Archives of Materials Science and Engineering
Volume 64
Issue 2
December 2013
Pages 152-159
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Influence of the HPDL surface treatment of the X40CrMoV5-1 and 32CrMoV12-28 tool steels on wear resistance

E. Jonda*, K. Labisz, W. Pakieła
Institute of Engineering Materials and Biomaterials, Silesian University of Technology,
ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding e-mail address: ewa.jonda@polsl.pl

Received 17.10.2013; published in revised form 01.12.2013

ABSTRACT

Purpose: This paper presents the results of laser remelting influence on structure and properties of the surface of the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels, carried out using the high power diode laser (HPDL). Structure changes were determined in the work, especially structure fragmentation. Also hardness investigation of the different remelting areas was performed. The purpose of this work was also to determine technological and technical parameters for a right performed HPDL remelting process. Boron nitride powder was used for alloying. The goal of this work was also to determine technical and technological conditions for remelting the surface layer with HPDL.

Design/methodology/approach: Here are discusses the new methodology ways which can be applied in case of improving of the surface layer properties. A new laser treatment techniques applied in metal surface technology is here the most important feature. Also the influence of ceramic powders to the structure in all zones is investigated. Optical and scanning electron microscopy, EDS point wise and area microanalysis was used to characterize the microstructure and to investigate the intermetallic phases occurred.

Findings: The most important factor is the zone structure of the surface layer which was coming into existence without cracks and defects as well as has a considerably higher hardness value compared to the non remelted material. It was find out, that the hardness of the alloyed surface layer increases according to the applied laser power. The highest power applied gives the highest hardness value in the remelted layer mostly in all user ceramic powders.

Practical implications: The reason of this work was also to determine the laser treatment parameters, particularly the laser power, to achieve a good layer hardness for protection of this hot work tool steel from losing their work stability and to make the tool surface more resistant for work extreme conditions. The most important practical implication investigated in this work improves the appliance of HPDL laser for alloying and remelting of hot work tool steel.

Originality/value: The originality of this work is assured through the using of an high-level up-to-date laser device for improvement of steel surface layer mechanical properties.

Keywords: Wear resistance; HPDL; Tool steel; Remelting; Alloying; Surface; Boron nitride powder

Reference to this paper should be given in the following way:

E. Jonda, K. Labisz, W. Pakieła, Influence of the HPDL surface treatment of the X40CrMoV5-1 and 32CrMoV12-28 tool steels on wear resistance, Archives of Materials Science and Engineering 64/2 (2013) 152-159.

PROPERTIES

1. Introduction

The laser treatment as a part of the new generation techniques applied in metal surface technology is discussed in this paper. Laser treatment is presented with remelting of hot work tool steels X40CrMoV5-1 and 32CrMoV12-28 with ceramic powders, especially boron nitride (BN). The investigated hot-work tool steel belongs to the group of martensitic steel used in the production of forging tools. The microstructure of these hot-work tool steels changes several times during the complex thermo-plastic treatment. The aim of this processing is to obtain high wear and thermal fatigue resistance. The structure investigation, and improvement of mechanical properties, is the practical aim of this work, as well as improvement of hardness as a very important property for practical use.

High power diode lasers (HPDL) are widely used in a range of applications including industrial materials processing and as pump sources for high power solid state and fibre lasers. Such applications exploit the intrinsic HPDL advantages of very high electrical-to optical conversion efficiency, small size, convenience in usage and reliability.

Properties of the laser beam in combination with the positioning accuracy of the order of hundredths of a millimetres allow to carry out a very precise production processes of surface layers, including repairing , and even the production of finished components. Since the direct production techniques are still at the research stage, there are of particular interest the special techniques, which use radiation laser. The main goal of laser remelting of material surface layers is to modify the structure and increasing the mechanical and functional properties. With the occurrence of chemically homogeneous, fine-crystalline structure of the surface layer without changing the chemical composition of the material, it is possible primarily to increase the wear resistance and thermal fatigue of the treated surface. Even better results in improved functional properties can be obtained by alloying the surface layer of the material with solid phase particles containing carbides, oxides or nitrides [1-9].

High-power diode lasers usually come in the form of bars (approximately 10 mm × 0.6 mm) comprising about 25 monolithic groups of up to 20 parallel single-laser stripes. A major drawback of high-power broad-area diode lasers is their satisfactory beam quality. This allows focusing of the total beam as it is the addition of many single beams. Hence, power density at the work piece is limited as well, leaving high-power diode lasers with restricted application opportunities. Crucial for reliability and lifetime of bars is proper heat sinking. Although power efficiency is extremely high, one half of the absorbed pump power has to be removed as waste heat. Mounting high-power diode-laser bars on cooling elements requires high precision and the complete mastering of the electrical, thermal, and mechanical junction process. This is the fundamental concept for direct-diode applications. Laser diodes are numerically the most common laser type, with 2004 sales of approximately 733 million units, as compared to 131,000 of other types of lasers [10-20].

