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# Comparison of the abrasion wear resistance of the laser alloyed hot work tool steels

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## ABSTRACT

**Purpose:** The paper presents the comparison of the abrasion wear resistance of the laser alloyed hot work tool steels X40CrMoV5-1 and 32CrMoV12-28.

**Design/methodology/approach:** 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.

**Findings:** The performed investigations leads to the conclusions that for both types of steels - X40CrMoV5-1 and 32CrMoV12-28 the wear resistance measured using pin-on-disc, wear resistance test in the metal – metal arrangement, and wear resistance test in the metal – ceramic material arrangement, the wear resistance increases together with the hardness of the surface layer. This relationship is valid for all types of ceramic powders used. It is characteristic for the obtained surface layers, that the high roughness, multiple pores, irregularity, and flashes at the borders increases also together with the increasing of the laser power.

**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 steels have shown significant improvement concerning properties. 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 carbide particles allows the essential improvement of the surface layer properties - their quality and abrasion resistance, 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.

**Keywords:** Wear resistance; Surface treatment; Laser alloying and remelting; Hot work alloy tool steel; High Power Diode Laser HPDL

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## MATERIALS MANUFACTURING AND PROCESSING

## 1. Introduction

Lasers are one of the possible tool for surface engineering. In 1958 Shawlow and Towns first established the theoretical concept of the laser. In 1960 Maimam first invented the working ruby laser (Fig. 1). Around 1970 have been development of continuous $CO_2$ lasers with many kilowatts of power. The application of the lasers for materials processing has grown considerably since the invention of the high power $CO_2$ (Fig. 2). Around mid of 1970 more dependable lasers were made achievable for realy practical applications in the industrial environment. By 1980 and 1990 the lasers were examined for surface connected adoptions. On the other hand the processes of laser cutting, welding and laser heat treatment have already found their way into actual manufacturing floors. The lasers have evolved from brittle equipment's to dependable industrial tools. Therefore the development of lasers since the first operative devices in 1960 has been extremely quick [1,2,6,8].

Laser is a device that amplifies light and produces a highly directional, high intensity beam. It can be say that laser is another type of light source. Laser has many special properties that make it unique light source. Laser consisting on obtain or amplifying medium and a set of mirrors to feed the light back into the amplifier for continued growth of the developing beam. It needs relatively special conditions within the laser medium for amplification to occur but it is the capacity of taking light and concentrating that light into a beam traveling in a single direction [3-8].

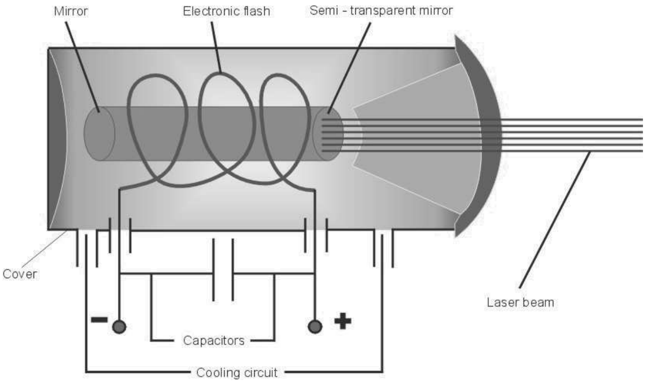

Fig. 1. Schematic diagram of continuous ruby laser

The word laser is an acronym of the English description „Light Amplification by Stimulated Emission of Radiation", which may be explained as the light amplification by a forced (stimulated) emission of radiation" [3, 5, 7, 9].

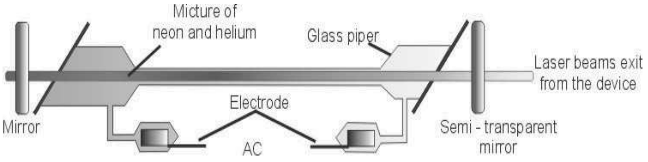

Fig. 2. Schematic diagram of the $CO_2$ gas laser

It has been almost a two decades since the first direct diode laser application for materials processing was reported in 1991 for soldering using a 15 W medical diode laser. Currently the HPDL (High Power Diode Laser) feature the up-to-date energy source. They are used for the industry scale only in materials engineering from 1998. The HPDL reaches up to 6 kW in the beam focus (Fig. 3). 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/cm$^2$.The high coefficient of radiation absorption, do not require leading the laser beam by any complex optical systems causing energy loss in the range of 10-30%, they achieve 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 [9-12].

