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Laser surface treatment of the hot work tool steel alloyed with TaC and VC carbide powders

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ABSTRACT

Purpose: The paper presents investigation results of the structure and properties of alloying surface layer of the X40CrMoV5-1 hot work tool steel, using the high power diode laser HPDL. Tantalum and vanadium carbides powders were used for alloying and the X40CrMoV5-1 conventionally heat treated steel was used as reference material.

Design/methodology/approach: Metallographic examinations of the material structures after laser alloying surface layer were made on light microscope and transmission electron microscope. The resistance research has been done with the use of the pin-on-disc method. Hardness tests were made with Rockwell method in C scale.

Findings: It was found out in examinations of the surface layer that it can be possible to obtain high quality top layer with better properties compared to material after a standard heat treatment.

Research limitations/implications: In this research two powders (TaC and VC) were used for alloying of the surface layer of investigated steel.

Practical implications: The structure as well as improvement of mechanical properties is a practical aim of this work as well as improvement of hardness as a very important properties for practical use.

Originality/value: The research results of this type of heat treatment show that there is a possibility of applying the worked out technology to manufacturing or regeneration of chosen hot working tools.

Keywords: Laser remelting and alloying; High Power Diode Laser (HPDL); Tantalum carbide; Vanadium carbide

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Laser alloying (LSA) is the state - of - the - art thermo - chemical treatment process, consisting on enrichment of the surface layers of materials with the alloying elements and change of their structure. Because of the laser alloying, the hot work tool steels, attain the surface layer of a small thickness and specific properties. Laser modification by the appropriate selection of the alloying elements and process parameters makes it possible to obtain the surface layers with the structure and parameters comparable to the high - alloy steels. The alloying additions used in the laser alloying process are usually metal alloys, mainly: Co, Cr, Mn, Nb, Ni, Mo, V, W, superalloys, stellits, 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. Laser surface alloying allows forming surface layers with little thickness and special properties, with a high resistance to abrasion and activity of aggressive chemical agents, with high hardness, fatigue strength and heat resistance.

There is an opinion that laser manufacturing techniques belong to the most promising and efficient ones, for ensuring the development in many industry branches, and especially, those in which materials processing dominates. Thanks to the very precise energy delivery laser radiation makes it possible to carry out the technological operations better or faster within the framework of the technologies known to date. It makes also possible introduction of the new technologies whose realization is impossible when using the conventional power density. Laser radiation is used in this process, featuring currently the only source of energy with the power density exceeding even 10^9 W/ cm^3. The high energy densities 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.

Hot-work tool steels are used in many industry branches as the material deciding efficiency, labour demand, and manufacturing process reliability. Tool life is dependant on its quality, and therefore, on the material from which it is made. Requirements posed to the alloy tool steels depend mostly on the diversified service conditions of the particular tool groups. Ensuring the tool form factor stability in service conditions belongs to the main requirements. Therefore, these steels should be characteristic of the abrasion wear resistance and carrying the load without plastic strain. This is dependant on steel hardness. Its increase causes ductility fall, and therefore, the maximum hardness value after heat treatment is one of the most important criteria of the appropriate heat treatment process selection. These steels are employed in hot working and in casting into the metal moulds as material for tools subjected to periodical temperature changes [1 - 18].

2. Investigation methodology

The examinations have been made on the specimens of hot work tool steel X40CrMoV5-1. Test pieces for the examinations have been obtained from the vacuum melt and made as the O.D. 75 mm round bars. The material for specimens has been delivered in the annealed state. Specimens were twice subjected to heat treatment consisting in quenching and tempering, austenizing was carried out in the vacuum furnace of 1020°C with the soaking time 0,5 h. 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. After heat treatment the surface of specimens were grounded on magnetic grinder. The paste of VC (Fig. 1 a) and TaC (Fig. 1 b) carbide powders were applied on specimens. All experiments were made at the constant remelting rate, varying the laser beam power in the range from 1.2 ÷ 2.3 kW (Fig. 2).