For alloying of the tool steel, boron nitride was used, which is a rarely used tool material sometimes used in metal machining because of its high hardness and high resistance to softening at high cutting speed and at high cutting temperature. Tool life is an important parameter to be considered in tool selection since it will affect tool change scheduling, production planning and unit production cost. The tool life of a hot work tool is commonly determined with an actual machining operation by using the tool with a particular work material under certain working conditions to reach the maximum allowable life time. However, this is also an expensive process since a lot of work material is consumed in the test. The major concern of laser alloying is to avoid defects after treatment such as cracking, bubbles and unacceptably rough surface. The second concern is to achieve a maximum hardness in the surface layer to ensure good working parameters. Laser diodes find wide use in telecommunication as easily modulated and easily coupled light sources for fiber optics communication. They are used in various measuring instruments, such as rangefinders. Another common use is in barcode readers. Visible lasers, typically red but later also green, are common as laser pointers. Both low and high-power diodes are used extensively in the printing industry both as light sources for scanning (input) of images and for very high-speed and high-resolution printing plate (output) manufacturing. Infrared and red laser diodes are common in CD players, CD-ROMs and DVD technology. Violet lasers are used in HD DVD and Blu-ray technology. Diode lasers have also found many applications in laser absorption spectrometry (LAS) for high-speed, low-cost assessment or monitoring of the concentration of various species in gas phase. High-power laser diodes are used in industrial applications such as heat treating, cladding, seam welding and for pumping other lasers, such as diode-pumped solid-state lasers. Many applications of diode lasers primarily make use of the "directed energy" property of an optical beam. In this category, one might include the laser printers, barcode readers, image scanning, illuminators, designators, optical data recording, combustion ignition, laser surgery, industrial sorting, industrial machining, and directed energy weaponry. Some of these applications are well-established while others are emerging, generally an increase of the laser power can be found, where the beam size corresponds to the applied laser power (Fig. 1). High-power diode lasers are continuously making inroads into industrial applications, as they are compact, easy to cool, yield a power efficiency beyond 50%, which is about five times higher than any other kind of laser has to offer, and their costs are becoming increasingly attractive. To exploit the tremendous application potential of high-power diode lasers, research and development programs are performed in many industrial countries [21-33].

This study was conducted to make clear an effect of BN powder addition and the solidification rate on structure and properties in the laser melted metal surface of the hot work tool steels X40CrMoV5-1 and 32CrMoV12-28. On the other hand, the solidification mode in the weld metal was changed from the primary ferrite to the primary austenite, as the solidification rate was raised.

The purpose of this work is to study the effect of a HPDL laser melting on the hot work tool steels, especially on their structure and hardness. Special attention was devoted to monitoring of the layer morphology of the investigated material and on the particle occurred.

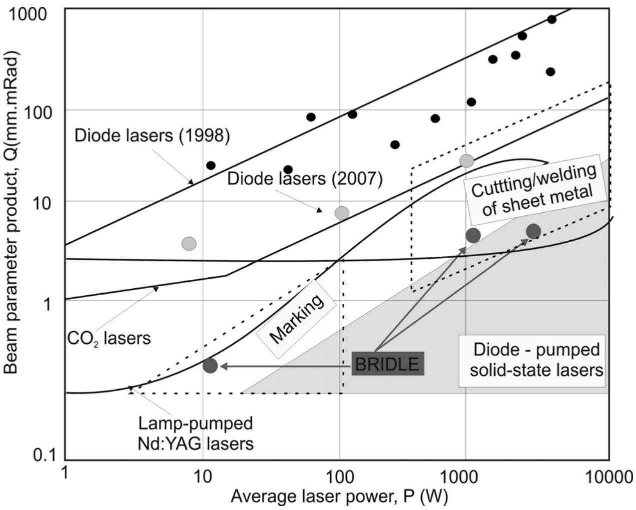

Fig. 1. Parameters of the laser beam for different materials treatment applications [according to: BRIDLE]

2. Experimental conditions

For investigation there were used two types of tool steel; especially hot work tool steel, which has been supplied annealed in form of rods 76 mm in diameter and in the length of 3 m. Samples of this material were of the plate form, of the rectangular shape, with dimensions 70 x 25 x 5 mm.

The samples were heat treated according to the steps for this steel type, at first tempering was performed and then annealing. Austenization was performed in a vacuum furnace at a temperature of 1040ºC, the heating time was 0.5 h. During the heating to the austenitic temperature two isothermal holds were applied. The first one at the temperature of 585ºC, the second at 850ºC. After tempering two annealing operations were performed for the time of 2 h, the first at 550ºC and the second at 510ºC. After heat treatment the samples surfaces were grind on a magnetic grinding machine. Special care was set to avoid micro cracks, which can disqualify a sample on future investigation. Boron nitride powder was put to the so prepared and degreased samples. The powder was initially mixed before with the inorganic sodium glass in proportion 30% glass and 70 % powder. A paste layer of 0.5 mm in thickness was put on. The properties of boron nitride powder (BN) are presented in Table 1. Based on the preliminary investigations results a high power laser diode HPDL Rofin DL 020 with process rate of v = 0.5 m/min was. All other work parameters are presented in Table 2. 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. For laser power values of 0.4 to 0.8 kW there are no remelted areas present at all.