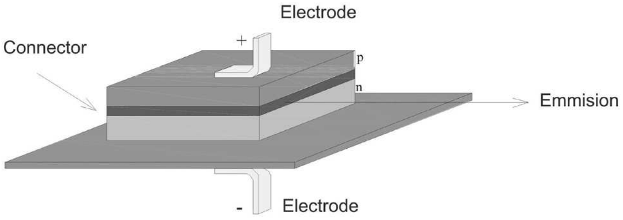

Fig. 3. Schematic diagram of the laser diode [21]

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 manufacturing of coatings.

Applications of the lasers in surface alloying, cladding, glazing and annealing of semiconductors offer the possibility of producing new materials with better quality. In recent years, surface modification using advanced heat source like laser replaces the conventional methods to produce the surface layer with better hardness, wear resistance, heat resistance or some other property (13-15).

Laser surface alloying (LSA) is used for improving mechanical and chemical properties of the surface layer. It consists on surface layer enriched with alloying elements with structure changes. The alloying additions used in the laser alloying process are usually metal alloys, 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 [10, 11]. Alloying consists of 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 are intensively mixed and the fash can be observed on borders of the pool. A rich in alloying elements surface of the alloy is characterized by a higher hardness than the surface and the base material, increased fatigue strength, tribological and anticorrosion to properties, decreased smoothness of the surface in comparison the one before alloying. All those properties depend mostly on the homogeneity of alloy in the liquid state, which depends, in turn, on the intensity of convective mass changes in this zone [16-22].

## 2. Investigation methodology

The material used for investigation were hot work tool steels X40CrMoV5-1 and 32CrMoV12-28 (the chemical composition of the investigated hot work tool steels 32CrMoV12-28 and X4CrMoV5-1 is given in Table 1).

Table 1.
Chemical composition of the investigated hot work tool steels 32CrMoV12-28 and X40CrMoV5-1

| Mass concentration of the elements, % | | |
|---|---|---|
| Steel type | 32CrMoV12-28 | X40CrMoV5-1 |
| C | 0.308 | 0.41 |
| Si | 0.25 | 1.09 |
| Mn | 0.37 | 0.44 |
| P | 0.020 | 0.018 |
| S | 0.002 | 0.010 |
| Cr | 2.95 | 5.40 |
| Mo | 2.70 | 1.41 |
| V | 5.35 | 0.95 |

The samples of X40CrMoV5-1 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 carbide powders were applied on specimens by put down in each case.

The 32CrMoV12-28 steel samples were heat treated according to the steps for this steel type, at first tempering was performed and then annealing. Austenisation was performed in a vacuum furnace at a temperature of 1040°C, the heating time was 0.5h. 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 2 h, the first at 550°C and the second at 510°C. After heat treatment the samples surfaces were grind on a magnetic grinding machine. Special care was put to avoid micro cracks, which can disqualify a sample on future investigation. Also in this case the paste of carbide powders were applied on specimens by put down.

Based on the preliminary investigations results a high power diode laser HPDL Rofin DL 020 with process rate was =0.5 m/min. To ensure good work parameters the investigations were carried out at a constant remelting process rate, changing the laser power in a range of 1.2-2.3 kW.

In order to define the resistance to abrasive wear of the laser alloyed X40CrMoV5-1 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.

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 testing conditions showed in Table 2.