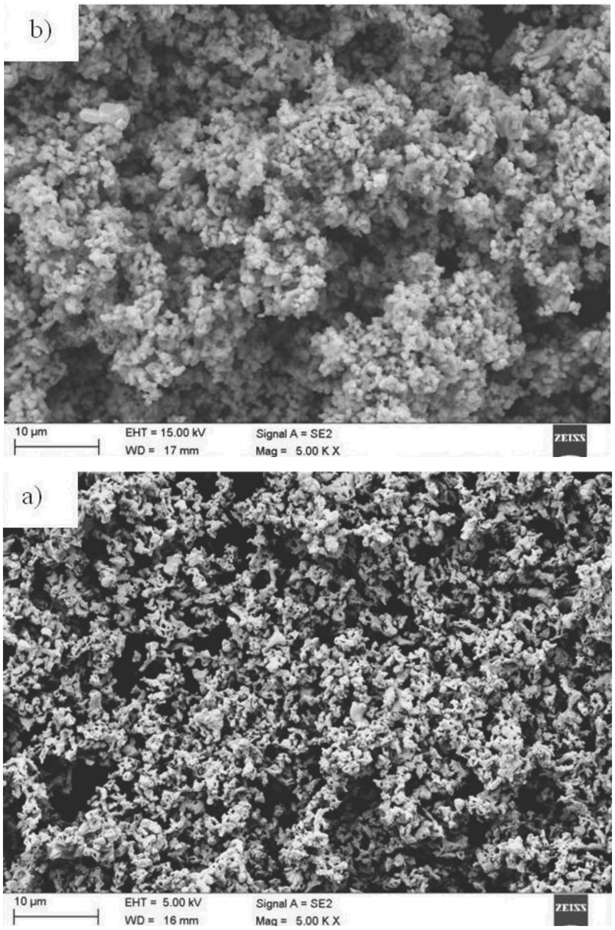


Fig. 1. a) Vanadium carbide powder, b) Tantalum carbide powder (SEM)

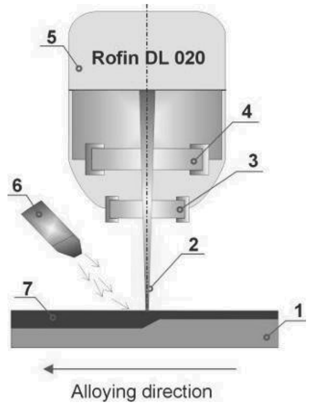


Fig. 2. Experimental setup with High Power Diode Laser (HPDL) ROFIN DL 020: 1- native material, 2- laser beam, 3- protective glass, 4- lens, 5- laser's head, 6- protective gas, 7- alloying material

Metallographic examinations of the material structures after laser alloying surface layer were made on Zeiss Leica MEF4A light microscope and transmission electron microscope JEM 3010 with 300 kV voltage acceleration. 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. The resistance research on the dry abrasive wear with the use of the pin – on – disc method has been done on the CSEM High Temperature Tribometer, connected directly to a computer that allowed to define the size of the load, the rotation speed, the radius of the specimen, the maximal coefficient of friction and the time of the test duration. As a counter - specimen the 6 mm diameter ball from the aluminum oxide Al_2O_3, has been used. Roughness tests were made with contact profilometr Surtronic 3+ Taylor – Hobson.

3. Investigations results

It was found out based on hardness tests results of the X40CrMoV5-1 alloy hot work steel alloyed with the VC or TaC carbides powders than laser treatment causes in most cases hardness increase of the investigated steel. Table 1 presents the detailed hardness tests results of the surface layer of the investigated steel.

The highest hardness of the surface layer alloyed with the vanadium carbide was achieved using the laser power of 2.0 kW for alloying; whereas, in case of alloying with the tantalum carbide the highest hardness is characteristic of the surface layer alloyed using the laser beam power of 2.3 kW. Hardness of the X40CrMoV5-1 steel after its standard heat treatment is 53.9 HRC, which gives grounds to statement that the process of laser alloying with the VC or TaC carbides powders results in improving the average hardness of the surface layer. Hardness of the surface layer alloyed with carbides powders grows along with the increase of the laser power used for alloying (Fig. 3).

