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Improvement of the hot work tool steel surface layers properties using a high power diode laser

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Properties

ABSTRACT

Purpose: The purpose of this research paper is focused on the X38CrMoV5-3 hot work tool steel surface layers properties using HPDL laser.
Design/methodology/approach: The aim of this research paper is to present deposition technologies, investigation of structure and properties of the X38CrMoV5-3 hot work tool steel alloying with ceramic particles using high power diode laser HPDL. Selection of laser operating conditions is discussed, as well as beam face quality after remelting, hardness, micro hardness test, wear resistant, EDX, TEM and X-ray microanalysis results.
Findings: The structure of the solidified material after the laser remelting is characterized by the diversified morphology connected with the multiple changes of the crystal growth direction from little dendrites to tiny equiaxed grains in the near-surface zone. The main axes of the dendrites are directed according to the heat abstraction directions on the border of the solid and liquid phases with the carbides' clusters arranged according to the whirls caused by a convectional movement in the pool of the metallic liquid as well as partly unremelted conglomerates NbC, TaC, VC, WC and TiC as a melting material in the middle area of the remelted zone.
Research limitations/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.
Practical implications: Practical implications are: regeneration and manufacturing of various tools from the X38CrMoV5-3 hot-work tool steel.
Originality/value: The laser treatment as a part of the new generation techniques applied in metal surface technology.
Keywords: Improvement properties; Surface layers; HPDL laser; Ceramic particles; Hot work tool steel

1. Introduction

The laser treatment as a part of the new generation techniques applied in metal surface technology is discussed in this paper. Laser treatment is presented with remelting and alloying of hot work tool steel X38CrMoV5-3 with ceramic powders. 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. The material behavior for the HPDL processing has been found to be different from the other high-power lasers in the following aspects: fewer cracks and less spallation for surface glazing/sealing, more uniform melt/heating zones, smoother surface, better beam absorption for metallic materials, more consistent and repeatable [1-10]. 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) [11-19].

Tool steels still feature the widely used group of tool materials, especially interesting because of their low price and very good functional properties. Big interest in these steels gives base for carrying out investigations focused on improvement of the functional properties of these materials.

2. Experimental procedure

Investigations were carried out on test pieces from the X38CrMoV5-3 hot work tool steel (Figure 1) with the composition according to PN-EN ISO 4957:2002U standard. Chemical composition of the steel is given in Table 1. The investigated steel was molten in the electric vacuum furnace at the pressure of about 1 Pa, cast into ingots weighing about 250 kg, and were roughed at the temperature range 1100-900ºC into the O.D. 76 mm bars 3 m long, which were soft annealed. Test pieces for structural and tribological tests were made using the test pieces with the following dimensions: 65 x 25 x 5 mm. Specimens prepared like that were subjected to heat treatment consisting in quenching and tempering twice. Austenitising was carried out in vacuum furnace at the temperature of 1040ºC, at the holding time of 0.5 h. Two isothermal stops were used during heating to the austenitising temperature were used - at temperatures of 585ºC and 850ºC. The specimens were tempered twice after quenching, each time for 2 hours, at the temperature of 575°C and next at 560 ºC. Surfaces of specimens were ground on magnetic grinder after heat treatment. Particular attention was paid to prevent development of micro-cracks that might disqualify the specimen from further examination.

Remelting and alloying of surface layers were made using the HPDL high power diode laser Rofin DL 020 (Figure 2) in the laser power range of 1.2÷2.3 kW, with parameters presented in Table 3. The following carbides were used as the alloying material: TaC, NbC, WC, VC, and TiC with the average grain size showed in table 2. Remelting and alloying was carried out perpendicularly to the longer side of the focused beam with the multimode energy distribution, which makes it possible to obtain the wide surface.

It was found out in the preliminary investigations that the maximum feed rate at which the process is stable is 0.5 m/min.

Further experiments were carried out at the constant remelting rate, changing the laser beam power in the 1.2 - 2.3 kW range during remelting the surface layer of the test pieces. It was revealed that the argon blow-in with the flow rate of 20 l/min through the 12 mm circular nozzle oppositely directed in respect to the remelting direction provides full remelting zone protection.

Metallographic examinations of the material structures after laser alloying its surface layer were made on Zeiss LEICA MEF4A light microscope. Microscopic examinations were made also on the OPTON DSM 940 scanning electron microscope.

Table 1.
Chemical composition of X38CrMoV5-3 steel

The mass concentration of main elements, %							
C	Si	Mn	P	S	Cr	Mo	V
0,372	0,42	0,43	0,022	0,002	4,95	2,72	0,42

Table 2.
Chemical composition of applied powders

Powder	Grain sice, µm	Melting temperature,°C	Density g/cm^3	Hardness, HV
Niobium carbide	10	3500	7,6	2100
Tantalum carbide	10	3880	15,03	1725
Vanadium carbide	1,5	2830	5,36	2850
Titanium carbide	3	3140	4,25	2800
Tungsten carbide	5	2770	15,6	2600

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

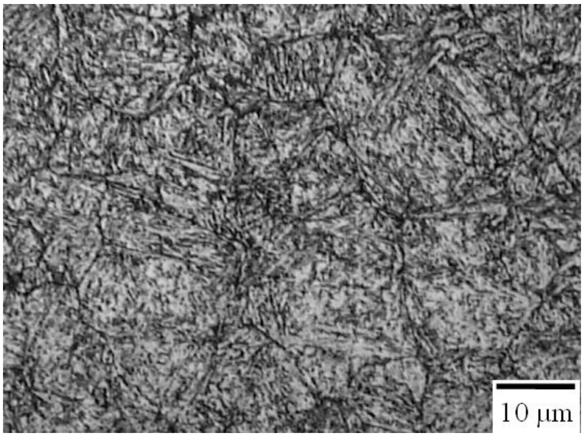

Fig. 1. Structure of hot work tool steel X38CrMoV5-3 after standard heat treatment

