



Mechanical and tribological properties of the surface layer of the hot work tool steel obtained by laser alloying

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Received 19.04.2007; published in revised form 01.07.2007

ABSTRACT

Purpose: The paper presents results on the mechanical and tribological properties examinations of the X40CrMoV5-1 hot work alloy tool steel alloyed with carbide powders using the high power diode laser (HPDL).

Design/methodology/approach: Metallographic examinations of the material structures after laser alloying of their surface layer were made on light microscope. The tribological wear relationships using pin-on-disc test were specified for surface layers subject to laser treatment, determining the friction coefficient, and mass loss of the investigated surfaces. 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. X-ray diffraction (XRD) technique was used to investigate crystalline structure and phases in the layers.

Findings: Metallographic examinations carried out on the light microscope confirm that the structure of the material solidifying after laser remelting is diversified, which is dependant on the solidification rate of the investigated steels. The investigations carried out made it possible to state that due to the heat treatment and remelting of the X40CrMoV5-1 tool steel with the WC, TaC or TiC powders it is possible to obtain the high quality surface layer with no cracks and defects and with hardness significantly higher than the substrate metal.

Research limitations/implications: In order to evaluate with more detail the possibility of applying these surface layers in tools, further investigations should be concentrated on the determination of the thermal fatigue resistance of the layers.

Practical implications: The alloyed layers which were formed on the surface of the hot work steel have shown significant improvement. Good properties of the laser treatment make these layers suitable for various technical and industrial applications.

Originality/value: A modification of tool steels surface using a laser beam radiation, as well as coating them with special pastes containing carbides particles such as tungsten, tantalum and titanium allows the essential improvement of the surface layer properties – their quality and abrasion resistance, decreasing at the same time the surface quality.

Keywords: Surface treatment; Laser alloying and remelting; Hot work alloy tool steel; High power diode laser HPDL

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Laser surface engineering is one of these technologies that have attracted vast research interest recently. Laser surface cladding and alloying using different metals, alloys and ceramics have been an object of a number of researches focused on various degrees of improvement on the surface hardness, pitting corrosion potential and wear-resistant properties [1]. A laser alloying technique can be used for obtaining thin surface layers in order to increase its wear-resistance. In laser surface alloying the high energy of a laser beam is used to alloy the surface of a material with another material. The properties of the alloyed layer depend on its preparation, e.g. laser beam power, traverse speed, feeding method and the amount of the alloying material. Concentrated energy fluxes, such as laser, electron beam, etc., have unique possibility for fast melting and intensive remixing of alloying elements. These processes are characterized by extremely high cooling rates being able to quench the melt. The main features of these processes are the following: -thickness of modified layer varies from 0.1 up to a few millimeters, -opportunity to regulate the features of mass transfer and therefore distributions of alloying elements in a wide range: from quite non-uniform up to rather uniform [2-4].

It has been almost a decade since the first direct diode laser application for materials processing was reported in 1991 for soldering using a 15 W medical diode laser. In the last 9 years, on average the diode laser output power has doubled each year to the present commercially available 4kW continuous wave diode laser units, which have a power level comparable to other high-power lasers for materials processing.

Owing to the excellent coherence and directionality, laser beam has found increasing application in recent years in the surface modification of metals, particularly in the fabrication of coatings. Laser treatments have several advantages over generally used heat treatment 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. However, their disadvantages are the relatively high purchase cost of the high power lasers and high surface roughness after laser treatment [5,6].

Steels are the most often enriched materials, whereas elements increasing the abrasion and erosion wear resistance, heat- and corrosion resistance feature the alloying additives.

Hot work tool steels belong to the martensitic group of steels, used among others for the forging tools. The hot work tool steel microstructure changes several times during their complex plastic and heat treatments, which and effect is obtaining high thermal wear fatigue resistance. Carbide precipitations are responsible for the high mechanical properties: primary ones originated during crystallization and secondary ones developed in the heat treatment process [5-7]. The materials for the manufacture of diode lasers are based on semiconductors of group III-V.