Table 2.
Testing conditions of the resistance research on the dry abrasive wear with the use of the pin-on-disc method

| Testing conditions | Power range, kW | | | |
|---|---|---|---|---|
| | 1.2 | 1.6 | 2.0 | 2.3 |
| Pressure force $F_N$, N | 10 | 10 | 10 | 10 |
| Travel speed v, cm/s | 13.75 | 7.5 | 13.75 | 7.5 |
| Radius r, mm | 22 | 12 | 22 | 12 |

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. 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 50x.

Wear resistance investigations of the 32CrMoV12-28 steel of the metal-metal type were performed on the device designed at the Faculty of Mechanical Engineering ,Silesian University of Technology. The scheme of the device is presented in Figure 4. For investigation there were used samples with a length of 65 mm and with width of 25 mm. As a counter pad there was applied a steel ball with a diameter of 8.7 mm. The number of cycle was constant for each of the samples and equal 5000 rotations, which corresponds to a length of 120 m. There was applied a load of 10 N. Abrasion wear resistance tests of the X40CrMoV5-1 and 32CrMoV12-28 steels surface layers in the metal-ceramic material arrangement were carried out on a device developed in the Department of Welding of the Silesian University of Technology according to the ASTM G65 standard (Fig. 5). The surface layers obtained consisted of four adjacent welding sequences. Two test pieces of each type of the investigated gradient surface coatings were examined according to the requirements of the standard. The ceramic material-quartz sand with the granularity of 212-300 μm - was delivered by the nozzle with the flow rate of about 350 g/min during the test. The nozzle was between the examined test piece and the rubber circle with the diameter of 229 mm. The test piece was loaded with the constant force of 130 N and was pressed down to the rotating rubber wheel. 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 X40CrMoV5- and 32CrMoV12-28 conventionally heat treated steels were used as reference materials.

The measurement of a mass decrement after the wear abrasion test has been performed on a laboratory weight with the sensibility up to 0,0001g. According to the standard, the results of the tests can be considered reliable only in the case when the trace created after the experiment is uniform.

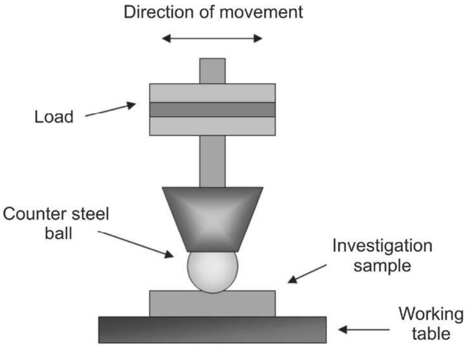

Fig. 4. Experimental stand for the abrasive wear investigations in a metal-metal system

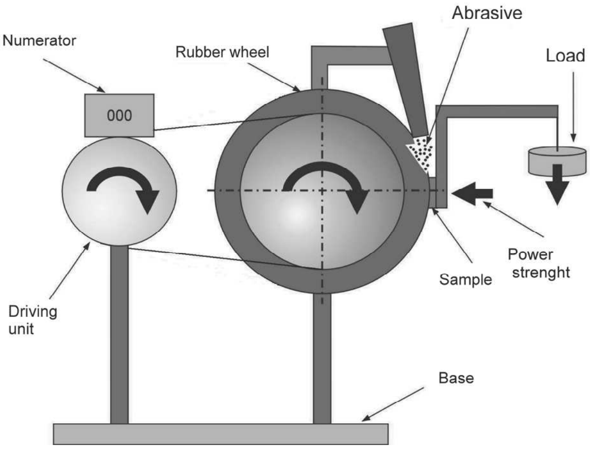

Fig. 5. Experimental stand for the abrasive wear investigations in a metal-ceramic system according to the ASTM G65

## 3. Investigations results

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 case of X40CrMoV5-1 steel specimen, alloyed with the tungsten carbide, the minimal value of the friction factor is μ=0.42 for the laser beam of 2.0 kW whereas the maximal friction factor value is μ=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 μ=0.52 has been achieved for the laser power of 1.5 kW, while the biggest value of the coefficient of friction μ=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 μ=0.52 for the 1.2 kW laser beam and μ=0.74 for the 2.0 kW laser beam respectively (Figs. 6-7).

