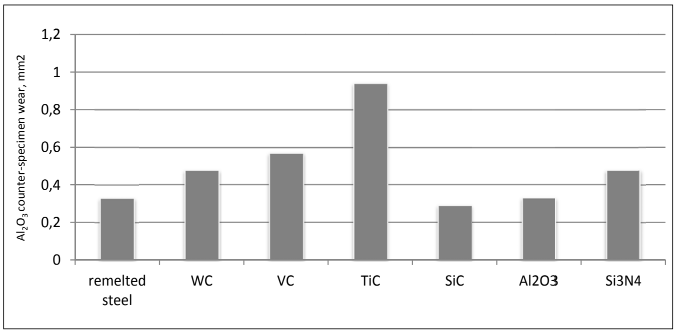


Fig. 9. Comparison of the surface area of the $Al_2O_3$ counter-specimen wear

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