Currently the HPDL high power diode lasers feature the up-to-date energy source. They are used for the industry scale in materials engineering only from 1998. The HPDL (High Power Diode Laser) reaches up to 6 kW in the beam focus. The big advantage of these lasers is that they make possible obtaining rectangular, square, linear or circular shapes of the laser beam focus. They have the controlled energy distribution in the focus area with power density of up to 10^5 W/cm², the high coefficient of radiation absorption, do not require guiding the laser beam by any complex optical systems causing energy loss in the range of 10-30%, they have the high energetic efficiency reaching 50%. Robotisation of the technological processes is easy; they are reliable and all-purpose, which makes them a very attractive tool in material engineering [8-12].

In HPDL the laser radiation is generated as an effect of the current flow, with the amperage in the range of 10-50 A, through p-n connections of a diode made of GaAs admixed with Al, In, or P. The radiation power of single diode is very small and doesn't usually exceed a few MW. Because in high power diode lasers there's no phenomenon of energy collecting, they are a source of a high stable and easy to control energy. High power diode lasers are also characterized by a high energetic efficiency which can achieve values of 30-50% [13-15].

2. Investigation methodology

Investigations were carried out on test pieces from the X40CrMoV5-1 hot work tool steel (Figures 1, 2). It has been supplied annealed in the form of rods of 76 mm in diameter and in the length of 3 m. Samples of these materials were of plate form and rectangular shape with dimensions 65×25×5mm and Ø55×6×16 (Figures 3, 4).

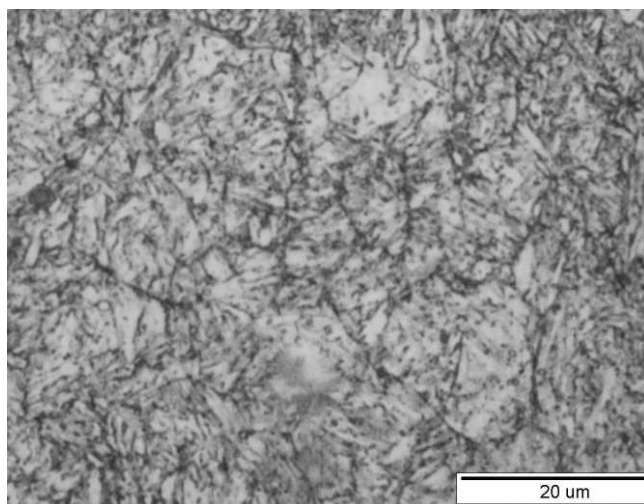


Fig. 1. Structure of hot work tool steel X40CrMoV5-1 after standard heat treatment

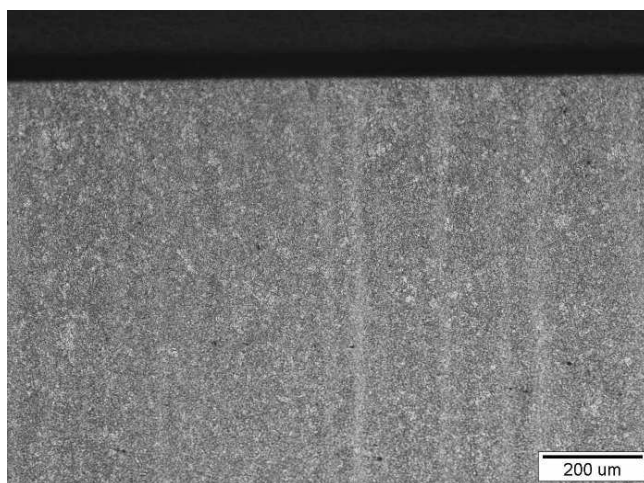


Fig. 2. Structure of hot work tool steel X40CrMoV5-1 after standard heat treatment

Table 1
Chemical composition of X40CrMoV5-1 tool steel

Type of steel	Mean concentration of elements (wt) [%]								
	C	Mn	Si	P	S	Cr	Mo	V	Ni
X40CrMoV5-1	0,41	0,44	1,09	0,015	0,010	5,40	1,41	0,95	–

Table 2
Selected properties of WC, TaC and TiC powders

Type of coating	Hardness [HV]	Melting point [°C]
WC	1550	2730÷2870
TiC	2800÷3800	3070÷3180
TaC	1550-1800	3780-3985

Table 3
Specification of the HPDL ROFIN DL 0.20 diode laser

Wavelength of the laser radiation, nm	808 ±5
Maximum output power of the laser beam (continuous-wave), W	2300
Laser power range, W	100÷2300
Focal length, mm	82/32
Laser spot size, mm	1.8×6.8
Range of the laser intensity, kW/cm ³	0.8÷36.5

The chemical composition of investigated steel is presented in Table 1. 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 WC, TiC and TaC carbide powders were applied on specimens. Paste coating of WC, TiC and TaC (Table 2) carbide powders was applied on specimens by put down in each case.