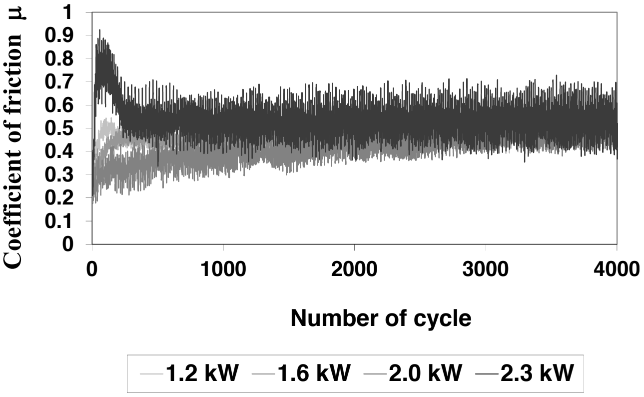

Fig. 6. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after VC alloying with the 1.2-2.3 kW laser beam

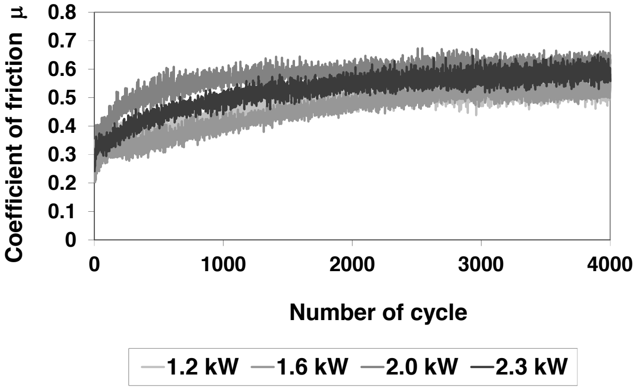

Fig. 7. The plot of the coefficient of friction depending on the number of cycles during the pin-on-disc test of X40CrMoV5-1 steel after TiC alloying with the 1.2-2.3 kW laser beam

In Figs. 8-9 there are wear traces presented, the result of the examinations of the resistance to abrasive wear, made with the use of pin-on-disc method on the surface of the alloyed, with an appropriate powder, specimens are presented.

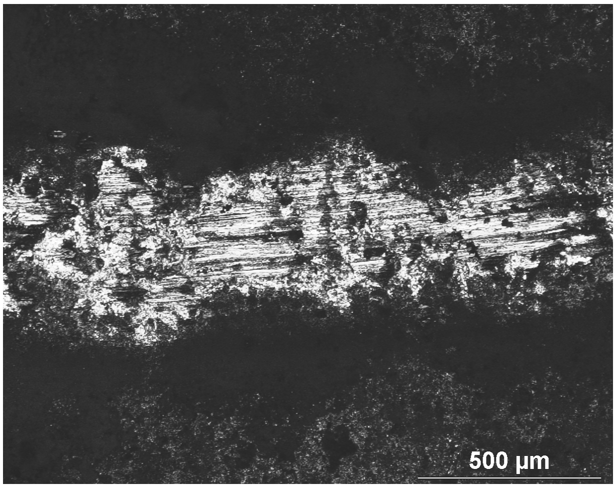

Fig. 8. The worn surface of X40CrMoV5-1 steel alloyed TaC (power range 1.2 kW) after pin-on-disc test

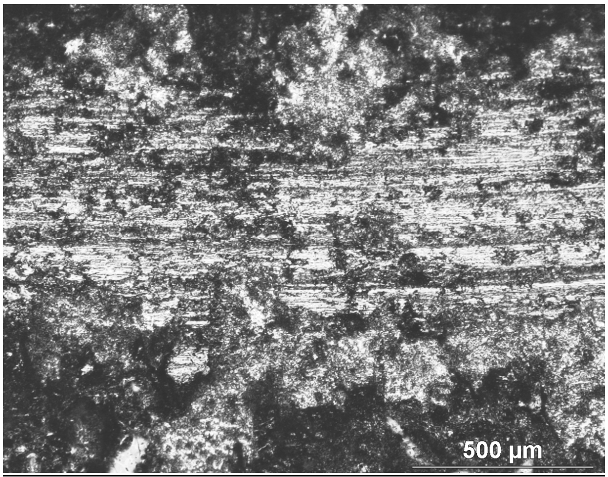

Fig. 9. The worn surface of X40CrMoV5-1 steel alloyed NbC (power range 2.3 kW) after pin-on-disc test