The investigations were performed on samples made from the hot work tool steel X40CrMoV5-1. The investigated steel was melted in an electric furnace in vacuum at pressure of about 1 Pa and cast into ingots of approximately 250 kg. Next the steel was forged at a temperature of 900-1100°C, to the shape of a rod having a diameter of 75 mm, as well as annealed for softening. From the rod with machining methods, samples with dimensions of 70 mm and a thickness of 6 mm were cut off and subjected to heat treatment. The samples were heat for austenitizing in a furnace in a salt bath and tempered in the furnace chamber in a protective argon atmosphere. The samples were heated gradually, with isothermal stops at 650°C and at 850°C for 15 min. Austenitizing was carried out for 30 min. at a temperature of 1060°C and cooled in hot oil. After quenching the samples were tempered twice, each time for 2 hours at 510°C.

The samples were mounted in the laser holder for remelting. On each sample surface four laser process trays were made of a length of 25 mm, with the power 1.2, 1.6, 2.0, 2.3 kW.

It was experimentally determined that a full protection of the remelting area is ensured by argon gas flow rate of 20 l/min through a circular nozzle with a diameter of 12 mm, which is directed opposite to the direction of the laser beam movement. After remelting and alloying the samples were machined by removing the dirty surface layer containing rests of the BN powder. Metallographic examination of the structures of the material after laser remelting were carried out on a light microscope LEICA MEF4A at magnifications in the range between 100 - 1000 times. Microstructure investigations and thickness measurement of the surface layer were also performed on samples in the scanning electron microscope SEM at magnifications in the range between 1000 - 5000 times. For thickness measurement of the obtained surface layer each a computer image analysis software was applied supplied by Leica.

For surface preparation the standard metallographic procedure was applied in form of grinding using SiC 220, 500, 800 and 1200, polishing with 1 μm Al_2O_3 polishing paste 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.

Structure investigation was performed using the light microscope Leica MEF4A supplied by Zeiss in a magnification range of 50 - 500 x. The micrographs of the microstructures were made by means of the KS 300 program using a digital camera.

Hardness measurements results were registered for each remelting area, for this reason the Rockwell hardness tester supplied by Zwick was used according to the PN-EN ISO 6507-1 standard, by a load of 147.2 N for 15 s.

Table 1.
Properties of boron nitride powder BN

Powder	Grain size, μm	Melting temp., °C	Density, kg/m^3	Structure
BN	10	3000	2.25	regular

Table 2.
HPDL laser parameters, applied for the surface treatment

Parameter	Value
Laser wave length, nm	940 ± 5
Peak 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/cm²	0.8-36.5
Dimensions of the laser beam focus, mm	1.8 x 6.8

3. Results and discussion

Preliminary investigations of the remelted hot work tool steels X40CrMoV5-1 and 32CrMoV12-28 show a clear effect of the laser power respectively 1.2, 1.6, 2.0 and 2.3 kW on the shape and thickness of the remelted material. It can be seen that with the increasing laser power the roughness of the remelted metal surface increases. The layers are showed on Fig. 2.

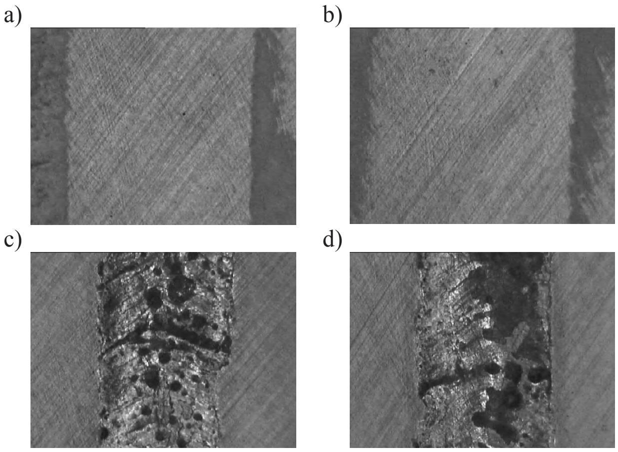

Fig. 2. Shape of the laser tray of the 32CrMoV12-28 steel remelted with BN powder, laser power a) 1.2 kW, b) 1.6 kW, c) 2.0 kW, d) 2.3 kW, mag. 10x