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 (Figs. 4 - 5).

It was revealed based on examinations on the light microscope that the remelted zone of the steel subjected to laser alloying with the vanadium - or tantalum carbides had the dendritic structure. The dendritic structure occurs during laser alloying of steel with the TaC in the remelted zone and at the boundary of the liquid and solid phases boundary, which is originated according to the heat transfer direction; whereas, in case of the laser alloying of steel with the VC powder the granular structure occurs (Fig. 6). Structure of the steel after alloying is characteristic of occurrences of areas with very differentiated morphology which is connected with the material solidification. Clusters of the un - fused carbides of the alloying material occur in the central area of the remelted zone (Figs.7 and 8).

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. Based on examinations of thin foils made from the surface layer of the hot work tool steel alloyed with the vanadium - or tantalum carbides the occurrences were observed on grains boundaries of the relevant carbides used for alloying. 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. These carbides are located at the martensite lathes boundaries and at the micro - twins boundaries (Figs.9 and 10).

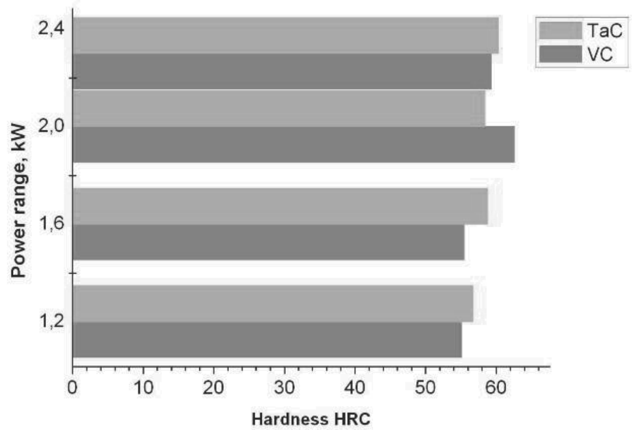


Fig. 3. Hardness of the X40CrMoV5-1 hot work tool steel alloyed with VC and TaC powders, power range 1.2 – 2.3 kW, scanning rate 0.5 m/min

Table 1.
Hardness test results for the surface layer alloyed with VC and TaC carbides by HPDL laser

Power range	1.2 kW	1.6 kW	2 kW	2.3 kW
		VC		
Average value	55.1	55.5	62.6	59.3
Standard error	0.12	0.2	0.16	0.16
Standard deviation	0.57	0.7	0.77	0.5
		TaC		
Average value	56.7	58.8	58.4	60.3
Standard error	0.24	0.2	0.12	0.23
Standard deviation	0.77	0.62	0.37	0.73

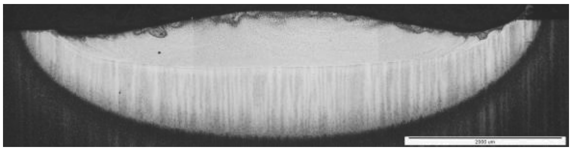


Fig. 4. Surface layer of the X40CrMoV5-1steel after alloying VC with parameters: scanning rate 0,5 m/min, power range 2.3 kW

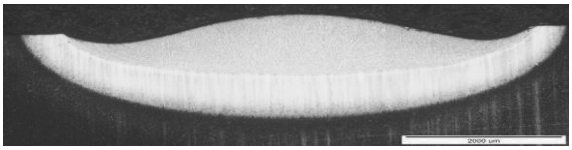
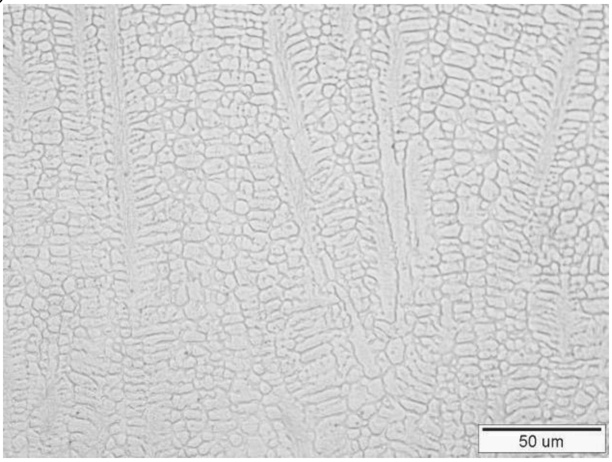