As a result of wear resistance investigations performed in the metal-metal arrangement of 32CrMoV12-28 tool steel, which imitates working in industrial environments e.g. wear of dies, forging tools, it was state that the steel alloyed with vanadium and titanium carbide powders reveals the highest wear resistance. Performed profiles allow to conclude, that the highest wear resistance occurs in case of vanadium and titanium carbide powders using for alloying (Figs. 10-13).

In case of X40CrMoV5-1 steel specimen there was a significant scattering of the measurement results of the friction factor observed. The material of the tantalum carbide alloyed layer with the power range of 2.0 kW, features the maximal coefficient of friction μ=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 μ=0.52 was ascertained. The similar dependence was observed when alloying the steel surface with titanium carbide.

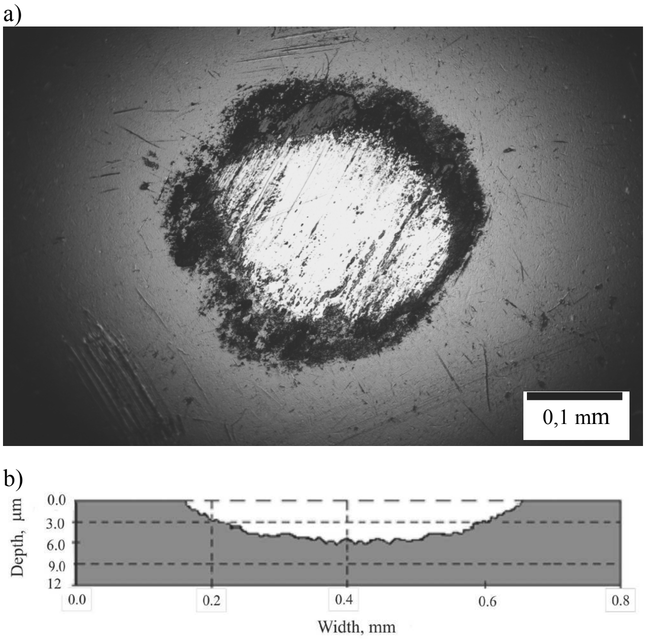

Fig. 10. a) Trace the steel counter face wear after 1000 cycles of friction with the surface layer of steel after laser alloying with niobium carbide (power range 1.6 kW); b) The shape of the surface layer after wear abrasion test of the 32CrMoV12-28 steel after laser alloying with niobium carbide (power range 1.6 kW)

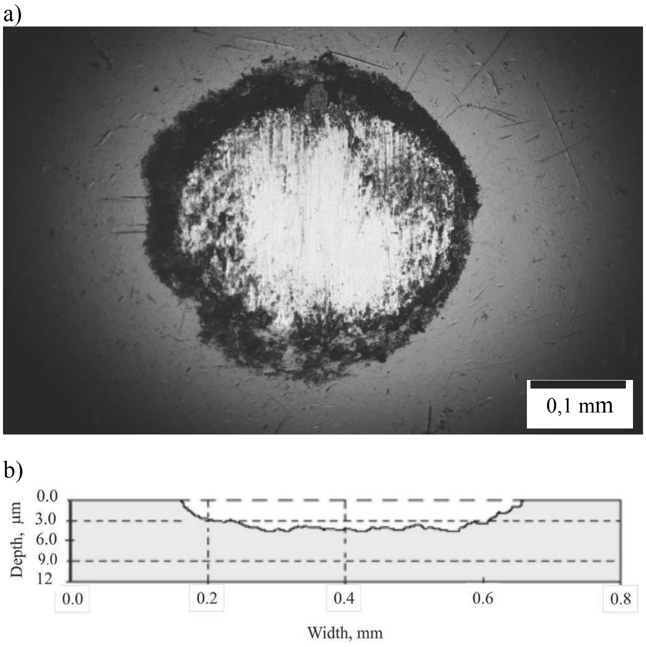

Fig. 11. a) Trace the steel counter face wear after 1000 cycles of friction with the surface layer of steel after laser alloying with niobium carbide (power range 2.0 kW); b) The shape of the surface layer after wear abrasion test of the 32CrMoV12-28 steel after laser alloying with niobium carbide (power range 2.0 kW)