The obtained samples after alloying and remelting reveals a flat shape of the alloyed face, without partially melted areas in the heat affected zone and relatively high smoothness. On the laser path formed during the laser alloying of the surface layer there are a few surface irregularities which occur due to the intense heating. The main decisive factor about creating layers is the transport of material into the liquid metal, caused by surface tension forces. A lack of homogeny heating of the material surface by the laser beam action causes that the formed surface layer reveals a high surface tension gradient. The heat input directed from the center of the beam, where the temperature is highest, causes that the molten material moves to the edges of the remelted material and deposits at the edges of the remelting path. The increase of the laser power and thickness (Fig. 11) of the coating on the steel surface before remelting at a constant feed rate of the laser beam causes an increase of the surface roughness and irregularity of the shape of the laser path face. This effect is associated with an increase in the absorption of laser radiation by the surface of the sample, due to the higher absorption coefficient of the applied carbide ceramic powders compared to the absorption coefficient of the steel surface. The increase in absorption intensity causes an enhancement of the entire laser surface treatment process of the steel surface layer. Obtaining of different thickness of the alloyed surface zones is combined also with the feed rate or with the inorganic polymer binder used for alloying. The binder causes a dynamic evaporation during the alloying process but does not change the chemical composition of the steel surface. A significant role in the remelting and alloying process plays also a shielding gas stream used as a protective layer against the oxidation process of the liquid steel in contact with air before removing the inorganic binder.

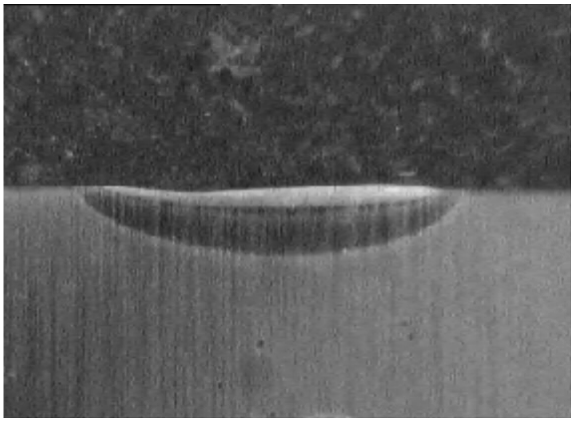

Fig. 3. Shape of cross-section of the laser remelted samples of 32CrMoV12-28 with laser power 2.0 kW, mag. 200x

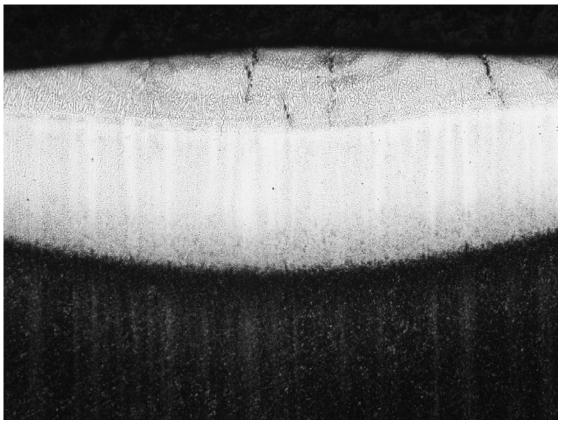

Fig. 4. Shape of cross-section of the laser remelted samples of X40CrMoV5-1 with laser power 2.0 kW, mag. 50x

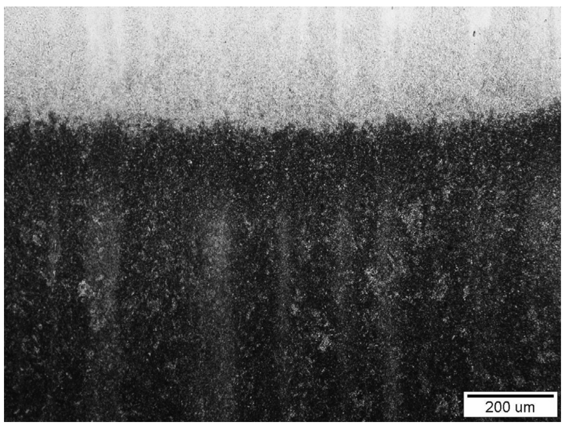

Fig. 5. Structure of the laser remelted samples of X40CrMoV5-1 with laser power 2.0 kW

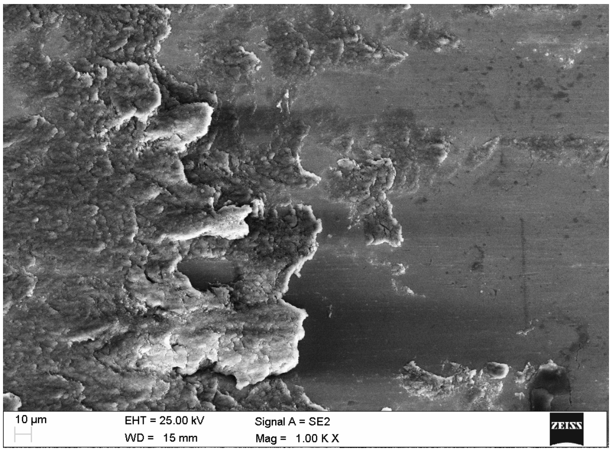

Fig. 6. Surface of the X40CrMoV5-1 sample after wear resistance test, laser power 1.2 kW

