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The influence of laser modification on the structure and properties of the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels

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ABSTRACT

Purpose: The aim of this paper was to study the laser treatment technique and parameters, particularly the laser power, to achieve a high value of layer properties like hardness and microhardness for protection of this hot work tool steel from losing their work stability and to make the tool surface more resistant for work. The purpose of this work was also to determine technological and technical conditions for remelting the surface layer with HPDL.

Design/methodology/approach: This work presents the results of new laser treatment techniques applied in metal surface technology. There is presented laser treatment with remelting and/or alloying of X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels with carbide powders as well as results of laser remelting influence on microstructure and properties of the surface, carried out using the high power diode laser (HPDL). Special attention was devoted to monitoring of the layer morphology of the investigated material and on the particle occurred.

Findings: The layer is without cracks and defects as well as has a considerably higher hardness value compared to the non remelted material. The hardness value increases according to the laser power used so that the highest power applied gives to highest hardness value in the remelted layer.

Research limitations/implications: The results present only four selected laser powers by one process speed rate. Also carbide powders were used for alloying with the particle size in a chosen range.

Originality/value: The originality of this work is based on applying of High Power Diode Laser for improvement of steel mechanical properties.

Keywords: Surface treatment; Heat treatment; Hot work tool steel; Laser alloying

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Alloys requiring a high technical application are often producing by the use of laser. Laser treatment technologies are widely used to modify superficial layers of different materials. In general the aim of these treatments is to provide specific properties, such as hardness and corrosion resistance, or to develop new surfaces by means of alloying techniques. Laser surface alloying plays a major role in the manufacturing of metals for industrial, medical and scientific applications. This type of treatment has found increasing application in recent years in the surface modification of metals, particularly in the fabrication of coatings. Surface modifications by laser treatments have several advantages over commonly used methods, including precise control over the width and depth of processing, ability to selectively process specific areas of a component, and ability to process complex parts. Conventional heat treatments such as carburizing, nitriding or boronizing have some disadvantages such as long processing time, thin treated layer and easy deformation of the workpiece being treated. Laser alloying is a material processing method which takes advantage of the high power density available from defocused laser beam to melt both metal coatings and a part of underlying substrate. Laser radiation is used in this process, featuring currently the only source of energy with the power density exceeding even 10^9 W/ cm^2. The high energy density and the controlled energy distribution in the laser beam focus area make heating possible and melting at high rates of the small metal volumes, at the simultaneously minimum heat influence on the substrate metal and at the minimum line energy values. Laser alloying is the thermo - chemical treatment process, consisting in enrichment of the surface layers of materials with the alloying elements and change of their structure. Alloying consists in a simultaneous melting and mixing the alloying material with the alloyed material (base material). As a result of the influence of a laser beam the materials are melting and the pool of remelted materials is created, in which, as a result of convection and gravitation movements and the pressure of the laser beam, the materials intensively mix and the fash can be observed on borders of the pool. After the laser beam is stopped, the created alloy solidifies and the base material in its neighborhood self quenches. The structure, chemical composition, physical and chemical properties of the alloy differs from the alloying material as well as from the base material. The alloying additions used in the laser alloying process are usually metal alloys, mainly Co, Cr, Mn, Nb, Ni, Mo, V, W, superalloys, stellites, carbides, nitrides and borides. The structure and chemical composition of the surface layer created in the laser alloying process, as well as its physical properties are highly different from the base and alloying material.

The phenomenal of wear of the working surface of the tools, to which laser modification of the surface layer is applied, due to friction features an important aspect of the contemporary surface engineering. The friction process between two surface leads to their wear and is connected with energy losses. It is disadvantageous especially when it occurs along with other factors deteriorating properties of the surface layer, like corrosion, erosion, mechanical and thermal fatigue [1 - 21].