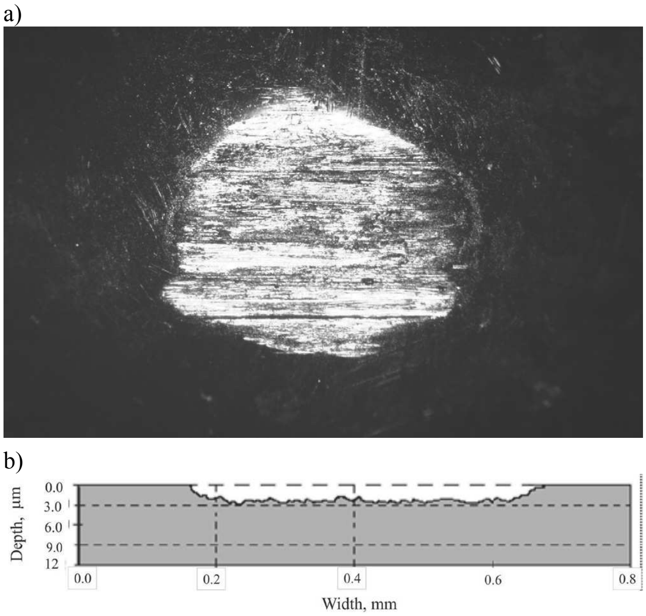

Fig. 12. a) Trace the steel counter face wear after 1000 cycles of friction with the surface layer of steel after laser alloying with vanadium carbide (power range 1.6 kW); b) The shape of the surface layer after wear abrasion test of the 32CrMoV12-28 steel after laser alloying with vanadium carbide (power range 1.6 kW)

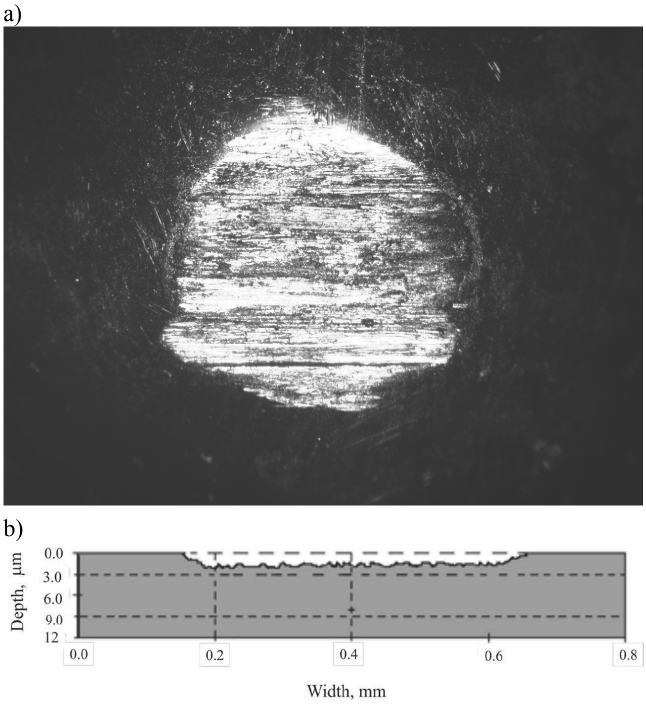

Fig. 13. a) Trace the steel counter face wear after 1000 cycles of friction with the surface layer of steel after laser alloying with vanadium carbide (power range 2.0 kW), b) The shape of the surface layer after wear abrasion test of the 32CrMoV12-28 steel after laser alloying with vanadium carbide (power range 2.0 kW)

The lowering of the coefficient of friction of the laser alloyed steel was ascertained which in the area of the surface layer obtained by the power of the 1.2-2.3 kW laser beam amounts to $\mu=0.42\text{-}0.74$ 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 $\mu=0.82$.