Fig. 2. Alloying process of ceramics particles of hot work tool steel using high power diode laser HPDL Rofin DL 020

Further experiments were carried out at the constant remelting rate, changing the laser beam power in the 1.2 - 2.3 kW range during remelting the surface layer of the test pieces. It was revealed that the argon blow-in with the flow rate of 20 l/min through the 12 mm circular nozzle oppositely directed in respect to the remelting direction provides full remelting zone protection.

Metallographic examinations of the material structures after laser alloying its surface layer were made on Zeiss LEICA MEF4A light microscope. Microscopic examinations were made also on the OPTON DSM 940 scanning electron microscope.

The X-ray qualitative micro-analysis and analysis of the surface distribution of the alloying elements in the test pieces of the investigated steel, subjected to the standard heat treatment remelted and alloyed, were made on the Opton DSM-940 scanning electron microscope with the Oxford EDS LINK ISIS X-ray energy dispersive spectrometer at the accelerating voltage of 20 kV.

The phase composition of the investigated coatings was determined on the Dron-2.0 X-ray diffractometer, using the filtered radiation of the cobalt anode lamp, powered with 40 kV voltage, at 20 mA heater current. The measurements were made in the angle range 2Θ: 35º - 105º

Abrasion wear resistance tests of the surface layers were carried out in the metal-ceramic material arrangement according to the ASTM standard (Figure 3).

The surface layer obtained consists of four adjacent welding sequences remelted or alloyed. Two test pieces of each type of the investigated surface coatings were examined according to the requirements of the standard. The schematic diagram of the device is presented in Figure 3; whereas the test conditions are specified by the requirements of 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 circle with the diameter of 229 mm.

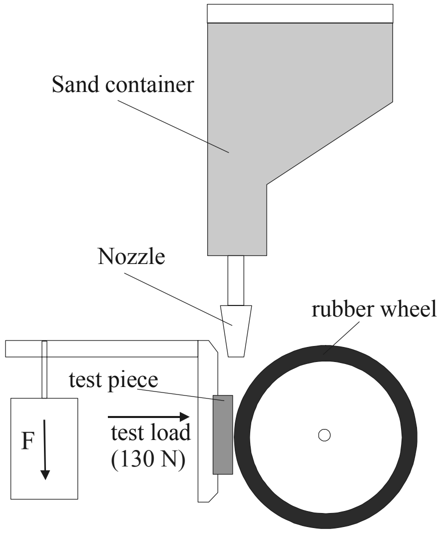

Fig. 3. Schematic diagram of the device for abrasion wear resistance tests of the surface layers in the metal-ceramic material arrangement according to the ASTM standard

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 0.0001g to check the mass loss, depending on the used particles and laser power. The X38CrMoV5-3 conventionally heat treated steel was used as reference material. The mass loss of the investigated layers was determined using the following relationship 1:

$$Mass\ loss = \frac{\Delta m\ specimen\ withcarbide\,[g]}{\Delta m\ heat\ treated\ specimen\,[g]} \times 100\% \qquad (1)$$

Abrasion resistance wear tests of the surface layers in the metal-metal arrangement were carried out using the device designed at the Faculty of Mechanical Engineering of the Silesian University of Technology (Figure 4).

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.

Tests were carried out on surfaces prepared in this way using the steel ball with 8.7 mm diameter as the counter-specimen. The load of 10 N and the constant number of cycles of 1000 were determined in the preliminary tests. Test pieces were rinsed in the ultrasonic washer to clean them before and after the test. Wear profiles were registered for the investigated surface layer, and also the wear trace of the counter-specimen to compare the test results for each type of the test pieces coated with various alloying particles at various laser power values.

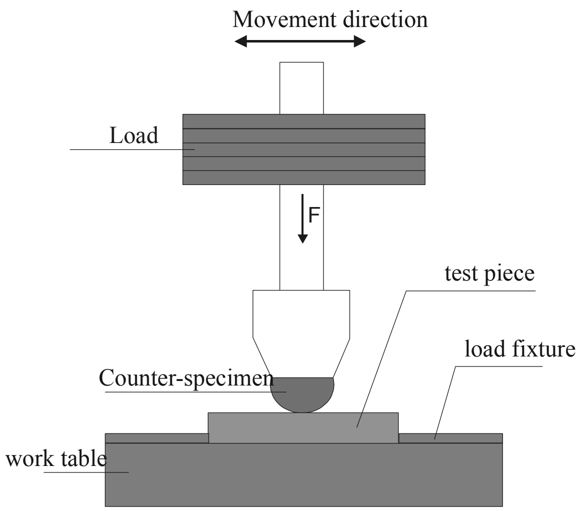

Fig. 4. Schematic diagram of the device for abrasion wear resistance tests of the surface layers in the metal-metal arrangement

Hardness tests were made with 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 buffed front surfaces of specimens.

Test results were analysed statistically. Micro-hardness tests were carried out on the Shimadzu DUH 202 ultra-microhardness tester. Hardness and microhardness were measured on the ground and buffed front surfaces of specimens.