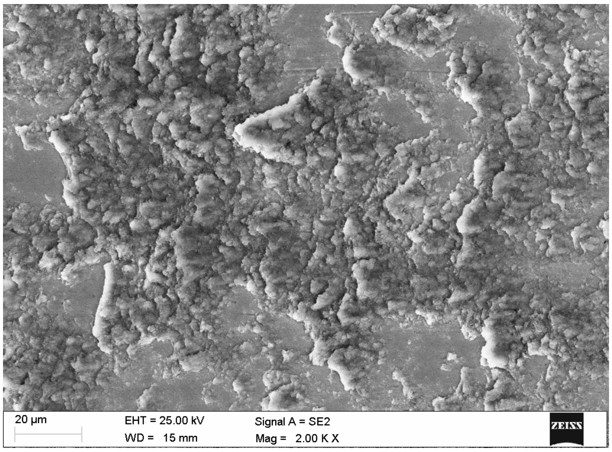

Fig. 7. Surface of the X40CrMoV5-1 sample after wear resistance test, laser power 2.3 kW

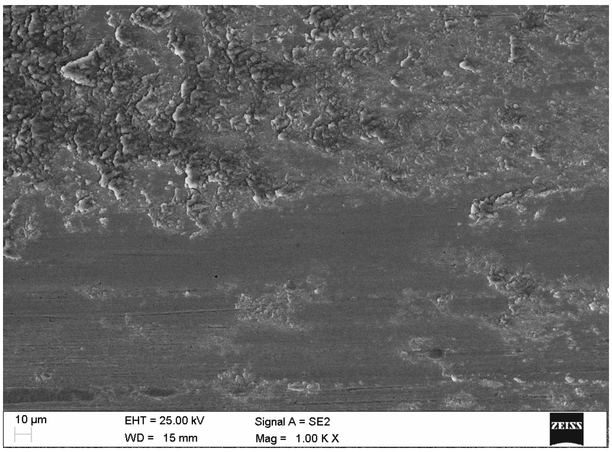

Fig. 8. Surface of the 32CrMoV12-28 -1 sample after wear resistance test, laser power 2.3 kW

Fig. 9. Structure of the laser remelted samples of 32CrMoV12-28, laser power 2.0 kW, mag.200x

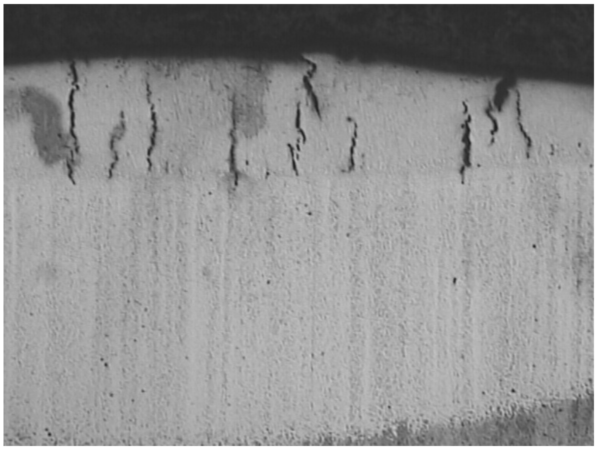

Fig. 10. Structure of the laser remelted samples of 32CrMoV12-28, laser power 2.3, mag. 50x

Microstructures presented on Figures 5, 9 and 10 reveals a dendritic structure in the remelted area. There is a clear relationship between the employed laser power and the dendrite size, namely with increasing laser power the dendrites are larger.

The hot work tool steel has a ferritic structure with homogeny distributed carbides in the metal matrix in the annealed state. After tempering martensitic structure is achieved, in the martensite are dissolved the alloyed additives, which is confirmed by the chemical EDX analysis. The required hardenability for this tool steel was achieving after a suitable tempering time, which assures alloying of the added carbides in the austenite. The structural investigations carried out using the high power diode laser allows to compare the surface layer as well as the shape and depth of the remelting area.

It was noticed that the depth of remelting area grows together with the increasing laser power, which was confirmed by the results presented on Figs. 3 and 4. It can be state, that in case of BN powder the difference of the remelted area thickness among the power of 1.2 kW and 2.3 kW is about 20% larger for the 2.3 kW power. Figure 11 shows the hardness measurements results of the remelted surface for 1.2, 1.6, 2.0 and 2.3 kW laser power, this relation is valid for both types of steel, between them there are only small differences. The highest hardness value is achieved for the 2.0 kW laser power in case of the X40CrMoV5-1 steel, and 2.3 kW laser power for the 32CrMoV12-28 steel. The smallest hardness value is noticed for the 1.2 kW laser power, for both types of steel. The differences are caused, by a slightly higher carbon content, responsible for martensitic structure occurrence, which has much higher hardness compared to bainite.

