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Microstructure and properties of the hot work tool steel gradient surface layer obtained using laser alloying with tungsten carbide ceramic powder

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ABSTRACT

Purpose: The aim of the paper is to present the innovatory investigation results of the impact of laser treatment consisting of multiple remelting and alloying using tungsten carbide ceramic powder on the microstructure and properties of hot work tool steel X40CrMoV5-1 surface layer.

Design/methodology/approach: Laser heat treatment allows the production of gradient surface layer with a thickness reaching from of tenths of a millimetre even to few millimetres with specific functional properties, including high hardness and abrasion resistance, while maintaining the properties of the substrate material.

Findings: Preliminary investigations of the effects of laser radiation on steel surface have showed, that in the surface layer there occur changes concerning the microstructure as well as in the chemical composition different from those occurring during conventional heat treatment.

Research limitations/implications: There was determined the effect of laser power on the remelting depth, the depth of the heat affected zone and the width of the laser tray face. There was also measured and compared to the hardness and roughness of the steel processed by remelting with different process parameters.

Practical implications: The current application areas for hot work tool steels are constantly growing, and the intensive development of techniques requires the use of new technologies, what leads to production of specific surface layer on materials, in order to meet the extremely difficult working conditions of modern tools.

Originality/value: The effect of a HPDL laser melting on the hot work tool steel, especially on their structure and hardness has been studied.

Keywords: Diode laser surface treatment; Multiple alloying; Hot work tool steels; Ceramic powders; Gradient layer

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MANUFACTURING AND PROCESSING

1. Introduction

In this work there is presented a laser treatment technique including the remelting of hot work tool steel X40CrMoV5-1 with ceramic carbide WC powder. The structure investigation and improvement of mechanical properties is an aim of this work; because the improvement of hardness of the surface layer is a very important factor for practical use. A grate number of the engineering applications requires a surface layer which is very hard and strong, with a high wear-resistant, but on the other hand has relatively soft interior structures contributing a proper ductility. Laser coatings are surfaces that have excellent metallurgical bonding to the matrix material. Diode lasers are used for surface preparation for producing of layers that have uniform composition and thickness with an extremely dense, crack-free and nonporous structure [1-5]. They are increasingly found in applications such as materials processing (welding, cutting, drilling, surface hardening, etc.) as well as in printing and graphical arts, in displays, and medical applications [6-13].

The purpose of this work is to study the effect of a HPDL laser melting on the hot work tool steel, 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.

2. Material and experimental procedure

2.1. Hot work tool steel

Investigations were carried out on test pieces from the X40CrMoV5-1 hot work high-speed tool steel with the compositions according to PN-EN ISO 4957:2004 standard. Chemical composition of the steels are given in Table 1.

Table 1.
Chemical composition of the investigated tool steel

Steel grade	Mass concentration of the elements, %								
	C	Mn	Si	Cr	W	Mo	V	P	S
X40Cr MoV5-1	0.41	0.44	1.09	5.40	0.01	1.41	0.95	0.015	0.010

Laser surface alloying was conducted by remelting of steel surface and multiple alloying of hard carbide particles. The alloying materials was WC powder (Table 2). The laser alloying was performed by high power laser diode HPDL Rofin DL 020 under an argon shielding gas. Argon was used during laser remelting to prevent oxidation of the coating and the substrate. The process parameters during the present investigation were: laser power 1.2, 1.6, 2.0 and 2.3 kW, scan rate 0.5 m/min.

Table 2.
Properties of the ceramic powder used for alloying

Properties	WC
Hardness, HV	2600
Density, kg/m^3	15.6
Melting temperature, °C	2770
Grain size, μm	5

2.2. HPDL laser device

For alloying the HPDL laser Rofin Dl 020 (Figs. 1 and 2) was used with the working parameters showed in Table 3. The samples were mounted in the laser holder for remelting. The constitution of the samples surface layer was carried out using two types of processes, in both cases, the laser path length of the remelting area at the sample surface was equal 25 mm.

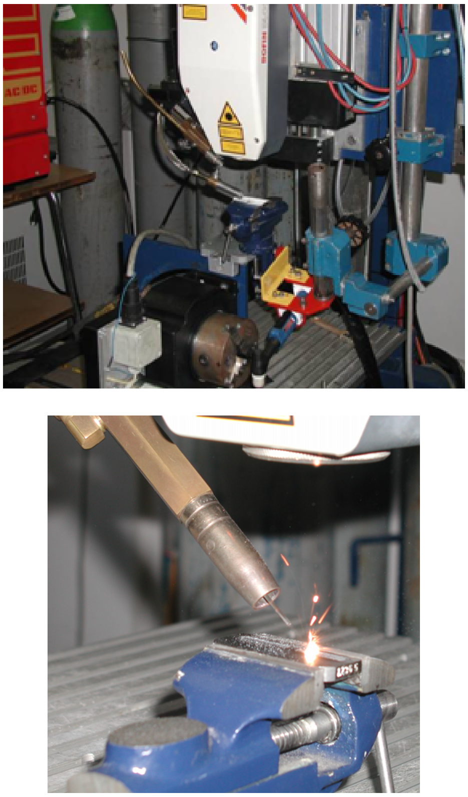

Fig. 1. HPDL laser Rofin Dl 020 used for remelting and alloying of the hot work tool steel samples