3. Discussion of experimental results

The investigated steel displays in the softened state the ferritic structure with carbides distributed uniformly in the matrix. The lathe, martensite structure is obtained after quenching, which is saturated with alloying elements, and which is confirmed by the EDX chemical composition analysis, and with carbon. The anticipated hardenability of these steels was attained at the austenitizing time long enough, which ensures dissolving most alloying carbides in the austenite. Structural examinations consist in comparing the effect of parameters of heat treatment and remelting of the hot work tool steel with the diode laser on the run shape and remelting depth.

The initial experiments consisting in alloying the X38CrMoV5-3 hot work steel indicate the clear influence of the laser power of 1.2, 1.6, 2.0, and 2.3 kW respectively on the surface shape and its depth. It was observed that the remelting depth grows with the laser power increase (Figure 9).

It was found out, that thickness of the analysed layers, evaluated based 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.

Metallographic examinations carried out on the light microscope and on the electron microscope confirm that the structure (Figure 5) of the material solidifying after laser remelting is diversified, which is dependant on the solidification rate of the investigated steels.

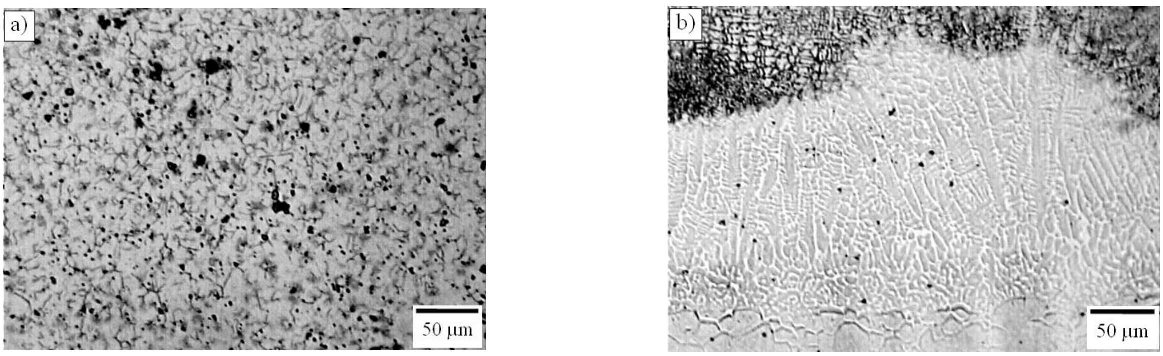

Fig. 5. Surface layer of the X38CrMoV5-3 steel alloyed after laser remelting with the ceramic particles with the scanning rate of 0.5 m/min: a) remelted zone – visible particles of vanadium carbide in the surface layer; b) transition between the remelted zone and the heat affected zone after alloyed with titanium carbides

Occurrence of structure with big dendrites (Figure 5) was revealed in areas on the boundary of the solid and liquid phases. Examinations of the chemical composition with the surface and pointwise methods reveal occurrences of the inundated NbC, TaC, VC, WC and TiC particles in big conglomerates (Figure 6). Moreover, using the X-ray microanalysis it was also found out that carbides occurs not only in the form of conglomerated but also the remelted layers (Figures 5, 6).

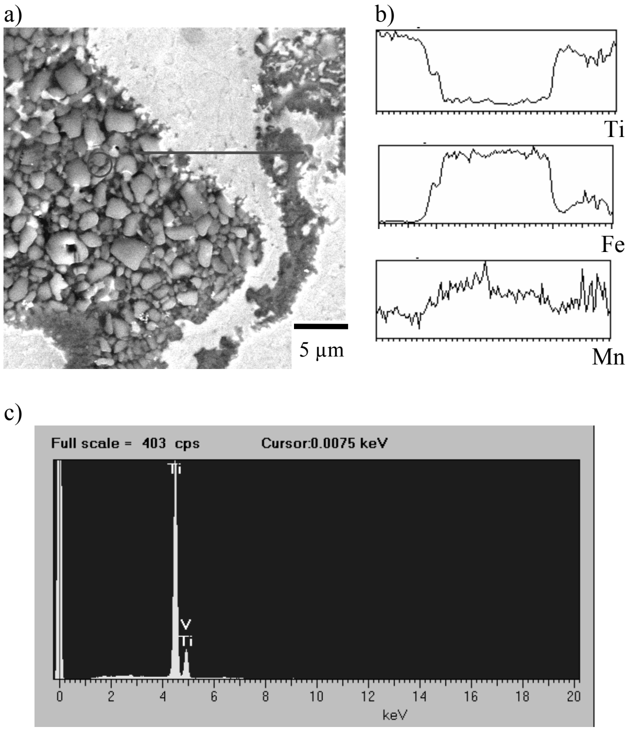

Fig. 6. Surface layer of the X38CrMoV5-3 steel alloyed with the TiC ceramic particles; a) structure – SEM, b) spectrum of the linear chemical composition analysis, c) spectrum of the pointwise chemical composition analysis

At the low power of the laser beam the remelting depth is small; therefore heat removal rate is the highest. High cooling rate causes occurrences of the super-fast phase transformations; therefore, the fine-grained martensite structure occurs in the material, responsible for hardness growth. The highest hardness of the steel surface layer subjected to laser remelting of 61.7 HRC, occurs after remelting with the laser beam with power of 1.2 kW (Figure 10). The steel surface layer alloyed with carbides demonstrates the maximum hardness growth of up to 67.4 HRC for tantalum carbide at the laser beam power equal to 2.3 kW.
The microhardness tests using the Vickers method were made on the dynamic ultra microhardness tester. The measurements were made in the „load - unload" mode.