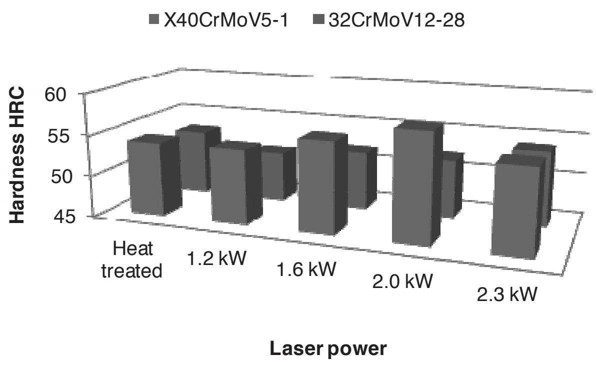

Fig. 11. Hardness measurements results of the remelted surface of X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels

The metallographic investigations on light microscope and electron scanning microscope show, that the structure of the material surface layer after the wear test can be characterized by a differentiation of the structure, which depends on the wear mechanism occurred during the chosen wear conditions. On Figs. 6-8 there are presented chosen areas, which reveals different structures, which can be compared to the possible mechanisms like abrasion wear, micromachining or ridging. In the first steep there occurs smoothing of the surface, than scuffing together with scratch building and micromachining. All possible wear mechanism are presented in Table 3. In Figs. 12-19 there are presented the wear profiles according to the steel type and laser power, with the maximal wear depth presented in Fig. 20.

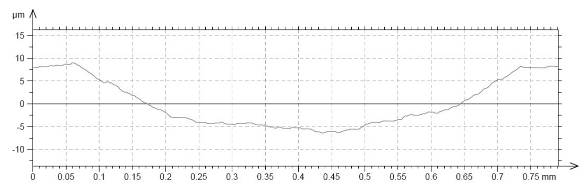

Fig. 12. Wear resistance investigation profile of the X40CoMoV5-1, remelted with 1.2 kW laser power

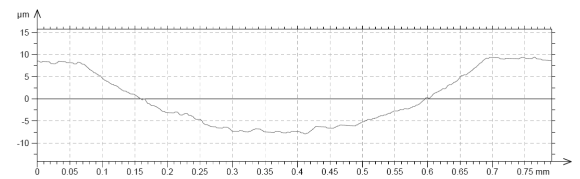

Fig. 13. Wear resistance investigation profile of the X40CoMoV5-1, remelted with 1.6 kW laser power

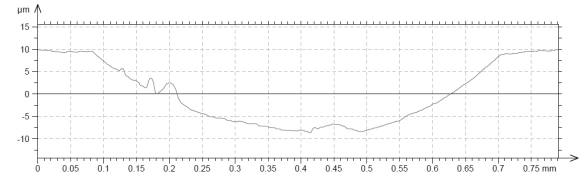

Fig. 14. Wear resistance investigation profile of the X40CoMoV5-1, remelted with 2.0 kW laser power

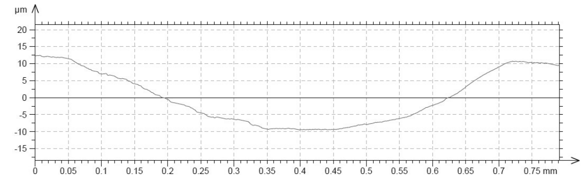

Fig. 15. Wear resistance investigation profile of the X40CoMoV5-1, remelted with 2.3 kW laser power

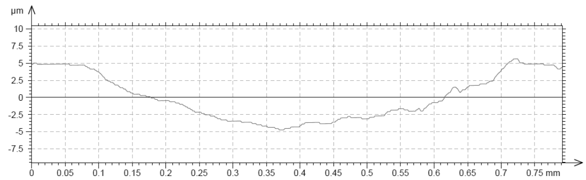

Fig. 16. Wear resistance investigation profile of the 32CoMoV12-28, remelted with 1.2 kW laser power

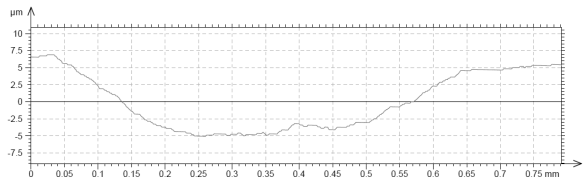

Fig. 17. Wear resistance investigation profile of the 32CoMoV12-28, remelted with 1.6 kW laser power

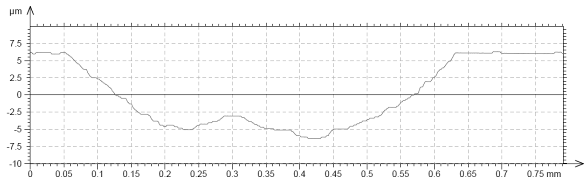

Fig. 18. Wear resistance investigation profile of the 32CoMoV12-28, remelted with 2.0 kW laser power

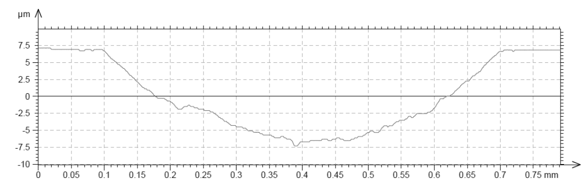

Fig. 19. Wear resistance investigation profile of the 32CoMoV12-28, remelted with 2.3 kW laser power

Table 3.
Basic tribological wear processes

Elementary tribological processes					
Material loss	Material transfer	Material discontinuities	Built-up edges	Geometric structure changes of the surface	Chemical composition changes
micromachining, separation of discontinuities, brittle break-off, spalling.	scratches, polishing, indentation.	scratches on the surface, deep cracking.	counter bodies, oxide layers, sedimentation.	deformation, directed structure deformation, phase transformations.	new compounds, surface oxides.