It was found in the preliminary investigations using HPDL (High Diode Power Laser) Rofin DL 020 with parameters presented in Table 3, that the maximum feed rate at which the process is stable is $v=0,5$ m/min. Therefore all experiments were made at the constant remelting rate, varying the laser beam power in the range from 1,2-2,3 kW.

Metallographic examinations of the material structures after laser alloying is surface layer were made on Zeiss Leica MEF4A light microscope. The phase composition of the investigated coating was determined on the DRON-2.0 X-ray diffractometer, using the filtered radiation of the cobalt anode lamp, powered with 40 kV voltages at 20 mA heater current. The measurements were made in the angle range 2θ : 30°–110°. 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. Hardness was measured on the ground and buffed front surfaces of specimens.

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. The research has been done at room temperature in the following testing conditions:

- for the 1,2 kW and 2,0kW laser alloyed specimen:
 - pressure force $F_N = 10N$
 - travel speed $v = 13,75$ cm/s;
 - radius $r = 22$ mm.
- for the 1,6kW and 2,3kW laser alloyed specimen:
 - pressure force $F_N = 10N$
 - travel speed $v = 7,5$ cm/s;
 - radius $r = 12$ mm.



Fig. 3. The shape of specimens

The number of cycles for each of the specimens has been established at 4000. Figure 5 presents the action diagram of the ball – disk pair. During the test the plots of the coefficient of friction μ as function of the friction distance have been made. The value of the coefficient of friction has been evaluated as the average of the instantaneous values, obtained for the part of the characteristics relevant for the stabilized friction. The analysis of the counter-specimen wear land (Al_2O_3 balls) has been made using the light microscope with the Image – Pro Measure Version 1.3 image analysis system at magnification $50\times$.



Fig. 4. The shape of specimens

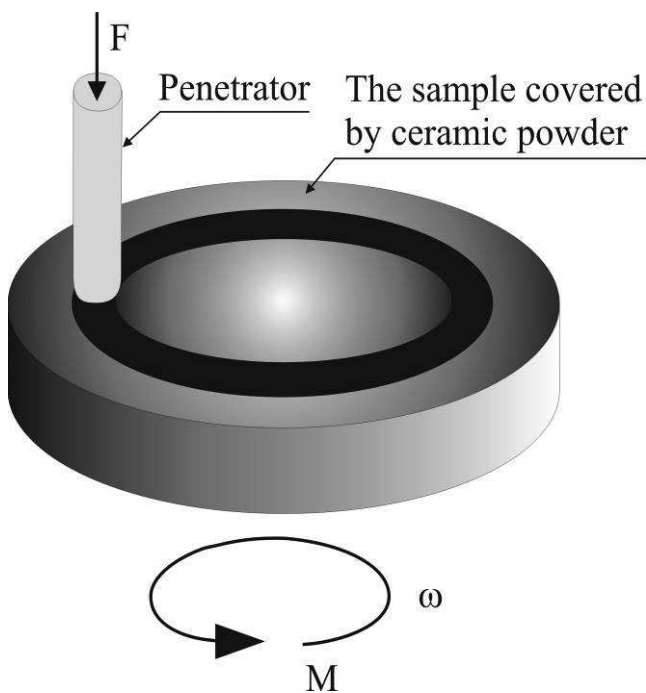


Fig. 5. Operation principle of the sphere-disc type tester

3. Investigation results

Basing on observations of structure photographs taken on the light microscope (Figures 6-8) one can state that during alloying the steel with the WC, TaC or TiC in the entire range of the laser power values used ($1.2\text{ kW} \div 2.3\text{ kW}$) the obtained run face is characteristic of the high roughness, multiple pores, irregularity, and flashes at the borders. At higher alloying laser power values run face convexity appears.