Table 3.
HPDL laser parameter

Laser radiation wavelength, nm	808±5
Laser beam output power (continuous wave), W	2300
Power range, W	100-2500
Laser beam focal length, mm	82/32
Laser beam spot dimensions, mm	1.8×6.8
Power density range in the laser beam plane, kW/cm^2	0.8-36.5

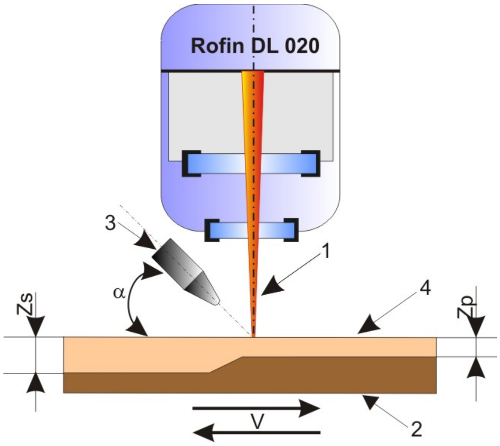

Fig. 2. Working scheme of the HPDL laser Rofin Dl 020, 1) laser beam, 2) sample, 3) powder supply, 4) surface layer, Zp) remelted zone, Zs) heat influence zone, v) laser beam velocity

It could be set experimentally, that the fully protection of the remelted place can be achieved by mind of an argon protective atmosphere with a gas flow rate of 20 l/min through a round nozzle with a diameter of 1 mm, which was directed inversely to the remelting process direction.

There were performed four alloying processes with the appliance of combinations of diverse laser power, where the parameter sequence of each the used alloying processes is presented in Table 4.

Table 4.
Alloying carried out for paste layer thickness of 0.05 mm and 0.10 mm

Thickness of the put on WC paste film, mm	0.05				0.10			
Process description	A1	A2	A3	A4	B1	B2	B3	B4
Laser power, kW	2.3 2.0	2.0 1.6	1.6 1.2	2.3 1.2	2.3 2.0	2.0 1.6	1.6 1.2	2.3 1.2

For surface preparation the standard metallographic procedure was applied in form of grinding using SiC papers 220, 500, 800 and 1200 size, polishing with 1 µm Al_2O_3 paste and drying, the samples were mounted in thermo hardened resin supplied by Struers. Than the samples were etched in Nital at room temperature for the experimental chosen time individual for each remelted tray.

Metallographic examinations were made on the Leica MEF4A light microscope equipped with the Leica-Qwin computer image analysis system at magnifications of 100-1000x. The Leica-Qwin computer image analysis system was used for thickness examination of the particular zones of the surface layer and for measurement of areas of grains. The observation were prepared perpendicularly to the cross section of the sample on the each remelted tray. Depth measurements of the remelting zone (RZ), the heat affected zone (HAZ) and the width of the laser path face were performed according to the scheme shown in Fig. 3.

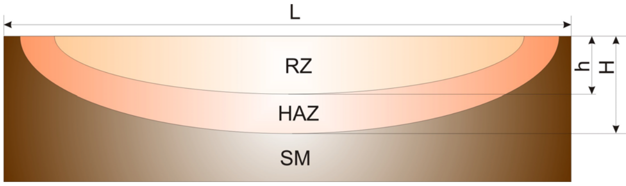

Fig. 3. Size of the samples; L - width of the laser path face, h - depth of the laser path face (RZ), H - depth of the heat affected zone (HAZ), MR - substrate material-steel X40CrM0V5-1

Roughness measurements were carried out using a Surtronic 3+ profilometer supplied by Taylor-Hobson. The surfaces of the specimens were cleaned, and then arithmetic mean deviation of the profile R_a (µm) were measured.

Hardness tests were made on specimens subjected to the standard heat treatment and remelted and alloyed using the high power diode laser at various parameters, making 10 measurements for each condition and calculating their average value. Test results were analysed statistically. Hardness was measured on the ground and buffed front surfaces of specimens. on the hardness tester supplied by Zwick ZHR 4150TK, according to the standard PN-EN ISO 6508-1:2007 in the mode “loading-unloading”.