The clear microhardness growth in the remelting zone was revealed also in case of the microhardness test. The maximum average microhardness of 1412 $HV_{0.01}$, of all steel test pieces subjected to laser modification, is ensured at the laser power of 2.3 kW for steel alloyed with tantalum carbide (Figure 8).

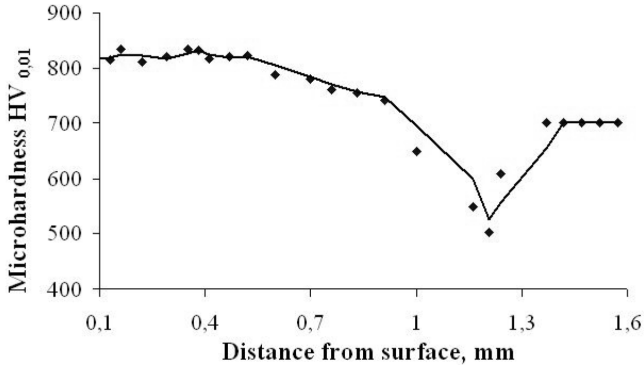

Fig. 7. Change of the X38CrMoV5-3 steel surface layer microhardness after remelting using the 2.0 kW laser

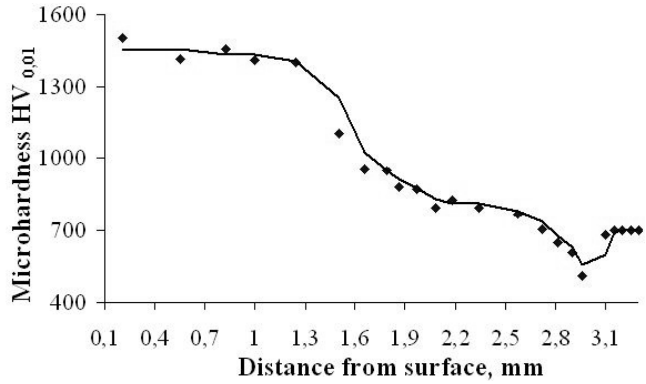

Fig. 8. Change of the X38CrMoV5-3 steel surface layer microhardness after alloying with TaC carbide using the 2.3 kW laser

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 (Figures 7-8, 11-12).

The highest average microhardness growth in the remelted zone in the remelted surface layer was observed in case of the laser beam power of 1.2 kW (Figure 11). In case of alloying, the highest microhardness growth compared to the material after the standard heat treatment was revealed for the steel surface layer alloyed with the TaC particles, for which the average microhardness growth is 712 $HV_{0,01}$, when the laser power used for alloying is 2.3 kW (Figure 12). For other particles used the average microhardness growth in the surface layer is: 521 $HV_{0,01}$ for vanadium carbide and laser power 2.0 kW, 546 $HV_{0,01}$ for niobium carbide and laser power 2.3 kW, 217 $HV_{0,01}$ for titanium carbide and laser power 2.3 kW.

Moreover, microhardness tests reveal occurrence of the hardness drop area to the value of about 550 $HV_{0,01}$ in the analysed steel, both after remelting (Figure 7) and after alloying (Figure 8). The hardness drop occurs over the entire width of the border between the heat-affected zone and native material. Such hardness drop was revealed in all examined specimens.

The hardness drop attests to development of the tempered material zone during laser treatment, heated to the temperature higher than the tempering temperature, i.e., 560ºC.

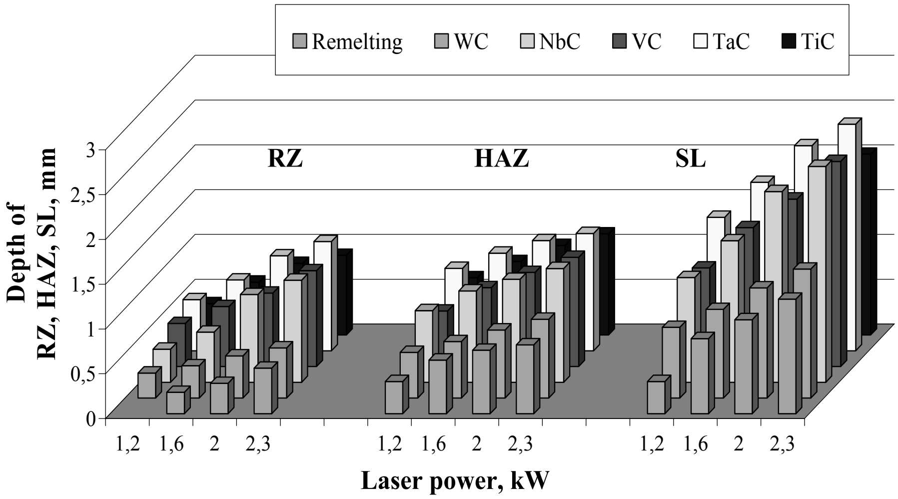

Fig. 9. Influence of the laser power on the remelted zone thickness RZ, heat affected zone HAZ, and surface layer SL of the X38CrMoV5-3 steel after laser alloying with carbides