2. Experimental conditions

The investigations have been carried out on test pieces from the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels. Test pieces for the examinations have been obtained from the vacuum melt and made as the O.D. 75 mm round bars. Samples of those materials were of the plate form, of the rectangular shape, with dimensions 70x25x5 mm. The heating to the austenitizing temperature has been done in two steps, with an isothermal stop. Austenisation of the 32CrMoV12-28 was performed in a vacuum furnace at a temperature of 1040 °C, the heating time 0.5 h. During the heating to the austenitic temperature two isothermal holds were applied. The first one at the temperature of 585 °C, the second at 850 °C. After tempering two annealing operations were performed for the time of 2h, the first at 550°C and the second at 510 °C. Specimens from X40CrMoV5-1 tool steel were twice subjected to heat treatment consisting in quenching and tempering; austenizing was carried out in the vacuum furnace in 1020 °C with the soaking time 0.5h. Two isothermal holds were used during heating up to the austenizing temperature, the first at the temperature of 640 °C and the second at 840 °C. The specimens were tempered twice after quenching, each time for 2 hours at the temperature 560 °C and next at 510 °C. The test pieces have been sand blasted and machined on a magnetic grinder after the heat treatment.

Next, powders layer of TiC or VC bounded with the sodium glass inorganic binding agent were put down onto the degreased specimens. Properties of the powders are presented in Table 1.

Table 1.
Selected properties of TiC and VC powders

Powder	Grain size, μm	Melting temperature, °C	Density g/cm^3	Hardness HV, GPa
TiC	4.5-7.0	3070-3180	4.90	2800-3800
VC	1.3-2.0	2650-2830	5.36	2800-2900

Next, the test pieces were melted with the Rofin DL 0.20 High Power Diode Laser. The experimental setup is presented on Figure 1.

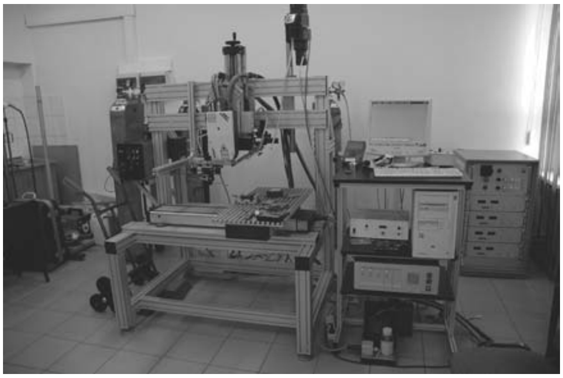


Fig. 1. Experimental stand with High Power Diode Laser (HPDL) ROFIN DL 020

Remelting and/or alloying processes were carried out at the constant remelting rate and focus shape. On each sample surface four laser process trays were made of a length of 25 mm, with the laser power 1.2; 1.6; 2.0 and 2.3 kW. For laser power values of 0.4 to 0.8 kW there are no remelted areas present at all. The protective gas (argon) blow - in rate was established experimentally as 20 l/min providing full remelting zone protection. All other work parameters are presented in Table 2. For surface preparation the standard metallographic procedure was applied in form of grinding using SiC 220, 500, 800 and 1200, polishing with 1μm Al_2O_3 polishing suspesion and drying, the samples were mounted in the thermo hardened resin supplied by Struers. Next the samples were etched in nital at room temperature for the experimentally chosen time selected individually for each remelted area.

Table 2.
The HPDL laser parameters

Parameter	Value
Laser wave length, nm	940 ± 5
Power, W	100-2300
Focus length of the laser beam, mm	82/32
Power density range of the laser beam in the focus plane, kW/cm^2	0.8-36.5
Dimensions of the laser beam, mm	1.8-6.8 with 82 mm focus length

Metallographic examinations of the material structures after laser remelting and/or alloying of their surface layer were made on Leica MEF4A light microscope and also on transmission electron microscope JEM 3010UHR with 300 kV voltage acceleration. Examinations of micro - hardness changes across the laser runs versus distance from the surface were carried out on the Shimadzu DUH 202 ultra - microhardness tester. The tests were carried out at 0.1 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. The measurements of Rockwell hardness have been performed using Zwick ZHR hardness intender equipped with electronic sensor that allows the direct readout of the hardness values. Test results were analysed statistically. The measurements of roughness have been made using Roundness and Straightness Measuring System “Surtronic 3+”.

