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Structure and tribological behavior of surface layer of laser modified X40CrMoV5-1 steel

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ABSTRACT

Purpose: The paper presents the effect of alloying with WC, TaC and TiC on structure and mechanical properties of the X40CrMoV5-1 steel surface layer using the HPDL (High Power Diode Laser).
Design/methodology/approach: The microstructure of the alloyed layers which were formed on the surface of the investigated hot work steel was examined using optical 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. X-ray diffraction (XRD) technique was used to investigate crystalline structure and phases in the layers.
Findings: The metallographic investigations on light microscope show that during alloying the X40CrMoV5-1 hot work tool steel with the WC, TaC and TiC powder layer the obtained run face is characteristic of the high roughness, multiple pores, irregularity, and flashes at the borders. The changes of the surface layers hardness formed as a result of remelting and alloying with ceramic powders containing carbides are accompanied with the increased tribological properties.
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: Structural and tribological behaviour of surface layer achieved by alloying and remelting using high diode power laser and selected ceramic powders were compared.
Keywords: Surface treatment; Laser alloying and remelting; Hot work alloy tool steel; High Power Diode Laser HPDL

1. Introduction

Laser surface treatment techniques are widely used for improving the mechanical, tribological and chemical properties of metal parts. The surface improvement is based on a rapid thermal cycle of a thin surface layer, which results in micro-structural refinement, phase transformation or the formation of alloyed or clad layers.

Laser alloying is one of many laser surface modification techniques. In the laser alloying procedure, not only the alloyed powder but also the substrate is melted by the laser beam, so a new surface coating whose composition differs from that of either the powder or the substrate is produced [1-3].

The laser treated tool steels have generally a high level of hardness and wear, corrosive, erosive and fatigue resistance. These advantages are brought by extremely high heating and cooling rates during the laser treatment and by high stresses produced by the high temperature gradient that cause elastic and plastic strain of the material [4-6].

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 of the surface layer. Moreover, methods which are not based on partial melting of surface alone, but on partial melting with the simultaneous introduction of the alloying elements with high hardness, like carbides, are being employed more and more widely for modification of the surface layer.

The advantages of laser treatment compared to other surface layer modification methods are: high processing rate, possibility to carry out treatment without protective guards, modification of small, arbitrarily selected fragments of the processed surfaces responsible for tools and machine elements life, as well as its material economy [7-9].

Diode lasers have been known for many years and used mainly in electronic devices and metrology. The dynamical development of materials engineering allowed for the introduction of industrial HPDL lasers. In that type of laser power density delivered to a surface layer of processed materials is smaller in a comparison with mono-mode distribution, characteristic of other types of lasers and energy is spread evenly on the surface of the laser beam focus. Thanks to that phenomenon an HPDL laser is suitable for the modification of a material surface layer. It is confirmed by an empirically proved high energy absorption coefficient for steels, high efficiency and the possibility of the precious control of the amount of energy delivered to a material surface layer [10,11].

The present application of diode lasers is alloying, fusion and surfacing by welding, soldering, and covering with glaze and welding. However, those operations create only a small part of the entire market, of the laser processed materials. It's expected that in the next 5-10 years the application of high power diode lasers will increase. It can be expected that in addition to the direct HPDL increase in market shares, diode pumped Nd:YAG lasers will also increase their market share dramatically.

Tool steels feature are widely used group of tool materials, especially interesting because of their low price and very good functional properties. Big inters in these steels gives the basis for carrying out investigations focused on the improvement of the functional properties of these materials [12-15].

2. Investigation methodology

The material used for investigation was a hot work tool steel X40CrMoV5-1. 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 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 1, 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 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.

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:

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

The number of cycles for each of the specimens has been established at 4000. 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.

3. Investigations results

The metallographic investigations on light microscope show that during alloying the X40CrMoV5-1 hot work tool steel with the WC, TaC (Fig. 1) and TiC 0.05 mm thick layer in the entire range of the laser power values used 1.2÷2.3 kW the obtained run face is characteristic of the high roughness, multiple pores, irregularity, and flashes at the borders. At the constant laser beam scanning rate (0.5 m/min) the beam power change affects clearly the area size in which structural changes occur in the surface layer of the steel.

It was revealed, basing on the metallographic examinations that the structure 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.

Table 1.
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

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

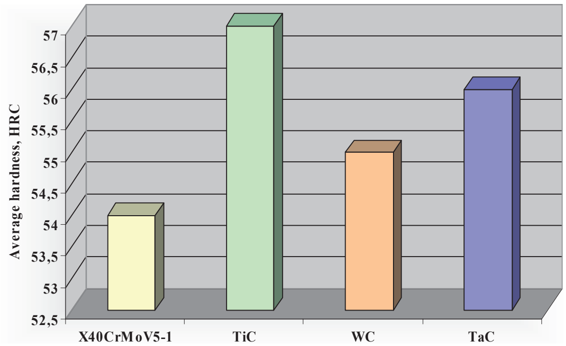

Fig. 2. The comparison of average hardness of the X40CrMoV5-1 hot work tool steel convential heat treated and alloyed with ceramic powders WC, TaC and TiC, power range 2.0 kW

Hardness tests of the X40CrMoV5-1 hot work alloy tool steel after standard heat treatment and after alloying with WC, TaC and TiC indicate that in most cases laser treatment of surfaces layers causes growth of their hardness (Fig. 2). Hardness of the surface layer of steel alloyed with titanium carbide alloying layer 0.05 mm thick increases to 57 HRC at the laser beam power equal to 2.0 kW and for tantalum carbide for 56 HRC at the same laser beam power. 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.