Fig. 5. Surface layer of the X40CrMoV5-1steel after alloying TaC with parameters: scanning rate 0,5 m/min, power range 2.3 kW

a)



b)

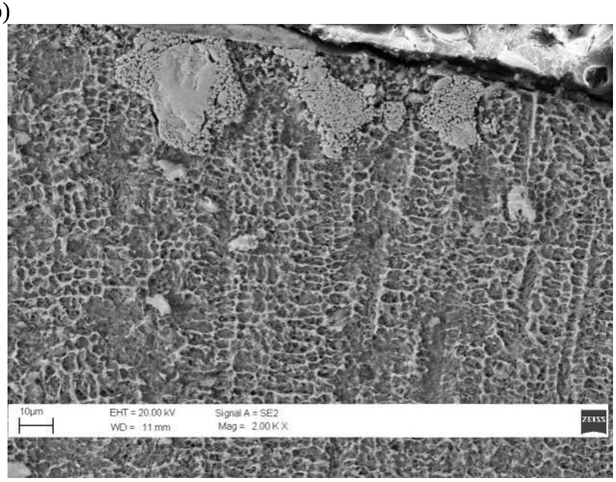


Fig. 6. The structure of the X40CrMoV5-1 hot work tool steel alloyed with TaC, scanning rate 0.5 m/min., a) power range 2.0 kW., b) power range 1.6 kW, (SEM)

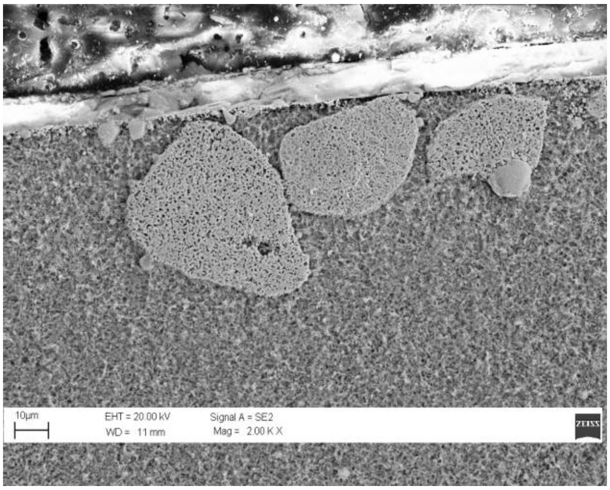


Fig. 7. The structure of the X40CrMoV5-1 hot work tool steel alloyed with TaC, scanning rate 0.5 m/min., power range 1.2 kW

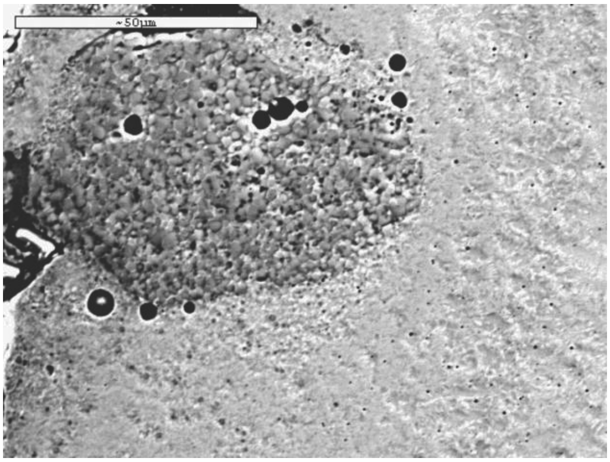


Fig. 8. Alloying material in the surface layer of the X40CrMoV5-1 steel alloyed with the VC powder, power range 1.2 kW, (SEM)

The roughness of surface layers obtained by alloying the investigated steel with the VC or TaC carbide powders with the 1.2 to 2.3 kW laser beam is within the range of R_a = 4.99 - 10.82 µm. The minimum surface roughness was revealed on the surface layer developed by alloying with the TaC particles with the 1.2 kW laser beam. However, the maximum roughness occurs on surface of the layer alloyed with the VC carbide (Fig. 11.). Roughness of the surface layers obtained by alloying the steel with the laser beam with the power from 1.2 to 2.3 kW grows proportionally to the laser beam power.