3. Results and discussion

Metallographic investigations indicate that the surface layer after laser alloying is composed of three zones: laser alloyed zone (enriched in titanium or vanadium), the melted and rapid solidified zone and the heat affected zone (Figs. 2-5). The total surface layer thickness grows along with the laser power increase, both of its remelted zone and of the heat affected zone. Development of small irregularities is observed at the remelted bottom, having originated due to the intensified liquid motions in this area, is observed at the highest power used. The laser beam power affects also configuration of the remelted bottom and of the run face convexity, which is connected directly with the strong motions of the solidifying metal. It was found out that thickness of the remelted- and heat affected zones is in direct proportion to the laser power employed (Figs. 6 and 7).

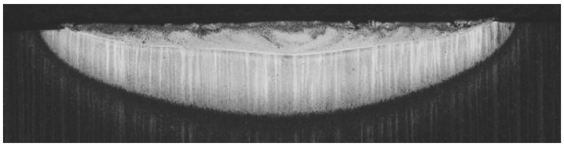


Fig. 2. Remelted and heat affected zone in the surface layer of the X40CrMoV5-1 hot work tool steel alloyed with VC, scanning rate 0.5 m/min., power range 1.6 kW, mag. 50x

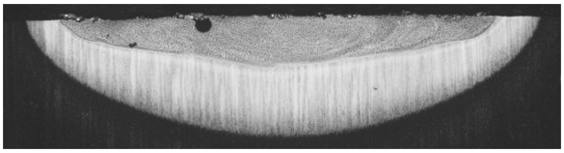


Fig. 3. Remelted and heat affected zone in the surface layer of the X40CrMoV5-1 hot work tool steel alloyed with TiC, scanning rate 0.5 m/min., power range 2.0 kW, mag. 50x

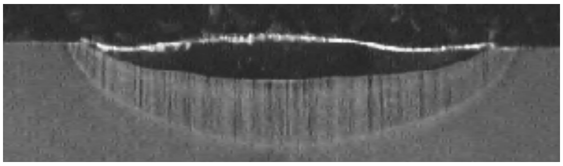


Fig. 4. Remelted and heat affected zone in the surface layer of the 32CrMoV12-28 hot work tool steel alloyed with VC, scanning rate 0.5 m/min., power range 2.0 kW, mag. 50x

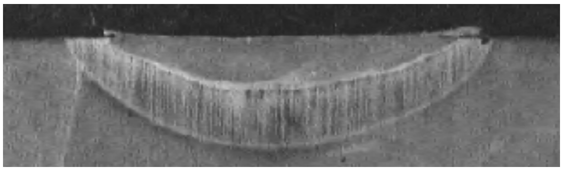
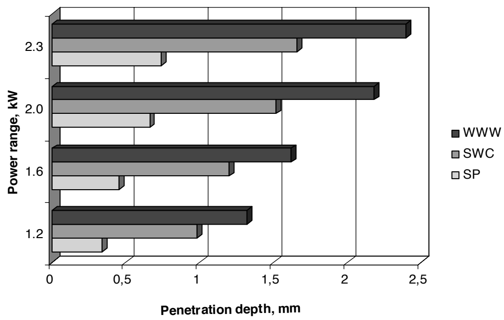


Fig. 5. Remelted and heat affected zone in the surface layer of the 32CrMoV12-28 hot work tool steel alloyed with TiC, scanning rate 0.5 m/min., power range 2.3 kW, mag. 50x

The obtained microstructure in the melted and rapid solidified zone is very refined but run face is characteristic of the high roughness and flashes at the borders. At higher alloying laser power values run face convexity appears. The microstructure of the material solidifying after laser remelting is characteristic of occurrences of areas with the diversified morphology connected with crystallisation of the steel. There is a clear relationship between the employed laser power and the dendrite size, namely with increasing laser power the dendrites are larger (Figs. 8-12).