X-ray diffraction patterns were made of the remelted steels and alloyed with the tungsten carbide, tantalum carbide and titanium carbide powders, occurrences of the WC, TaC and TiC carbides were observed using the X-ray qualitative phase analysis methods. 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.

In order to define the resistance to abrasive wear, the laser alloyed steel surface layers have been put to pin-on-disc test. With the use of the testing device, the coefficient of friction in the function of cycle number, has been evaluated (Fig. 3). The registered friction factor curves have got similar characteristics which can be divided into two parts. In the first part, up to about 500-1000 cycles, there have been sudden changes (in most cases the rise) of the friction factor along with the rise of the number of cycles observed. The wear of the counter-specimen with Al_2O_3 influences the rising tendency of the friction factor of the adequate carbide alloyed specimens. It has been accepted that it was an undetermined state of the plot of the friction process. The second part of the plot has got the characteristics similar to the determined state. The sudden changes of the coefficient of friction that appear along some curves may result from the contact of the counter-specimen (Al_2O_3 ball) with the grains of adequate, undissolved in the laser treatment carbides.

In Fig. 4 there have been changes of the average value of the coefficient of friction presented of the respectively alloyed steel with tungsten, titanium and tantalum carbides depending on the power of the laser in conditions similar to the determined state. In case of X40CrMoV5-1 steel specimen, alloyed with the tungsten carbide, the minimal value of the friction factor is $\mu = 0.42$ for the laser beam of 2.0 kW whereas the maximal friction factor value is $\mu = 0.58$ for the laser beam of 1.2 kW. In case of titanium carbide alloyed specimen, the smallest value of the coefficient of friction $\mu = 0.52$ has been achieved for the laser power of 1.6 kW, while the biggest value of the coefficient of friction $\mu = 0.61$ has been achieved for the laser energy of 2.0 kW. In case of tantalum carbide alloyed steel, the minimal and maximal values of the coefficient of friction are $\mu = 0.52$ for the 1.2 kW laser beam and $\mu = 0.74$ for the 2.0 kW laser beam respectively. There has been a significant scattering of the measurement results of the friction factor observed. The material of the tantalum carbide alloyed layer with the beam laser of 2.0 kW, features the maximal coefficient of friction $\mu = 0.74$. In the area of the obtained, however, layer, with the low power of the laser beam of 1.2 kW, the coefficient of friction equal to $\mu = 0.52$ has been ascertained. The similar dependence has been observed when alloying the steel surface with titanium carbide. The lowering of the coefficient of friction of the laser alloyed steel has been ascertained which in the area of the surface layer obtained by the power of the 1.2 – 2.3 kW laser beam amounts to $\mu = 0.42 – 0.74$ depending on the kind of the alloying material. As a reference material, the steel after a standard heat treatment was used, the average friction factor of which was $\mu = 0.82$.

Comparing the mass loss of tungsten, titanium and tantalum carbide alloyed specimens after the pin-on-disc resistance examination to abrasive wear, insignificant differences in the specimen masses have been ascertained. In all the analyzed cases there was an insignificant mass loss observed together with the growth of the laser beam power. A certain correlation between the coefficient of friction of the examined alloyed layers and their mass loss, depending on the laser beam power was observed.

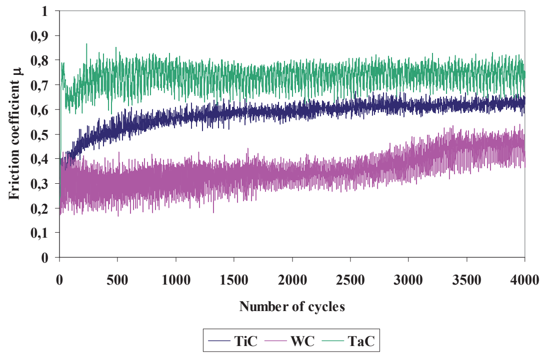

Fig. 3. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after alloying with the 2.0 kW laser beam

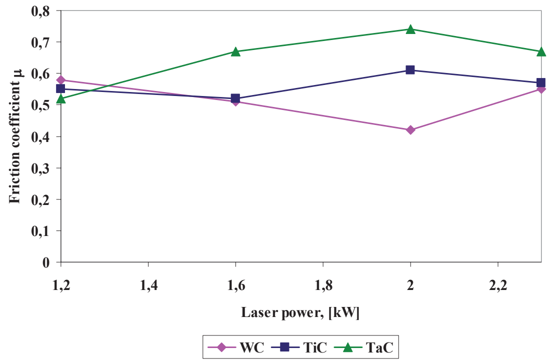

Fig.4. The influence of the power of the laser beam upon the average value of the coefficient of friction Al_2O_3 and the X40CrMoV5-1 steel surface layer after laser alloying

4. Conclusions

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.

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. The changes of the surface layers hardness formed as a result of remelting and alloying with ceramic powders containing carbides are accompanied with the increased tribological properties in comparison to the conventionally heat treated steels. The coefficient of friction of the examined surface layers increases with the growth of the laser beam power. When comparing the mass loss of the alloyed specimens after the test done using the pin-on-disc method, some insignificant disparities have been noted in the specimen masses. However, together with the increase of the coefficient of friction and the laser beam power, there was a growth in the mass loss of the examined layers as a result of friction. This may be caused by the increase of the volume of the remelted material related to the increase of the laser beam power as a result of which the alloying material is mixed and partly melted in the growing volume of the remelted steel. This way the resistance to wear falls down because of a relatively smaller participation of an appropriate alloying carbide in the matrix material.

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