Tribological investigations revealed the extensive wear in the contact area with the counter-specimen. The smallest wear area was observed in case of the surface layers alloyed with the vanadium carbide, and the biggest area was in case of contact with the surface of steel subjected to alloying with the tantalum carbide.

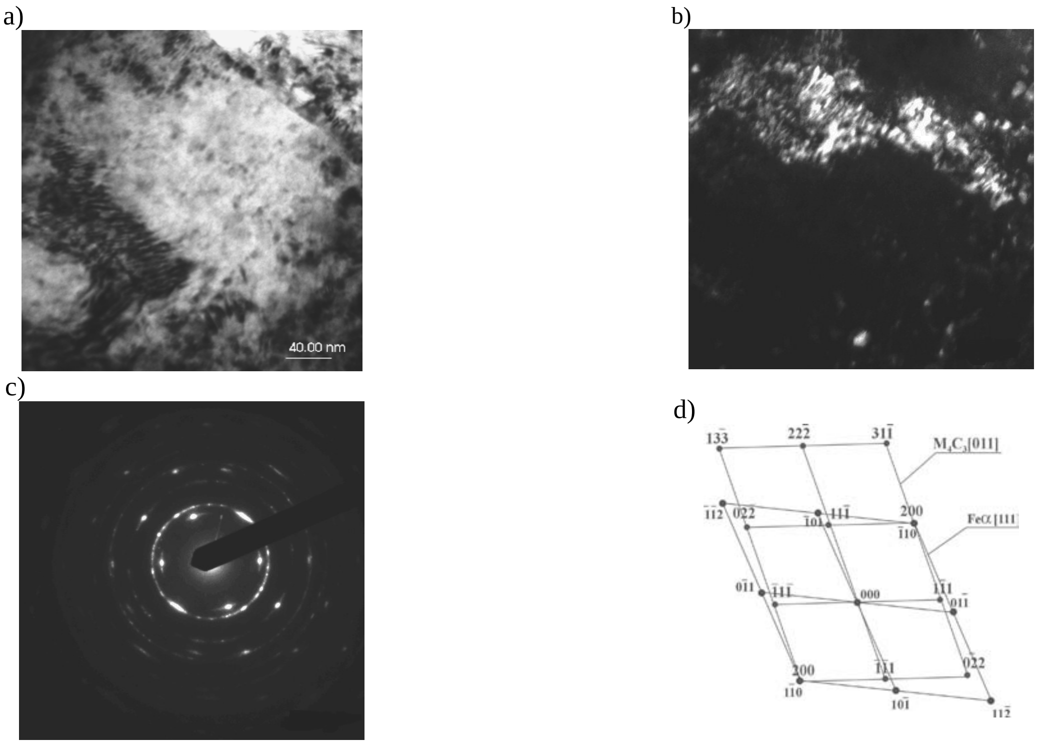


Fig. 9. Thin foil structure of X40CrMoV5-1 steel, after alloying with VC, power of bunch laser 1.6 kW: a) a bright field image, b) a dark field image, c) a diffraction pattern of area in fig. a), d) a solution of diffraction pattern from fig. c)