a)



b)

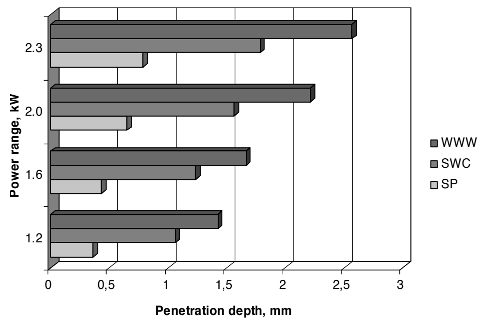
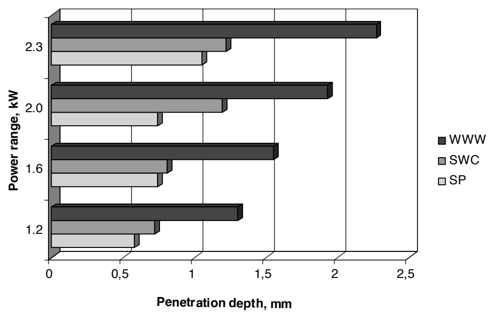


Fig. 6. Plots showing the laser power effect on the remelting zone depth of X40CrMoV5-1 hot work tool steel alloyed with: a) VC and b) TiC, power range 1.2 – 2.3 kW

a)



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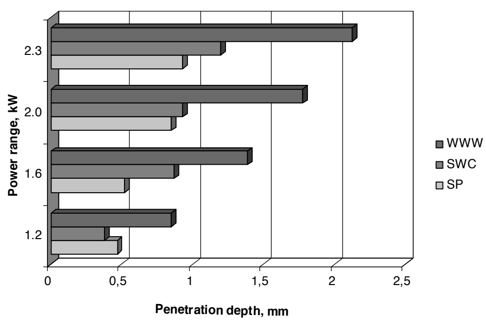

Fig. 7. Plots showing the laser power effect on the remelting zone depth of 32CrMoV12-28 hot work tool steel alloyed with: a) VC and b) TiC, power range 1.2 - 2.3 kW

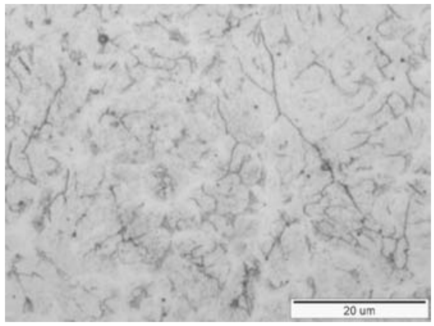

Fig. 8. Microstructure of the X40CrMoV5-1 hot work tool steel remelted with VC powder, power range 2.3 kW

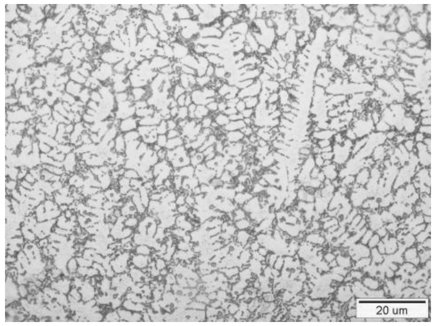

Fig. 9. Microstructure of the X40CrMoV5-1 hot work tool steel remelted with TiC powder, power range 2.3 kW

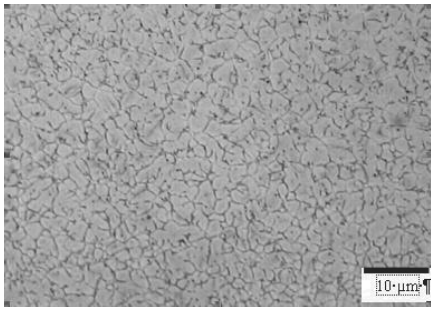

Fig. 10. Microstructure of the 32CrMoV12-28 hot work tool steel remelted with VC powder, power range 2.0 kW, mag.500x