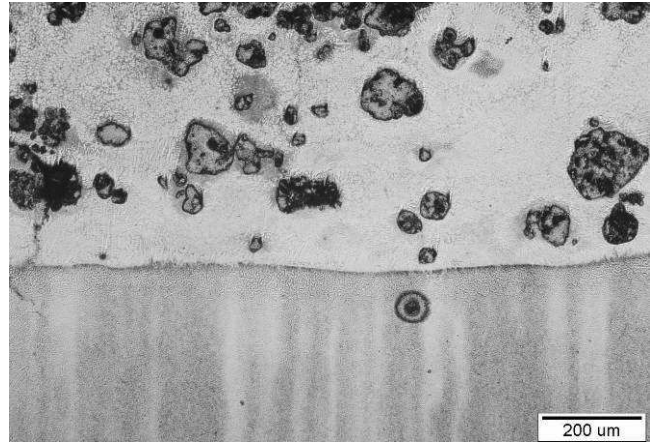


Fig. 6. The structure of the X40CrMoV5-1 hot work tool steel alloyed with WC, scanning rate $0,5\text{ m/min.}$, power range $2,0\text{ kW}$

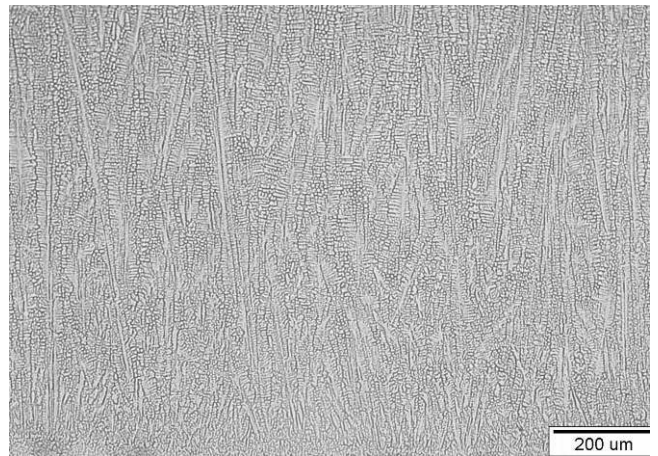


Fig. 7. The structure of the X40CrMoV5-1 hot work tool steel alloyed with TaC, scanning rate $0,5\text{ m/min.}$, power range $2,0\text{ kW}$

The initial experiments indicate the clear influence of the laser power on the run face shape and its depth. At constant speed laser beam scanning, the change of beam power range are strictly connected with the size of area of the surface layer in which structural changes take place. It has been stated that the increase of power range is followed by the increase in the thickness of the remelted area. It was found out that employing the higher laser power affects the remelting zone depth and that the remelted zone bottom gets corrugated due the influence of the strong movements of the liquid.

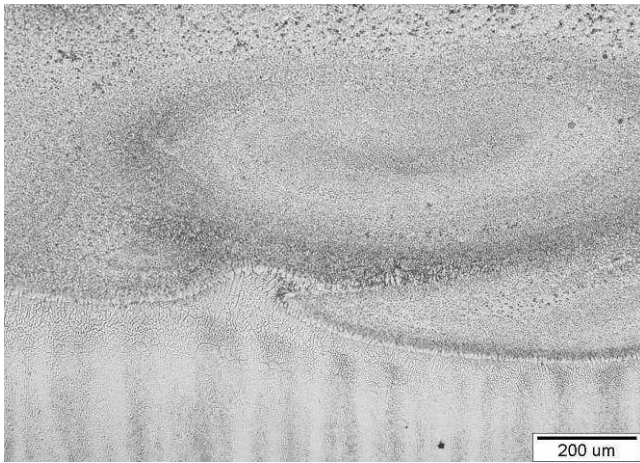


Fig. 8. The structure of the X40CrMoV5-1 hot work tool steel alloyed with TiC, scanning rate 0.5 m/min., power range 2.0 kW

The investigations showed that as a result of the applied laser processing there is the increase in the hardness of the surface layers in relation to the output material (Figure 9). It was observed that maximum hardness occurs on surface of the layer alloyed with TiC using the 1,2 – 2,3 kW. Hardness of the surface layer of steel alloyed with tantalum carbide increases to 56 HRC. Hardness of the surface layer of steel alloyed with tungsten carbide increases to 55 HRC and it's near to the hardness value of the material after the standard heat treatment.