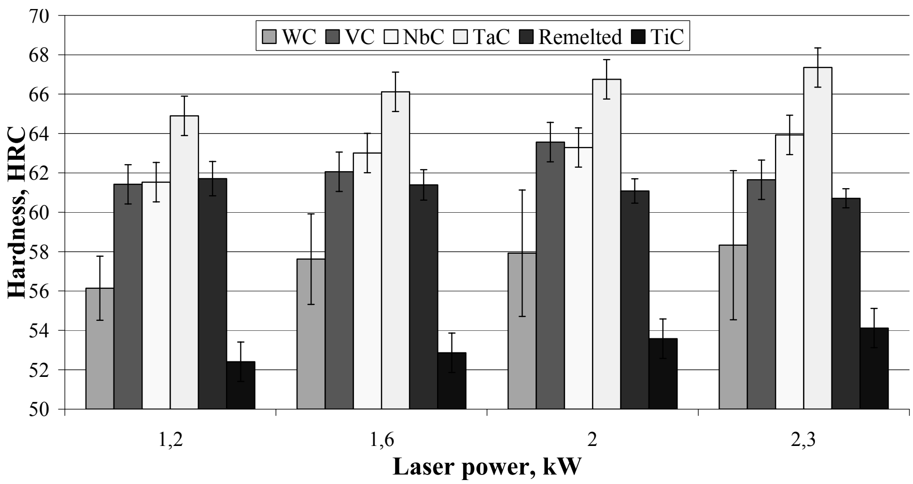

Fig. 10. Changes of the average hardness of the X38CrMoV5-3 steel surface layer after alloying with carbides using the variable power laser

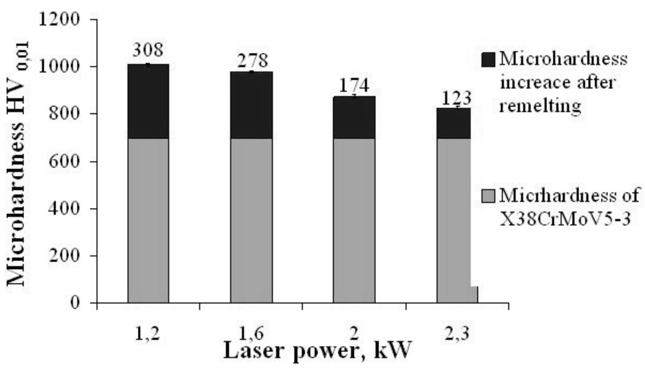

Fig. 11. Average changes of the X38CrMoV5-3 steel surface layer microhardness after laser remelting, compared to steel subjected to the conventional heat treatment

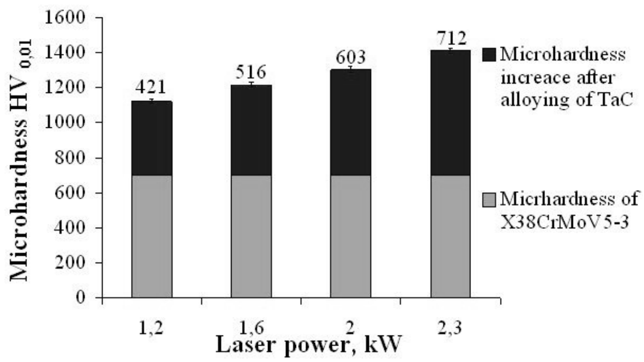

Fig. 12. Average changes of the X38CrMoV5-3 steel surface layer microhardness after laser alloying with the TaC carbide, compared to steel subjected to the conventional heat treatment

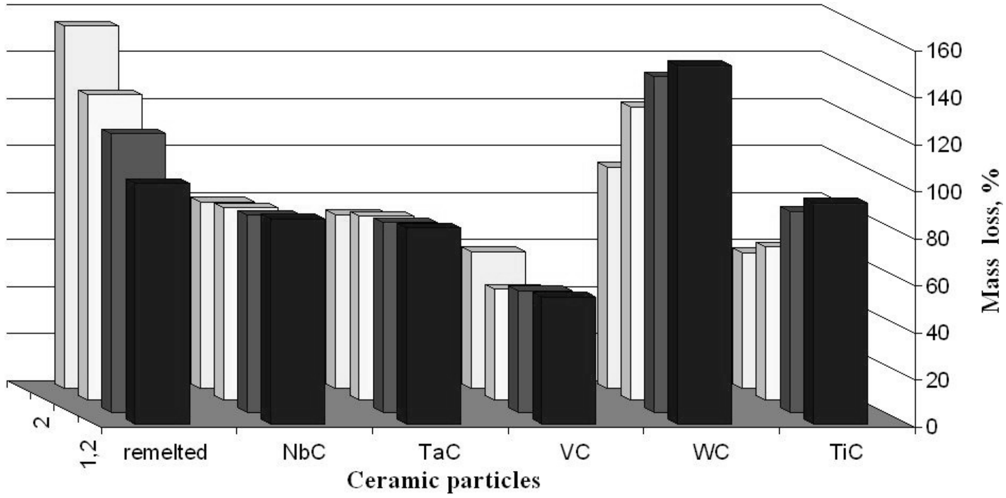

Fig. 13. Mass loss versus particle used, in the X38CrMoV5-3 steel surface layer after alloying with the NbC, TaC, VC, WC, and TiC carbides using the variable power laser

It turns out from the analysis of plots registered during the microhardness tests (loading an unloading versus indenter penetration into the native material) that the depth to which the indenter reaches decreases along with hardness growth. Moreover, the depth to which the indenter reaches in the native material and at the boundary of the heat affected zone of the native material in all analysed states of laser treatment is the same.

The hardness changes of the surface layers obtained by remelting and alloying with carbides using the high power diode laser (Figure 10) are accompanied by the improved tribological properties in comparison with the conventionally heat treated steel (Figure 13).