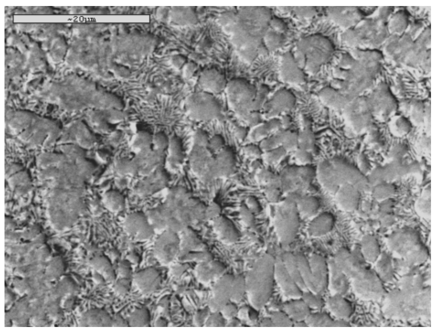

Fig. 11. Microstructure of the X40CrMoV5-1 hot work tool steel remelted with TiC powder, power range 2.3 kW (SEM)

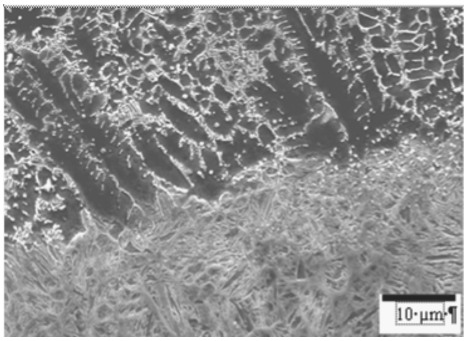

Fig. 12. Microstructure of the 32CrMoV12-28 hot work tool steel remelted with TiC powder, power range 2.0 kW (SEM)

Investigations on the transmission electron microscope of thin foils from the X40CrMoV5-1 steel reveal that structure of this steel in the hardened and twice tempered state is the tempered martensite with the dispersive precipitations of the M_7C_3 type carbide. Lathe martensite with the high dislocation density features the matrix of the surface layer after alloying. Lathes of this martensite are very fine, with the irregular shape and are twinned to a great extent. In the martensite of the surface layer of the alloyed steels there are also fine carbides of the M_3C or M_7C_3 types identified with the electron diffraction method, and in the steel alloyed with the vanadium carbide – precipitations of the M_4C_3 type carbides (Fig. 13).

Occurrences of the tempered martensite and M_6C carbide were revealed based on examinations of thin foils from the 32CrMoV12-28 hot - work steel in the hardened and tempered twice state made on the transmission electron microscope. Lathe martensite occurs in the twinned form. Occurrence of the VC carbides lattice was also revealed based on examinations of the thin foils from the hot-work alloy steel alloyed with the VC vanadium carbide. The VC carbides originate mostly on grain boundaries, creating the dispersive lattice. Sometimes they occur also inside of the grains as fine dispersive carbides (Fig. 14).

The microhardness tests on the transverse section of laser runs versus distance from the surface of the examined steel specimens show that the surface layers of the steel alloyed with titanium or vanadium carbides are characterized by the highest microhardness then the microhardness native material.

The microhardness tests results reveal that in case of laser alloying of the X40CrMoV5-1 and 32CrMoV12-28 steels with the VC or TiC carbides powders the microhardness growth occurs compared to microhardness of steels subjected to the conventional heat treatment. Appearance was also was found of the area in which the distinct hardness decrease occurs, taking place on the entire heat affected zone (HAZ) and the native material (NM) border breadth. This phenomenon is connected with tempering of steel during laser treatment, when steel heats up to the temperature higher that the tempering temperature (Figs. 15-17).

a) b) c) d)