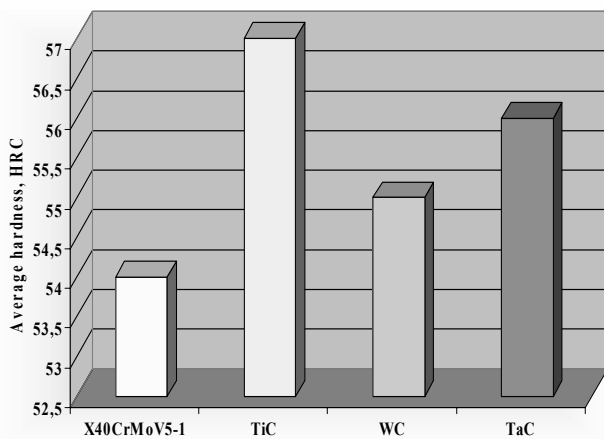


Fig. 9. The comparison of average hardness of the X40CrMoV5-1 hot work tool steel conventional heat treated and alloyed with ceramic powders WC, TaC and TiC, power range 2.0 kW, scanning rate 0.5 m/min.

The X-Ray diffraction showed on figures 10-12 was performed on the remelted samples, perpendicularly to the remelted surface. Results of the qualitative X-ray phase analysis of steel alloyed with WC showed the presence of martensite, retained austenite and M_7C_3 carbides.

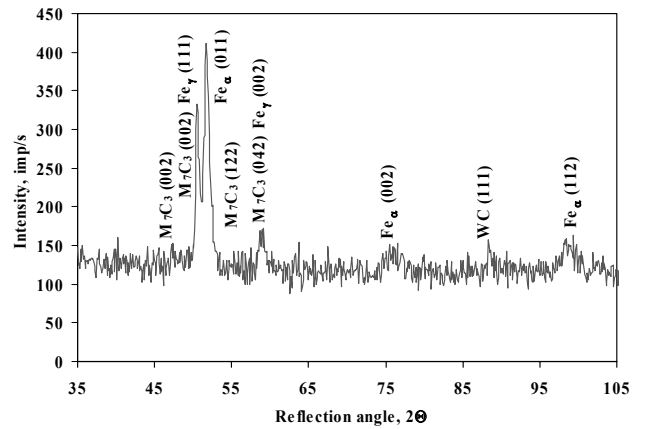


Fig. 10. X-ray diffraction pattern of the X40CrMoV5-1 hot work tool steel alloyed with (HPDL) high diode power laser with WC, power range 2.0 kW

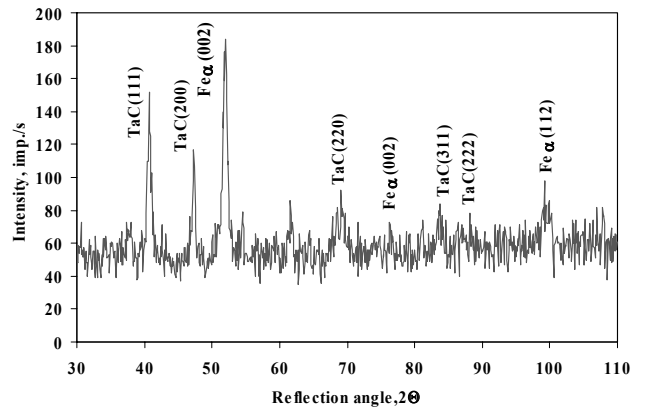


Fig. 11. X-ray diffraction pattern of the X40CrMoV5-1 hot work tool steel alloyed with (HPDL) high diode power laser with TaC powder, power range 2.0 kW

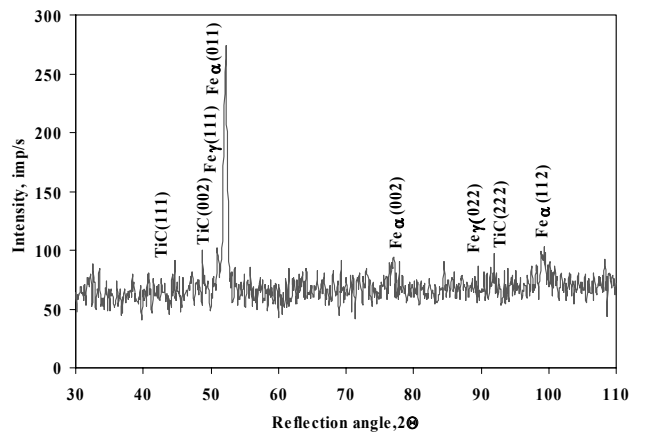


Fig. 12. X-ray diffraction pattern of the X40CrMoV5-1 hot work tool steel alloyed with (HPDL) high diode power laser with TiC powder, power range 2.0 kW

The examined specimens were tribologically damaged due to action of the counter - specimen with the load of 10 N. To analyse changes of the friction coefficient, plots of friction μ as function of the friction distance were made.(Fig. 13-16).