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 13 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.

However, in case of alloying the mass loss decrease was observed in proportion to the laser power increase (Figure 13), the smallest mass loss occurs in case of the surface layers subjected to alloying with vanadium carbide, among which the minimum mass loss determined according to formula 1 is 47.4085 % for laser power of 2.0 kW (Figure 13).

Whereas the biggest mass loss of about 152.3511 % was observed, among all particles used, in the surface laser of steel alloyed with tungsten carbide at laser beam power of 1.2 kW (Figure 13). One can also notice, basing on the abrasion wear resistance test, that the smallest average mass loss in proportion to the laser beam power employed occurs during alloying with the niobium carbide and vanadium carbide. The biggest mass loss for the majority of the analysed cases was observed for the alloyed surface layers obtained using the laser beam power of 1.2 kW (Figure 13).

The biggest mass loss was revealed for the laser beam power of 2.3 kW only in case of the surface layer alloyed with the vanadium carbide which may result from the fact that this layer is not free from defects like numerous cracks and micro-cracks (Figure 14).

The results presented above are also confirmed by research carried out on the device designed in the Institute of Engineering Materials and Biomaterials (Figure 4) in which the steel ball features the abrasive material. This test was intended to compare the abrasion wear resistance of the obtained surface layers with the service condition, therefore the test was made in the metal-metal setup.

The steel ball suffers the significant wear for surface layer alloyed with the VC and TiC particles; whereas, the wear profile of the surface layers is minimum.

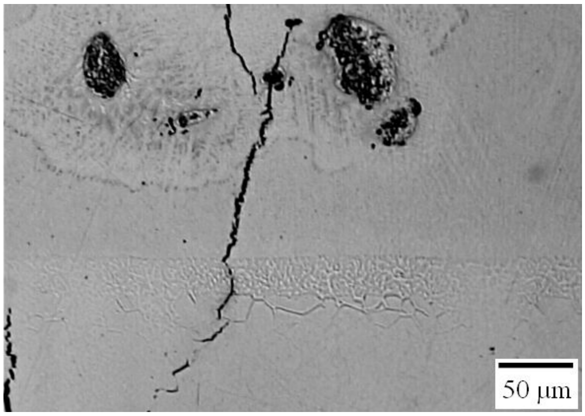

Fig. 14. Cracks in the remelted zone and in the heat affected zone of the steel surface layer after alloying with the WC carbide

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, which is presented in Figures 15-18.

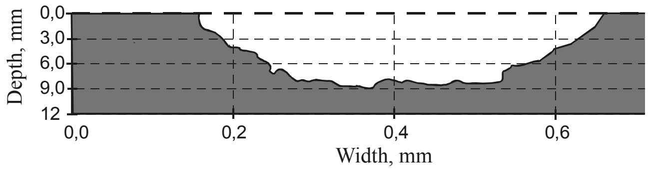

Fig. 15. Wear trace shape of the surface layer after the abrasion wear test of the conventionally heat treated X38CrMoV5-3 steel

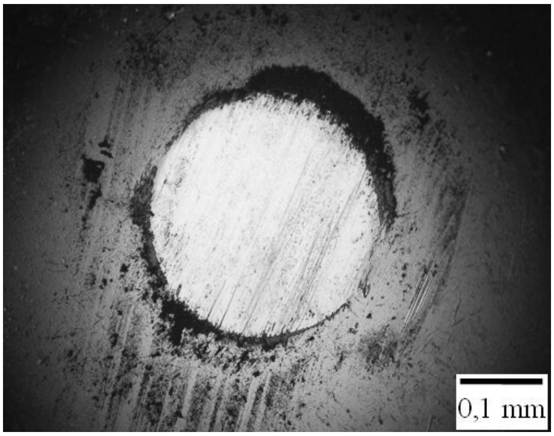

Fig. 16. Wear trace of the steel counter-specimen after 1000 friction cycles with the surface of the conventionally heat treated steel

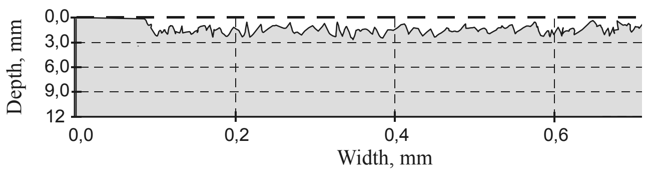

Fig. 17. Wear trace shape of the X38CrMoV5-3 steel surface after the abrasion wear test after alloying with titanium carbide using the 2.0 kW laser

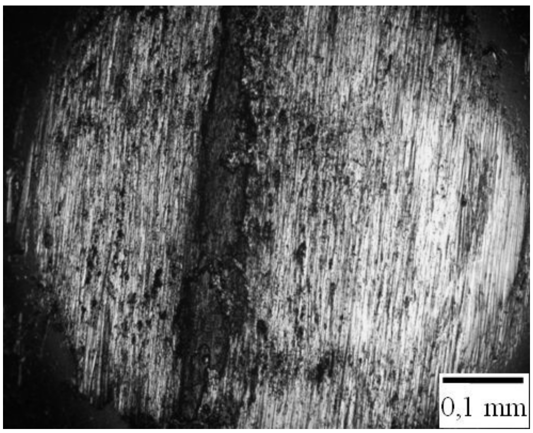

Fig. 18. Wear trace of the steel counter-specimen after 1000 friction cycles with the surface of the steel alloyed with the titanium carbide using the 2.0 kW laser

X-ray photographs 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 (Figure 19).