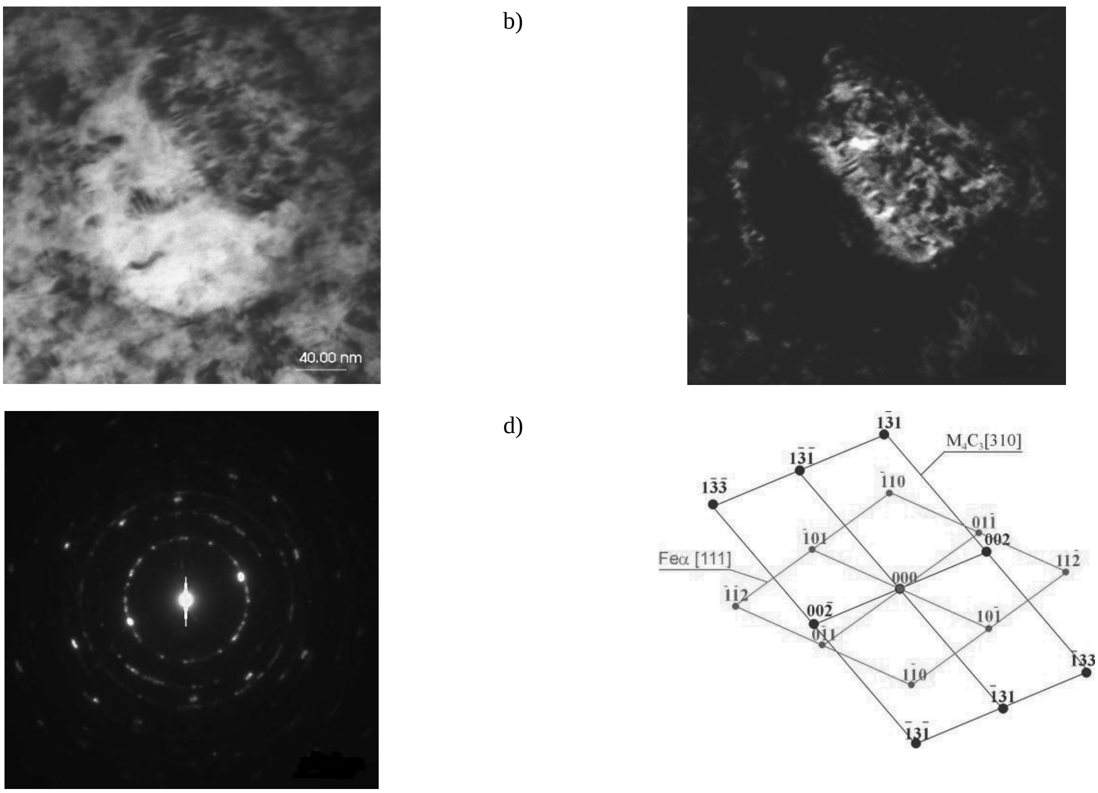

Fig. 13. Thin foil structure of X40CrMoV5-1 steel, after alloying with VC, power of laser beam 2.0 kW: a) a bright field image, b) a dark field image, c) a diffraction pattern of area in figs. a), d) a solution of diffraction pattern from fig. c)

a)

b)

c)

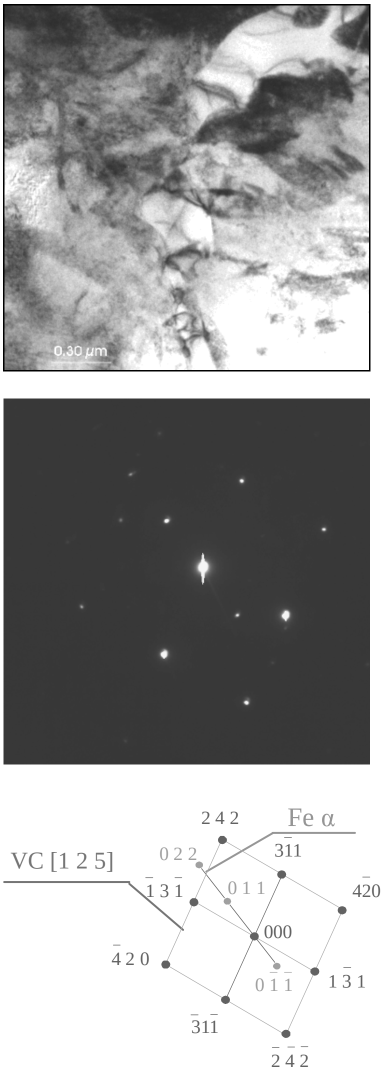

Fig. 14. Thin foil structure of 32CrMoV12-28 after alloying with VC, power of laser beam 2.0 kW,: a) a bright field image, b) a diffraction pattern of area in figs. a), c) a solution of diffraction pattern from fig. b)