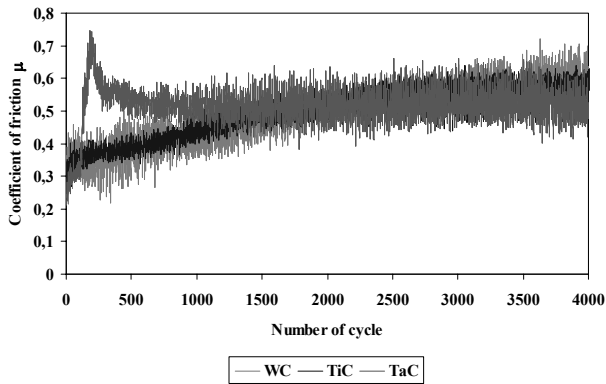


Fig. 13. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after alloying with the 1.2 kW laser beam

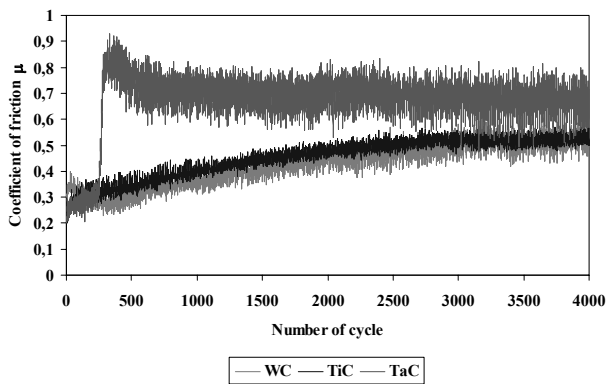


Fig. 14. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after alloying with the 1.6 kW laser beam

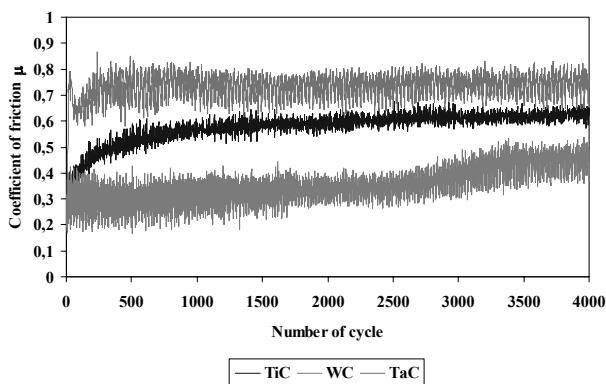


Fig. 15. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after alloying with the 2.0 kW laser beam

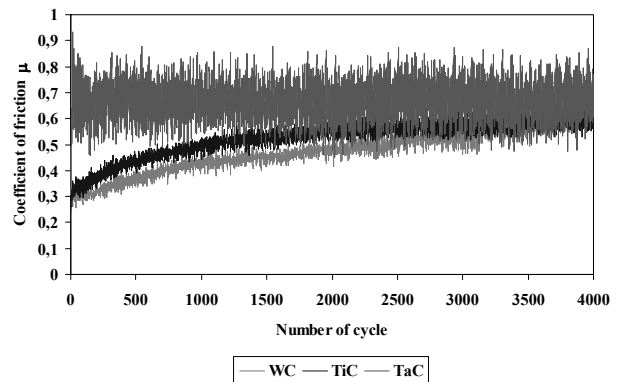


Fig. 16. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after alloying with the 2.3 kW laser beam

The registered friction coefficient curves have similar characteristics, which may be split into two parts. Sudden changes (in most cases - growth) of the friction coefficient along with the number of cycles were revealed in the first part, up to about 500÷1000 cycles. Wearing out of the counter-specimen from Al_2O_3 influences the growing trend of the friction coefficient of the test pieces alloyed with the relevant carbide. It was assumed that it was the transient state of the friction process plot. The second part of the plot has the character close to the steady state. Sudden changes of the friction coefficient occurring in the run of some curves may result from the counter-specimen's (ball made from Al_2O_3) contact with powder grains of the relevant carbides un-dissolved during the laser treatment.