The remelted zone structure is characterized by the significant martensite dispersion with its lathes length several times shorter than of those developed during the conventional quenching. Martensite twining occurs in some locations, retained austenite, and very fine precipitations of the MC type carbides are observed as broken network on dendrite boundaries, as well as the high-dispersive ones inside of certain grains.

It has been found out, basing on the investigations of thin foils in the transmission electron microscope that are the martensite, retained austenite, and alloy carbides of the MC and VC (Figures 20-22).

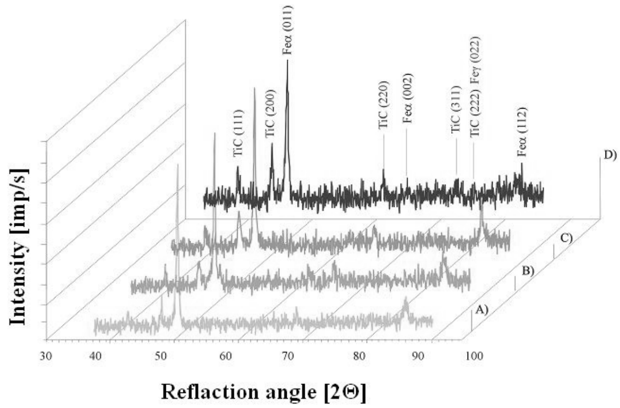

Fig. 19. X-ray diffraction pattern of the X38CrMoV5-3 hot work steel alloyed with the TiC ceramic powder

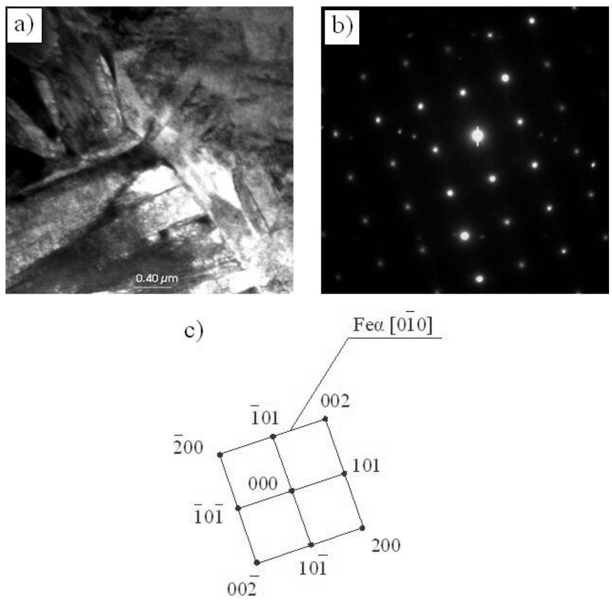

Fig. 20. a)TEM image of the X38CrMoV5-3 after standard heat treatment, b) diffraction pattern of area shown in a, c) part of solution for diffraction pattern shown in b

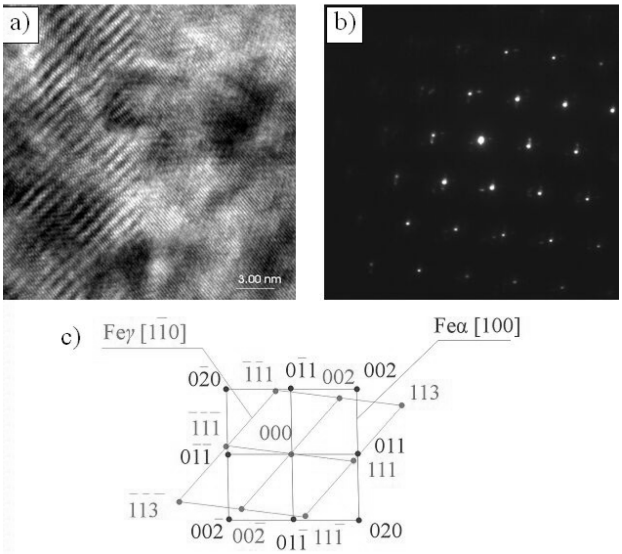

Fig. 21. a)TEM image of the X38CrMoV5-3 after remelted, b) diffraction pattern of area shown in a, c) part of solution for diffraction pattern shown in b

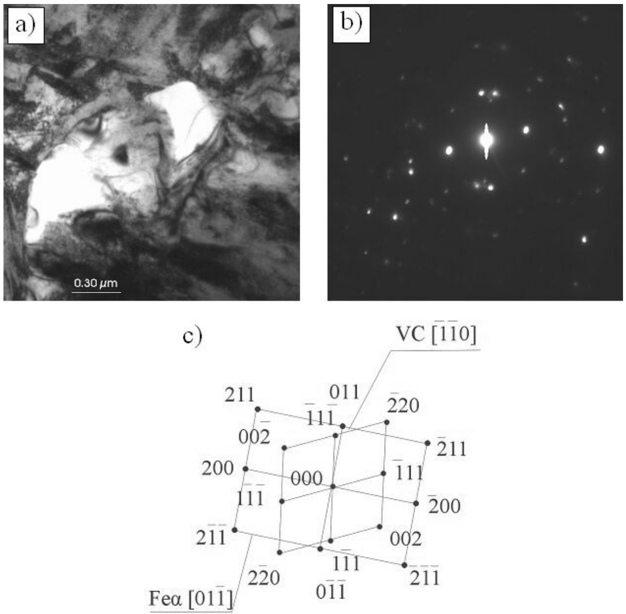

Fig. 22. a)TEM image of the X38CrMoV5-3 alloyed with VC ceramic particle, b) diffraction pattern of area shown in a, c) part of solution for diffraction pattern shown in b