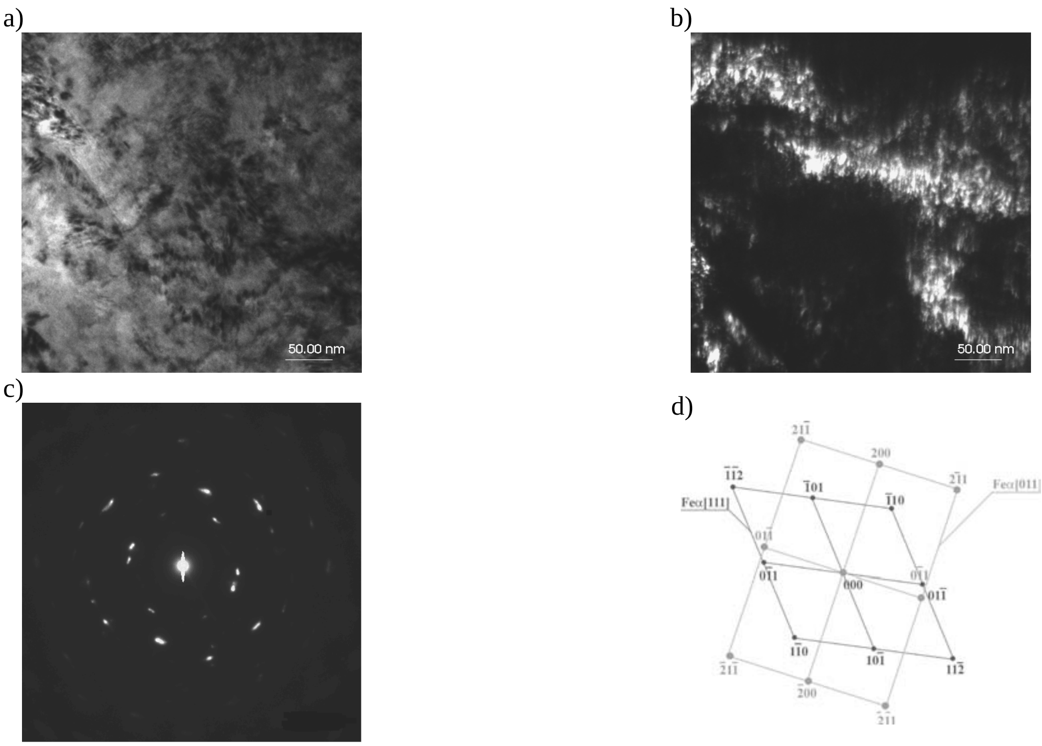


Fig. 10. Thin foil structure of X40CrMoV5-1 steel, after alloying with TaC, power of bunch laser 1.6 kW: a) a bright field image, b) a dark field image, c) a diffraction pattern of area in fig. a), d) a solution of diffraction pattern from fig. c)

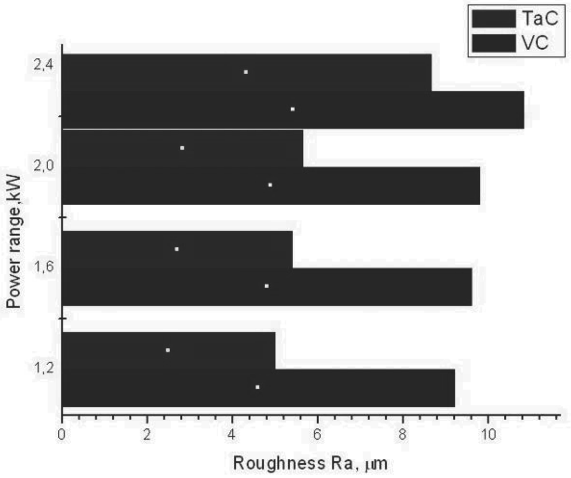


Fig. 11. Effect of the laser power on surface layer roughness of the steel alloyed with the VC and TaC with use of 1.2 ÷ 2.3 kW laser beam

In Figs. 12 - 13 there are wear traces presented, the result of the examinations of the resistance to abrasive wear, done with the use of pin - on - disc method on the surface of the alloyed, with an appropriate powder, specimens.