Fig. 17 presents changes of the averaged friction coefficient values of the steel alloyed with the tungsten-, titanium-, and tantalum carbides respectively, depending on laser power in conditions close to the steady state.

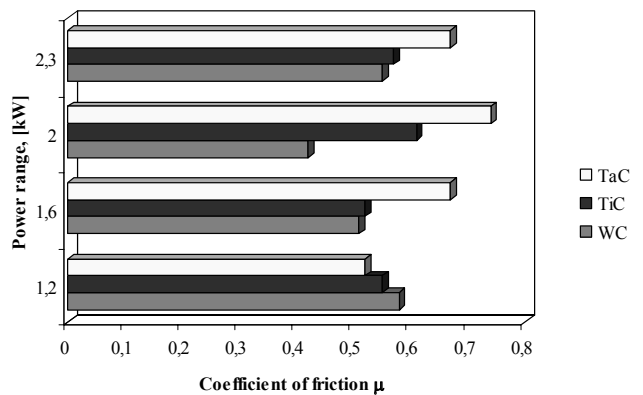


Fig.17. The influence of the power of the laser beam upon the average value of the coefficient of friction Al_2O_3 and the X40CrMoV5-1 steel surface layer after laser alloying.

In case of the test piece from the X40CrMoV5-1 steel alloyed with the tungsten carbide, the friction coefficient value is $\mu = 0.42$ at the beam power of 2.0 kW, whereas the maximum friction coefficient

value is $\mu = 0.58$ at the laser power of 1.2 kW. In case of the test piece alloyed with the tungsten carbide, the minimum friction coefficient value of $\mu = 0.52$ was obtained at the beam power of 1.5 kW, whereas the maximum friction coefficient value of $\mu = 0.61$ was obtained at laser power of 2.0 kW. However, in case of the test piece alloyed with the tantalum carbide, the minimum and maximum friction coefficient values were $\mu = 0.52$ for the beam power of 1.2 kW and $\mu = 0.7$ for the beam power of 2.0 kW, respectively.

The significant scatter of the friction coefficient measurement results was observed. Material of the layer alloyed with the tantalum carbide with the laser beam power of 2.0 kW is characteristic of the maximum friction coefficient of $\mu = 0.74$; however, the friction coefficient value of $\mu = 0.52$ was revealed in the coating area obtained at the low laser beam power equal to 1.2 kW. The same relationship was observed in case of alloying of steel surface with titanium carbide.

Lowering of the friction coefficient was revealed of the steel subjected to laser alloying, which is - in the area of the surface layer obtained using the laser beam power values in the range of 1.2÷2.3 kW is $\mu = 0.42 \div 0.74$, depending on the alloying material type. A steel after the standard heat treatment, whose average friction coefficient is $\mu = 0.82$ [10] was used as reference material.

Comparing the mass loss of the test pieces alloyed with tungsten carbide, titanium carbide, and 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. In Fig. 18 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.. Comparing the plots presented in Figs. 17 and 18 one may notice a certain correlation between the friction coefficient of the investigated laser alloyed coatings and their mass loss, depending on the laser beam power.

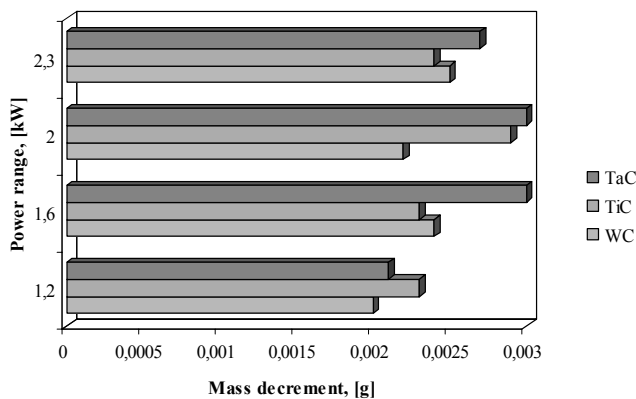


Fig. 18. An average specimen mass loss of X40CrMoV5-1 steel after alloying depending on the power of a laser beam

Fig. 19 presents a structure of thin foil, which was performed by alloy steel. Researches show that a warp superficial layer is a part of lathe martensite about major thickness of dislocations after alloying in the scanning electron microscopy. The slats of this martensite are a very expensive and about an irregular shape. Moreover, they are twinning to a large extent. There are located small carbides a type of M_3C or M_7C_3 . There is retained major thickness of dislocations in slats of martensite, some slats are in part twinned.