4. Summary

The investigations carried out made it possible to state that due to the heat treatment and remelting of the X38CrMoV5-3 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 subjected to remelting and alloying with carbides steel hardness growth occurs usually compared to hardness of about 51.8 HRC after the conventional heat treatment. The maximum hardness of 67.4 HRC the investigated steel achieves in case of alloying with the tantalum 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 100% 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. Only in case of the surface layer alloyed with the vanadium carbide the abrasion wear resistance deteriorates, which may result from the fact that these layers are not free from defects like numerous cracks and micro-cracks. 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 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, electron transmission 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 the tungsten carbide using the high power diode laser for manufacturing and regeneration of various tools from the X38CrMoV5-3 hot-work tool steel.

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References

[1] J de Damborenea, Surface modification of metals by high power lasers, Surface and Coatings Technology, 100-101 (1998), 377-382.

[2] L.A. Dobrzański, M. Bonek, E. Hajduczek, A. Klimpel, A. Lisiecki, Comparison of the structures of the hot-work

tool steels laser modified surface layers, Journal of Materials Processing Technology, (2005), Vol. 164-165, 1014-1024.
[3] L.A. Dobrzański, M. Bonek, E. Hajduczek, A. Klimpel, Employment of a high power diode laser for alloying the X40CrMoV5-1 steel surface layer with tungsten carbide, 12th Scientific International Conference „Achievements in Mechanical and Materials Engineering" AMME'2003, Gliwice-Zakopane, (2003), 207-210.
[4] L.A. Dobrzański, M. Bonek, A. Klimpel, A. Lisiecki, Tungsten carbide WC alloying of the WCLV steel with the high power diode laser (HPDL), Proceedings of the 10th International Scientific Conference „Achievements in Mechanical and Materials Engineering AMME`2001", Cracow - Zakopane, (2001), 133-136.
[5] L.A. Dobrzański, M. Piec, Mechanical and tribological properties of surface layers., Journal of Materials Engineering, (2005), (in print).
[6] L.A. Dobrzański, M. Piec, A. Klimpel, Z. Trojanova, Surface modification of hot work tool steel by high-power diode laser., International Journal of Machine Tools & Manufacture, (in press).
[7] L.A. Dobrzański, M. Piec, K. Labisz, M. Bonek, A. Lisiecki, A. Klimpel, Laser treatment of surface layer of chosen hot work tool steels, Journal of Material Procesing Technology (2005), (in print).
[8] L.A. Dobrzański, M. Piec, K. Labisz, Z. Trojanova, J. Lelątko, A. Klimpel, Laser alloying and its effects on microstructure and properties of hot work tool steel, CAM3S Contemporary Achievement in Mechanics, Manufacturing and Materials Science, 6th – 9th December (2005), Gliwice – Zakopane, Poland, 187 – 193.
[9] L.A. Dobrzański, M. Piec, K. Labisz, M. Bonek, A. Lisiecki, A. Klimpel, Laser treatment of surface layer of chosen hot work tool steels, Worldwide Congress of Materials and Manufacturing Engineering and Technology COMMENT 2005, Proceedings of the 13th International Scientific Conference, Gliwice-Wisła, 16-19 May (2005), 183 - 186.
[10] A. Klimpel, Welding application of high power diode laser. Polish Welding Journal, Warsaw, no. 6, (1999), 1 - 6.
[11] A. Klimpel, High power diode laser in welding industry. Polish Welding Journal, Warsaw, no. 8, (1999), 1 - 6.
[12] A. Klimpel, L.A. Dobrzański, A. Lisiecki, D. Janicki, The study of the technology of laser and plasma surfacing of engine valves face made of X40CrSiMo10-2 steel using cobalt-based powders, Journal of Materials Processing Technology , vol. 175, (2006), 251 – 256.
[13] J. Kusiński, Laser Applications in Materials Engineering, WN „Akapit", (2000) Cracow, (in Polish).
[14] H. Pantsar, V Kujanpää, Effect of oxide layer growth on diode laser beam transformation hardening of steels, Journal of Surface and Coating Technology, Vol: 200, January 24, 2006, 2627 - 2633.
[15] M. Piec, L.A. Dobrzański, K. Labisz, E. Jonda, A. Klimpel, Laser Alloying with WC Ceramic Powder in Hot Work Tool Steel using a High Power Diode Laser (HPDL), International Conference on Processing and Manufacturing of Advanced Materials, July 4-8, THERMEC (2006), Vancouver, Canada, 134 - 140.
[16] S. Yahong, H. Satoshi, Y. Masato, U. Hitoshi, T. Hironobu, Fatigue behavior and fractography of laser-processed hot work tool steel, Vacuum 73, (2004), 655 – 660.
[17] K. Dae-Hwan, H. Seong-Hyeon, K. Byoung-Kee, Fabrication of ultrafine TaC powders by mechano-chemical process, Materials Letters, vol. 58, (2004), 3863 - 3867.
[18] L.J. Yang, Wear coefficient of tungsten carbide against hot-work tool steel disc with two different pin settings., Wear, vol. 257, (2004), 481 - 495.
[19] S. Yahong, H. Satoshi, Y. Masato, U. Hitoshi, T. Hironobu, Fatigue behavior and fractography of laser-processed hot work tool steel., Surface Engineering, vol. 73, (2004), 655 - 660.