The coefficient of friction of the examined surface layers increases with the growth of the laser beam power. 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.

Also in the case of examinations results of the resistance to abrasive wear in the metal-ceramic material arrangement of X40CrMoV5-1 tool steel, the highest wear resistance, and thus the lowest mass loss of compared to the mass loss of steel samples after standard heat treatment was observed for samples after vanadium carbide powder alloying with a laser power of 1.6 kW as well as for titanium carbide alloyed samples with laser power of 2.0 kW laser. The highest mass loss of almost was found in case of the surface layer after tungsten carbide alloying with laser power of 1.6 and 2.0 kW as well for the remelted steel with the laser power of 2.0 kW. In case of the 32CrMoV12-28 the lowest mass loss was found in case of the surface layer after titanium carbide and vanadium carbide. The degree of weight loss of the steel alloyed by tungsten carbide, niobium carbide and tantalum carbide is comparable with the result of mass loss of remelted steel.

In Figs. 14-15 and 16-17 there are wear traces presented, the results of the examinations of the resistance to abrasive wear, done according to the ASTM G65 standard.

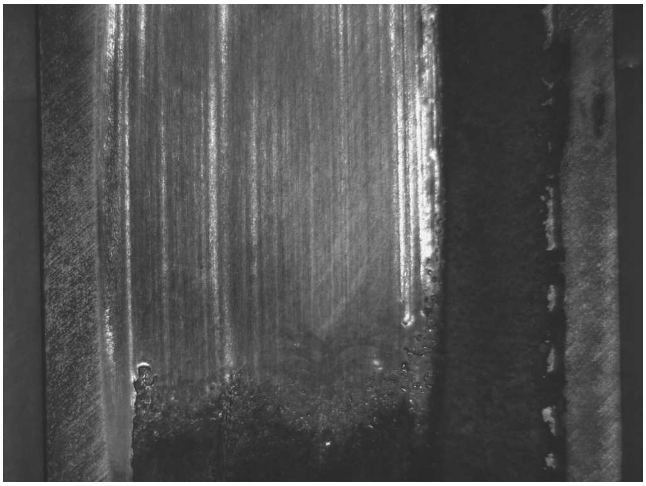

Fig. 14. Surface layer of the test sample from the X40CrMoV5-1 tool steel after wear test alloyed NbC, (power range 1.2 kW), magnification 10x

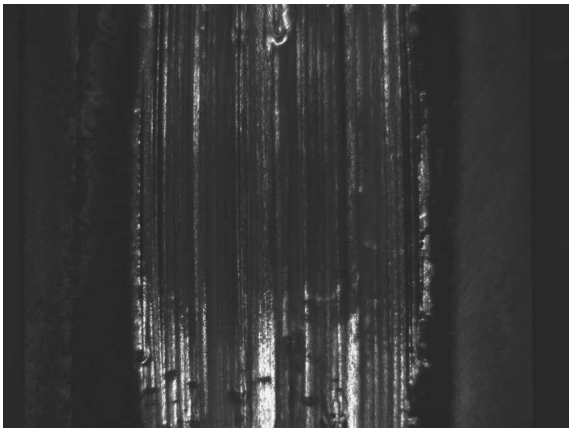

Fig. 15. Surface layer of the test sample from the X40CrMoV5-1 tool steel after wear test alloyed VC, (power range 2.3 kW), magnification 10x

Fig. 16. Surface layer of the test sample from the 32CrMoV12-28 tool steel after wear test alloyed NbC, (power range 1.6 kW), magnification 10x