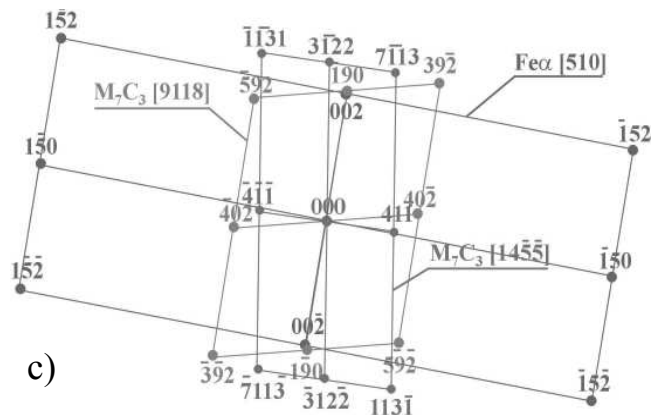
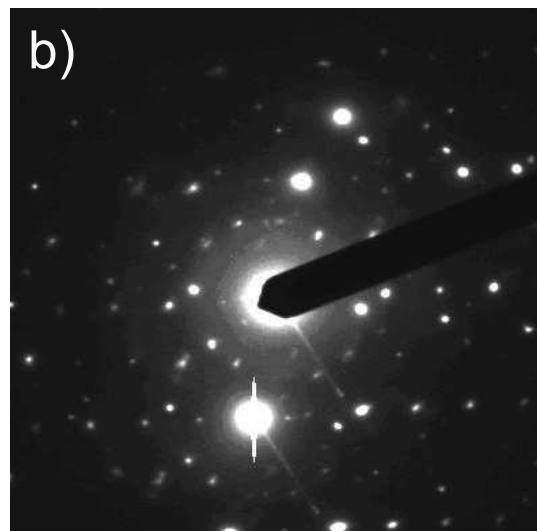
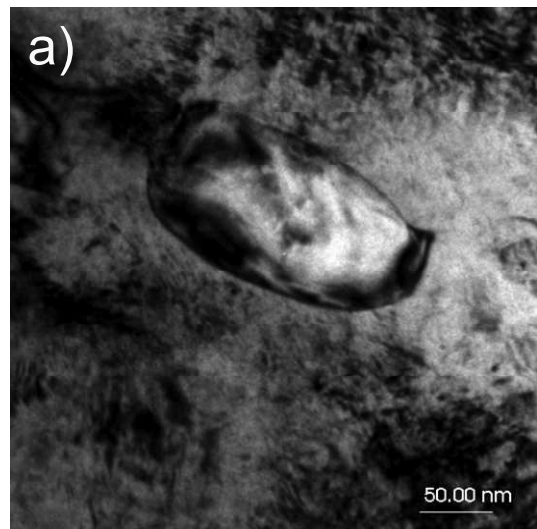


Fig. 19. Structure thin foil of X40CrMoV5-1 steel, after alloying TiC, power of bunch laser 2.6 kW: a) a picture in a bright area, a diffraction pattern of area as fig. a), a solution of diffraction pattern from fig. b)

4. Conclusions

A modification of tool steels surface using a laser beam radiation, as well as coating them with special pastes containing particles such as wolfram, titanium, or tantalum, allows the essential improvement of the surface layer properties – their quality, decreasing at the same time the surface quality, what is dependent on the processing parameters such as energy of impulse and the time of its work. The changes of the surface layers hardness formed as a result of remelting and alloying with powders containing carbides are accompanied with the increased tribological properties in comparison to the conventionally heat treated steels.

The friction coefficient of the investigated layers increases along with the laser beam power growth. Slight differences in the test pieces weight was revealed when comparing the mass loss of the alloyed test pieces due to the “pin-on-disc” test; however, along with the friction coefficient and laser beam power increase the investigated layers mass loss due to friction grows. This may be caused by the volume growth of the remelted material, connected with the laser beam power increase resulting in mixing and partial melting of the alloying material with the particular portion in the growing volume of the remelted steel. Therefore, the abrasion wear resistance deteriorates because of the relatively smaller portion of the relevant alloying carbide in the matrix material.

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