Surface fatigue often begins materials which are used for production of moulds or stamps due to soft or hard particles, occurred in the area between the mould and the treated material. This creates a stress riser occurred on the surface. Repeat high loading and stress reversals on the created berm or particles causes surface fatigue and eventually pits form. This leads to larger pits and finally even to spalls. On Figs 6 to 8 there can be recognized a different character of the surface structure after the wear test, where on fig 8 the structure seems to be caused by soft particles, whereas on Fig. 7 hard particles coming from the ceramic BN powder were responsible for this type of surface structure. On Fig. 6 there is visible a mixed character of the wear surface partially caused by soft as well as hard particles - the BN powder grains.

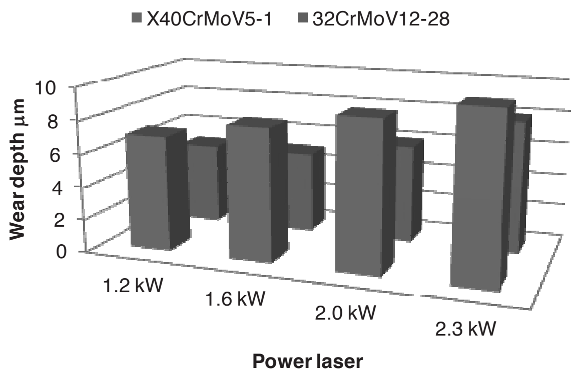

Fig. 20. Maximal wear depth of the remelted surface of X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels

4. Conclusions

The performed investigations allow to conclude, that as a result of heat-treatment as well as of remelting of the hot work steels X40CrMoV5-1 and 32CrMoV12-28 with BN powder high-quality top layer is possible to obtain. 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. Together with increasing of the laser power, also the depth of remelting material grows. The surface of the remelted area is more regular, less rough and more flat with increasing laser power. The metallographic investigations on scanning microscope using EDX analysis does not confirm the occurrence of boron nitride (BN) as well as other boron containing phases, on the other hand the available technique is not sensitive enough to detect the occurrence of boron in the steel matrix.

Based on observations on the variability of torque transients, the roughening of surfaces, and the formation of third-body layers, the sequence of stages undergone during the course of testing for metallic alloys can be summarized as follows:

1. Maximal wear depth increases according to the laser power increase, so the highest wear resistance is achieved for the lowest laser power of 1.2 kW.
2. High initial contact stress causing a disruption of any initial lubricious oxide films that formed under ambient conditions, and during heat-up, progressive scuffing, and the rapid wear-in of one or both surfaces to produce third-bodies.
3. Agglomeration and development of layers of mixed oxide particles and wear debris.

Acknowledgements

The author will express his great thanks to colleagues of the Division of Structure Studies, Institute of Materials Science, Faculty of Computer and Materials Science, University of Silesia, Katowice for scientific support in elaboration of this work.

References

[1] L.A. Dobrzański, E. Jonda, K. Labisz, Comparison of the abrasion wear resistance of the laser alloyed hot work tool steels, Archives of Materials Science and Engineering 55/2 (2012) 85-92.

[2] K. Labisz, T. Tański, D. Janicki, HPDL energy absorption on anodised cast Al-Si-Cu alloys surfaces during remelting, Archives of Foundry Engineering Special 2 (2012) 45-48.

[3] L.A. Dobrzański, E. Jonda, W. Pakieła, M. Bilewicz, Improvement of wear resistance of the hot work tool steel by laser surface feeding with ceramic powders, Archives of Materials Science and Engineering 60/2 (2013) 64-71.

[4] L.A. Dobrzański, E. Jonda, Influence of diode laser alloying on properties and structure of the surface layer structure of hot work tool steel, Proceedings of the National Scientific Conference 6/2013 Spała, 2013, 665-668 (in Polish).

[5] T. Tański, K. Labisz, J. Domagała-Dubiel, Laser modification of light alloys surface layer, Welding Cher's and Division Symposium entitled Modern applications of welding technologies (2012) 296-303 (in Polish).

[6] K. Labisz, T. Tański, L.A. Dobrzański, HPDL laser alloying of heat treated Al-Si-Cu alloy, Journal of Archives of Materials Science and Engineering 54\1 (2012) 13-21.

[7] K. Labisz, M. Krupiński, T. Tański, TEM microstructure investigations of aluminium alloys used for laser alloying, Journal of Achievements in Materials and Manufacturing Engineering 55/2 (2012) 734-741.