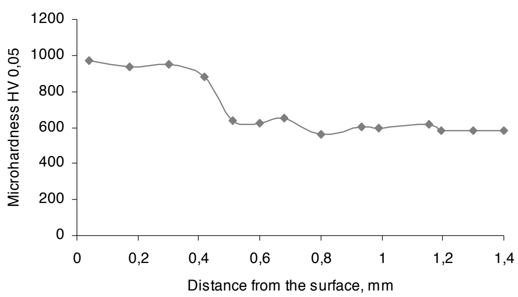

Fig. 15. Profile of the microhardness changes of the X40CrMoV5-1 steel surface layer after laser alloying with VC, power range 2.0 kW

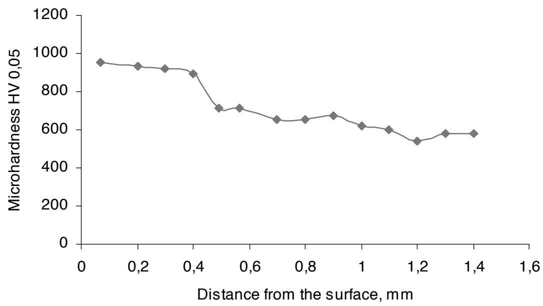

Fig. 16. Profile of the microhardness changes of the X40CrMoV5-1 steel surface layer after laser alloying with TiC, power range 2.0 kW

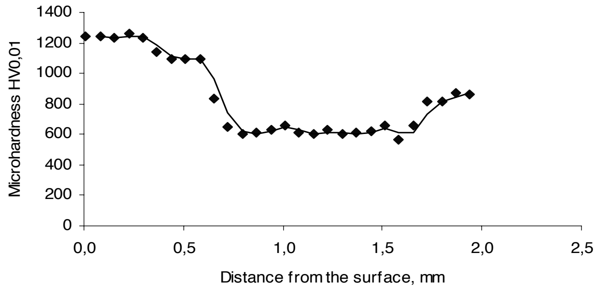

Fig. 17. Profile of the microhardness changes of the 32CrMoV12-28 steel surface layer after laser alloying with VC, power range 2.0 kW

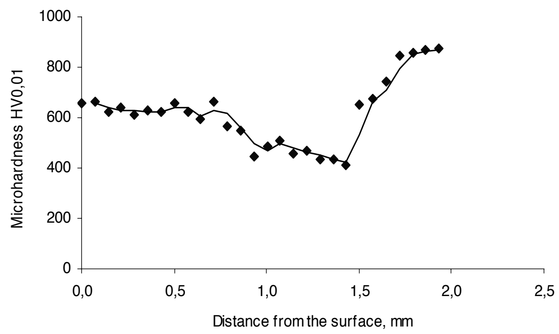

Fig. 18 Profile of the microhardness changes of the 32CrMoV12-28 steel surface layer after laser alloying with TiC, power range 2.0 kW

Hardness of the surface layer of investigated steels alloyed with TiC or ViC carbides powders grows along with the increase of the laser power used for alloying (Figs. 19 and 20). It can be found out that hardness decreases in by TiC powder use for alloying 32CrMoV12-28 steel.

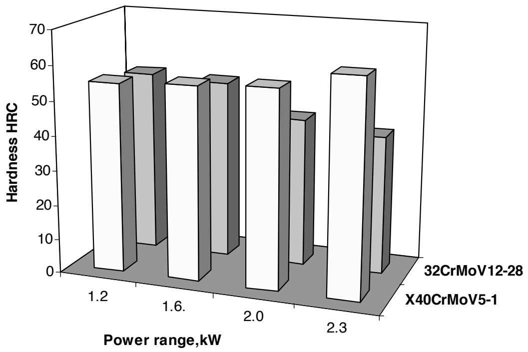

Fig. 19. Hardness of the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels alloyed with TiC powders, power range 1.2-2.3 kW, scanning rate 0.5 m/min