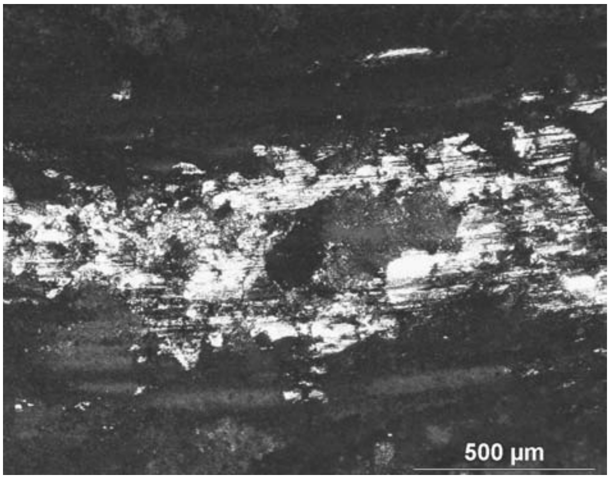


Fig. 12. The worn surface of X40CrMoV5-1 steel alloyed VC (power range 1.2 kW) after pin - on - disc test

The examined specimens were tribologically damaged due to action of the counter - specimen with the load of 10 N. To analyze changes of the friction coefficient, plots of friction μ as function of the friction distance were made (Figs. 14 and 15).

Comparing the mass loss of the test pieces alloyed with vanadium carbide or tantalum carbide after testing the abrasion wear with the pin - on - disc method the slight differences in the mass of the test pieces was found out. Figure 16 presents changes of the averaged friction coefficient values of the steel alloyed with the vanadium or tantalum carbides respectively, depending on laser power in conditions close to the steady state.

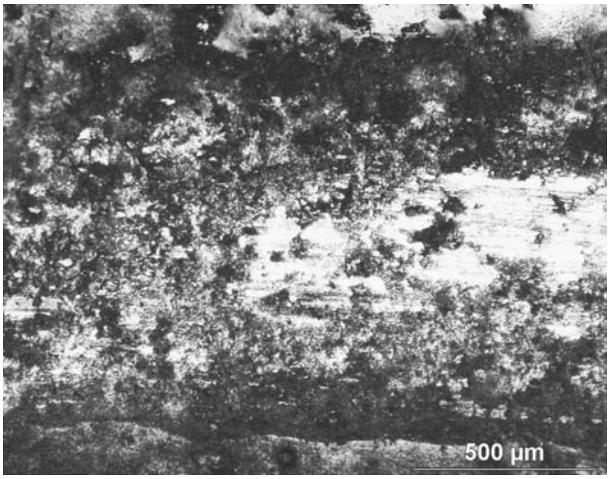


Fig. 13. The worn surface of X40CrMoV5-1 steel alloyed TaC (power range 1.2 kW) after pin - on - disc test

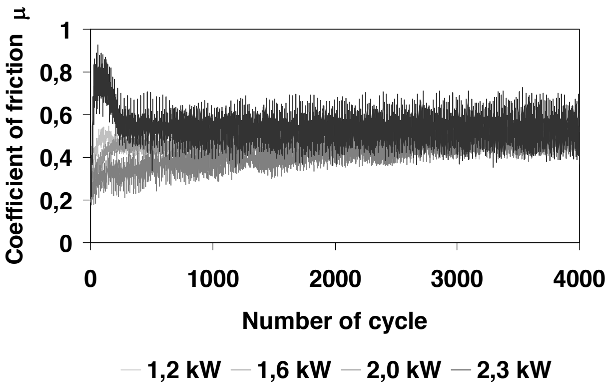


Fig. 14. The plot of the coefficient of friction depending on the number of cycles during the pin - on - disc test of X40CrMoV5-1 steel after VC alloying with 1.2 - 2.3 kW power range

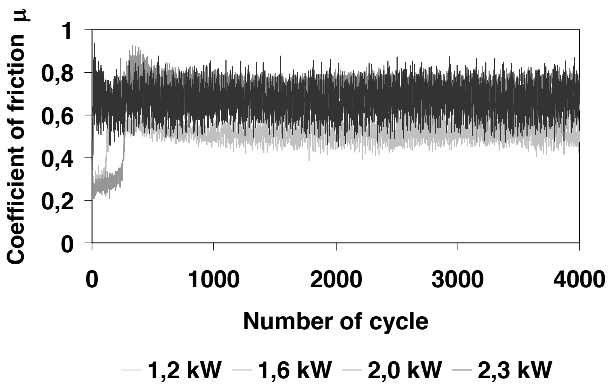


Fig. 15. The plot of the coefficient of friction depending on the number of cycles during the pin - on - disc test of X40CrMoV5-1 steel after TaC alloying with 1.2 - 2.3 kW power range