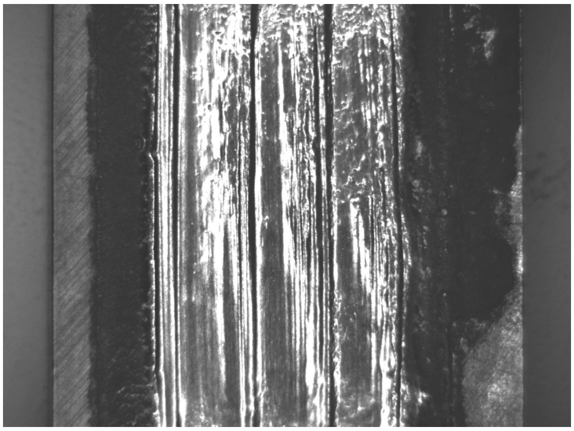

Fig. 17. Surface layer of the test sample from the 32CrMoV12-28 tool steel after wear test alloyed VC, (power range 1.6 kW), magnification 10x

In Figs. 18-19 are presented the relative mass loss measured when testing wear resistance for X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels.

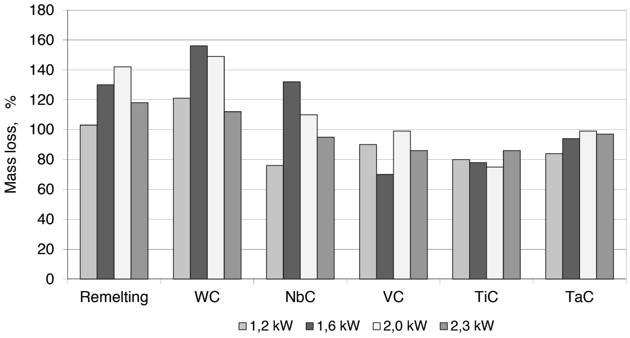

Fig. 18. The relative mass loss measured when testing wear resistance for X40CrMoV5-1 steel (100% - the mass loss of the heat-treated sample, not subjected to laser cladding or alloying with carbide powders)

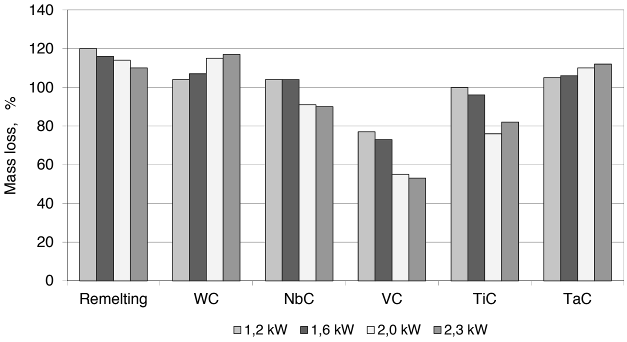

Fig. 19. The relative mass loss measured when testing wear resistance for 32CrMoV12-28 steel (100% - the mass loss of the heat-treated sample, not subjected to laser cladding or alloying with carbide powders)

## 4. Conclusions

To determine the optimal laser treatment parameters after laser alloying investigations were carried out, including wear resistance tests in the metal-metal and metal-ceramic material arrangement. Among the investigated carbide powders in the metal-ceramic system, the lowest mass loss occurs for steel alloyed with titanium carbide and vanadium carbide powders, for both kinds of steel. The measured mass loss of the 32CrMoV12-28 steel alloyed with tungsten carbide, niobium carbide and tantalum carbide is comparable with the result of mass loss of the only remelted steel, whereas for the X40CrMoV5-1 steel the tungsten carbide and niobium carbide alloying causes lowest resistance comparable to the only remelted steel. Also the investigations of wear resistance in the metal-metal system, simulating the tool working in industrial environments (abrasion of the dies, tools, forging), confirm the results of a previous study. In this arrangement, the steel alloyed with vanadium carbide and titanium carbide powder shows the highest wear resistance. The investigations carried out made it possible to state that due to the heat treatment and remelting of the X40CrMoV5-1 and 32CrMoV12-28 tool steels with the carbide powders it is possible to obtain the higher resistance to abrasion of the surface layers in relation to the output material.

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