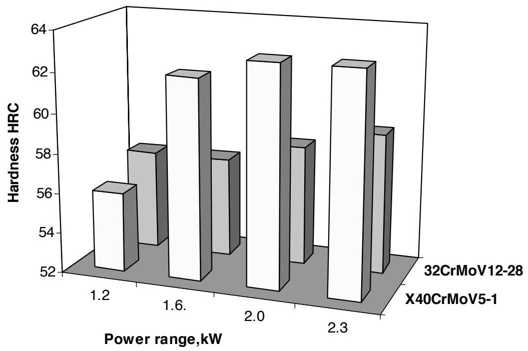

Fig. 20. Hardness of the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels alloyed with VC powders, power range 1.2-2.3 kW, scanning rate 0.5 m/min

Based on roughness measurements one can state that during alloying the steels with the TiC and VC in the entire range of the laser power values used (1.2 kW-2.3 kW) the obtained run face is characteristic of the high roughness (Figs. 21 and 22).

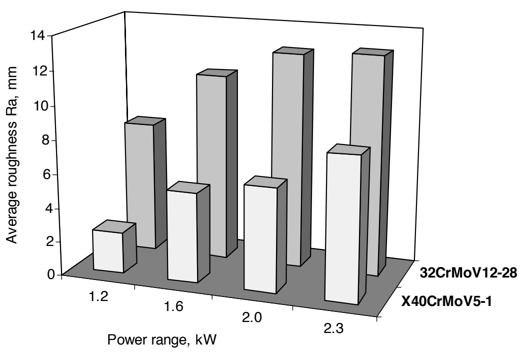

Fig. 22. Effect of the laser power on surface layer roughness of the X40CrMoV5-1 and 32CrMoV12-28 steels alloyed TiC with the 1.2-2.3 kW laser beam power

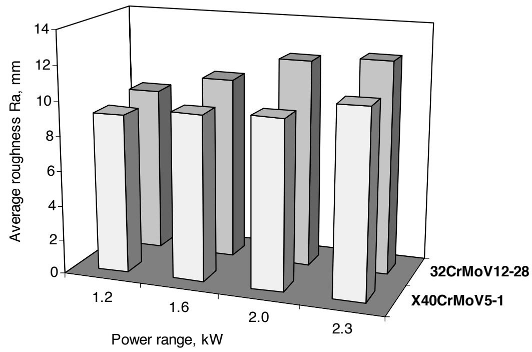

Fig. 22. Effect of the laser power on surface layer roughness of the X40CrMoV5-1 and 32CrMoV12-28 steels alloyed TiC with the 1.2-2.3 kW laser beam power

4. Conclusions

The paper presents results of the structure and properties examinations of the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels alloyed with TiC and VC powders using the high power diode laser (HPDL). The surface layer is obtained due to remelting of the investigated steel, in which one can differentiate the remelted zone (RZ) having the dendritic structure, and the heat affected zone (HAZ) as well as the intermediate zone (IZ). Growth of dendrites occurs from the remelted zone and heat affected zone boundary in the direction of heat removal. The dendrite grains at the boundary between the remelted and heat affected zones (RZ/HAZ) are fine, which is caused by the high temperature gradient. Development of the surface layer by alloying using the high power diode laser with the X4oCrMoV5-1 and 32CrMoV12-28 hot - work steels powders improves the service properties compared to properties of these steels subjected to the conventional heat treatment only. During alloying in the entire range of the laser power values used (1.2 kW-2.3 kW) the obtained run face is characteristic of the high roughness and irregularity of the remelting surface, which are connected with the increase of the laser beam power used in the laser remelting and alloying processes. Properties like hardness, abrasion wear resistance, and thermal fatigue resistance are improved also. The research results make it possible to state that surface layers fabricated using the vanadium - and titanium carbide powders, may be used for manufacturing new tools used for hot working.

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