[8] T. Tański, K. Labisz, J. Domagała-Dubiel, Laser modification of the light alloys surface layer, Proceedings of theWelding Cher's and Division Symposium entitled Modern applications of welding technologies "The bonding", 1/19 (2013) 20-22.

[9] T. Tański, K. Labisz, Surface treatment influence on properties of the heat treated light cast alloys, Proceedings of the 2nd International Conference on Recent Trends in Structural Materials COMAT 2012, 2012.

[10] T. Tański, K. Labisz, W. Pakieła, M. Bonek, The structure of aluminium alloys-dopped silicon, Proceedings of the 18th International PhD. Students` seminar, Semdok 2013, 52-55.

[11] A. Klimpel, High power diode laser in welding. Welding review 8, Warszawa, 1999 (in Polish).

[12] S. Yahong, H. Satoshi, Y. Masato, U. Hitoshi, T. Hironobu, Fatigue behaviour and fractography of laser-processed hot work tool steel, Science Direct 73 (2004) 128-134.

[13] L.J. Yang, Wear coefficient of tungsten carbide against hot-work tool steel disc with two different pin settings, Science Direct 257 (2004) 234-240.

[14] K. Dae-Hwan, H. Seong-Hyeon, K. Byoung-Kee, Fabrication of ultrafine TaC powders by mechanochemical process, Materials Letters 58/30 (2004) 87-92.

[15] B. Kosec, M. Brezigar, G. Kosec, J. Bernetic, M. Bizjak, Heat treatment of cold formed steel forgings for the automotive industry, Journal of Achievements in Materials and Manufacturing Engineering 22 (2007) 87-90.

[16] M. Hamedi, Optimizing tensile strength of low-alloy steel joints in upset welding, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 341-344.

[17] J. Kusiński, J. Przybyłowicz, S. Kąc, A. Woldan, Structure and properties change In case of laser remelting of surface layers and coatings, Hutnik (1999) 14-20 (in Polish).

[18] X. Changqing, J. Yucheng, Y. Guangli, Effect of a single peak overload on physically short fatigue crack retardation in an axle-steel, International Journal of Fatigue 19 (1996) 201-206.

[19] S. Rusz, L. Cizek, P. Filipec, Evaluation of fatigue of micro-alloyed 23MnB4 steel, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 223-226.

[20] R. Filip, Laser nitriding of the surface layer of Ti6Al4V titanium alloy, Archives of Materials Science and Engineering 30/1 (2009) 25-28.

[21] J. Kusiński, Laser Applications in Materials Engineering, WN „Akapit", Cracow, 2000 (in Polish).

[22] E. Kennedy, G. Byrne, D.N. Collins, A review of the use of high power diode lasers in surface hardening, Journal of Materials Processing Technology 155-156 (2004) 1855-1860.

[23] A. Lisiecki, A. Klimpel, Diode laser surface modification of Ti6Al4V alloy to improve erosion wear resistance, Archives of Materials Science and Engineering 32/1 (2008) 5-12.

[24] Y.S. Tian, C.Z. Chen, D.Y. Wang, Q.H. Huo, T.Q. Lei, Laser Surface Alloying of pure titanium with TiN-B-B-Si-Ni mixed powders, Applied Surface Science 250 (2005) 223-227.

[25] A.D. Dobrzańska-Danikiewicz, T. Tański, J. Domagała-Dubiel, Unique properties, development perspectives and expected applications of laser treated casting magnesium alloys, Archives of Civil and Mechanical Engineering 12 (2012) 318-326.

[26] Y. Issshiki, K. Mizumoto, M. Hashimoto, Synthesis of iron - tungsten alloy on mild steel by Laser Surface Alloying, Thin Solid Films 317 (1998) 468-70.

[27] A. Klimpel, L.A. Dobrzański, D. Janicki, A. Lisiecki, Abrasion resistance of GMA metal cored wires surfaced deposits, Journal of materials processing technology 164/165 (2005) 1056-1061.

[28] A. Lisiecki, A. Klimpel, Diode laser gas nitriding of Ti6Al4V alloy, Archives of Materials Science and Engineering 31 (2008) 53-56.

[29] A. Lisiecki, Welding of titanium alloy by different types of lasers, Archives of Materials Science and Engineering 58/2 (2012) 209-218.

[30] J. Turek, S. Okoński, W. Piekoszewski, Studies of abrasive wear resistance pf padding welds and hot-work tool steels for forging dies, Ductile Metal Forming 23/1 (2012) 39-44 (in Polish).

[31] G. Gajowiec, Assessment of the impact melt laser parameters from cryogenic to the structure of the surface layer of the Ti-Al-4V alloy, Advances in Materials Science 81/15 (2008) 44-51 (in Polish).

[32] J. Dutta Majumdar, I. Manna, Laser material processing, International Materials Rewievs 56/5-6 (2011) 341-388.

[33] A. Lisiecki, D. Janicki, A. Grabowski, K. Gołombek, Properties of composite Ti/TiN layers produced by in situ method with high power diode laser, Bulletin of Welding Institute 1 (2013) 23-29 (in Polish).