In Fig. 17 the mass loss of the test pieces versus laser power is presented. In all analysed cases a slight increase of the mass loss occurs along with the laser beam power growth.

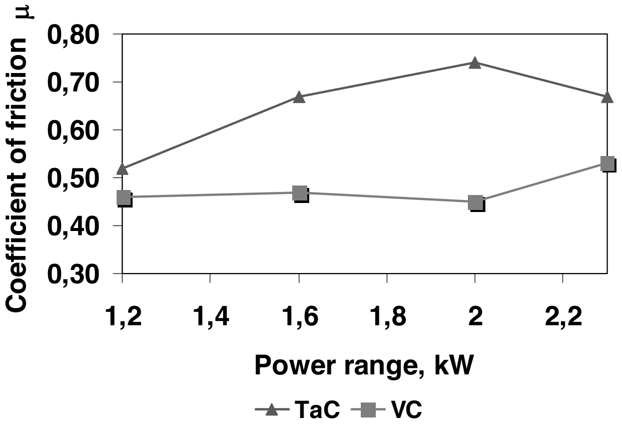


Fig. 16. Influence of the power of the laser beam upon the average value of the coefficient of friction Al_2O_3 and the X40CrMoV5-1 steel surface layer after laser alloying

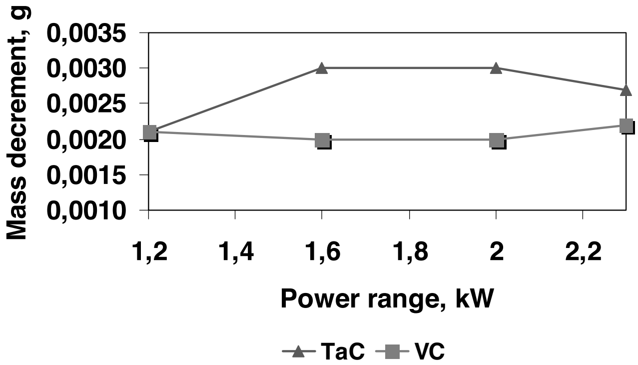


Fig. 17. Average specimen mass decrement of X40CrMoV5-1 steel after alloying depending on the power of a laser beam

4. Conclusions

The paper presents the effect of laser enrichment of the surface layers on structure and properties of the X40CrMoV5-1 alloy hot work tool steel. Laser enrichment of the surface layer with the alloy additions belongs to the unconventional surface heat treatment of materials nowadays. The nature of this process is quick heating of the processed element's surface, necessary for inducing the phase transformation, putting down the suitable coating or fusion penetration of the selected elements. The main goal of such treatment is forming of the structure leading to attaining properties of the surface layer impossible to obtain by the conventional heat treatment. Therefore, the practical goal of such treatment is obtaining the supersaturated fine - crystalline layers, characteristic of a significant chemical diversity and metallurgical purity, which leads to hardness increase as a consequence of the fast crystallization due to solidification of metal.

During laser alloying with powders containing VC or TaC their partial fusion may occur in the molten metal pool, or else the carbides may remain undissolved originating conglomerates because of inundation of the undissolved grains of the carbides powder into the molten metal substrate. Increasing the laser power results in decrease of the portion of the undissolved carbides dispersively hardening the remelted matrix of the steel surface layer.

This work presents laser treatment with alloying of hot work tool steel X40CrMoV5-1 with tantalum or vanadium carbides. This type of surface treatment is used for improvement of properties of the surface layer by changing the structure and improvement of the abrasion wear resistance, mostly by introduction of carbide to the material matrix.

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