3. Investigation results

Based on observations of the surface layer face of the steel X40CrMoV5-1 it has been found that after laser remelting the surfaces of the samples are smooth and regular (Figs. 4-5). In case of appliance for laser alloying of a sequence respectively 2.3 and 1.2 kW, there occurs microcracks and cracks on the sample surface caused by dissolving tungsten carbide in the steel surface layer, as well as locally surface irregularities and depressions, caused by its intense heating during alloying. In the other samples there also could be found small cracks. As a result of laser remelting with a laser beam with lower power the obtained surface layer is smooth, there is no surface damage in form of local depressions, undercuts, or they just appear very locally only in small areas. The surface structure of the treated layer after remelting depends clearly on the laser power, while the thickness of the obtained coating of tungsten carbide, does not affect the surface structure of the layer of the laser remelted steel. With increasing laser power there occurs an increase in irregularity of the edges of the laser path face.

The microstructure of the X40CrMoV5-1 steel solidifying after the alloying with tungsten carbide is characterized by areas containing different morphological features, what is associated with the crystallization of steel. The rapid solidification of the material causes the 'freezing' of the structure, which leads to the presence of several distinct zones in the laser alloyed material (Figs. 6a,b), with the thickness and width dependent on the used laser processing parameters. The laser remelted area has a structure of dendritic grains (Figs. 7a,b), which is associated with a large temperature gradient and caused additionally by the rapid and directional heat transfer from the melted zone. Micro-dendrite arms are arranged at an angle of 90° to the main dendrite axis. The space between the crystals is filled by eutectic with carbides. At the bottom of the remelting zone there was observed the presence of fine crystals was observed, coming into existence as a result of initiation of solidification on non-dissolved carbides and the matrix grains. In all variants of the laser treatment, the structure of the remelted zone consists of dendritic crystals, with a grow direction according to the heat transfer during crystallisation. As a result of remelting with a tungsten carbide film, in the remelted zone there is observed a highly fragmented structure.

With the increase of the laser beam power used for alloying there increase also the thickness of the remelted layer, and the depth of the HAZ. Reducing the power of the laser beam results in a structure revealing more non-remelted tungsten carbide particles with irregular shapes and sizes (Figs. 8 a, b). The remelting laser tray is not flat, with the occurrence of material burrs directed towards to the surface (Fig. 8b). The occurrence of non-remelted carbides is caused due to the fact that the remelting temperature of tungsten carbide of about 2500°C, and is lower than the melting point of steel. The scan time of the laser beam during alloying of the surface was too short to achieve a temperature at which the tungsten carbide could be remelted in the steel matrix. The presence of non-alloyed carbides causes increase of the hardness of the surface layer of remelted steel.

In samples with a thickness of the coated tungsten carbide film of 0.05 mm, there are present in the structure a few isolated carbides, which can be explained by the fact that the laser scan time and the energy delivered to the surface of the sample was sufficient to remelt the powder located on the surface of the sample and fed it by diffusion to the steel structure.

The laser treatment parameters such as laser power and time of a laser beam interacting with the substrate material affects the depth of remelting, and the depth of the heat affected zone in case of the X40CrMoV5-1 tool steel (Table 5). The higher the laser power used for alloying, the higher the remelting depth, and therefore the higher the depth of the heat affected zone. If there are used smaller beam powers for laser alloying, the remelting trays are more regular, with a semi-circular shape with a uniform remelting depth. As a result of increasing the power of the laser beam remelting laser trays becomes corrugated with variable depth, which is caused by the intense heat convection movements in the liquid metal pool.

Table 5.
Remelting depth of the heat affected zone and width of the laser tray face after laser alloying using different laser power in the range from 1.2-2.3 kW

Process description	Remelting depth, mm	SWC depth, mm	WW depth, mm	Laser face width, mm
A1	0.81	1.77	2.59	9.24
A2	0.64	1.68	2.33	9.11
A3	0.34	1.18	1.53	7.69
A4	0.79	1.81	2.60	8.21
B1	0.94	1.61	2.56	8.76
B2	0.57	1.59	2.16	8.52
B3	0.63	1.20	1.84	7.97
B4	0.95	1.81	2.76	8.71

The roughness measurement results of the surface layers of the X40CrMoV5-1 steel obtained as a result of laser alloying is in the range of R_a=10.3-15.5 µm. The maximal surface roughness of R_a=15.5 µm was obtained using the following sequence of laser alloying: 2.3 kW and 2.0 kW laser power, with the tungsten carbide coating thickness of 0.05 mm, while the minimum surface roughness of R_a=6.62 µm was obtained on the sample surface obtained as a result of alloying with the laser power sequence: respectively 2.3 kW and 2.0 kW laser power, with the tungsten carbide coating thickness of 0.10 mm (Fig. 9).

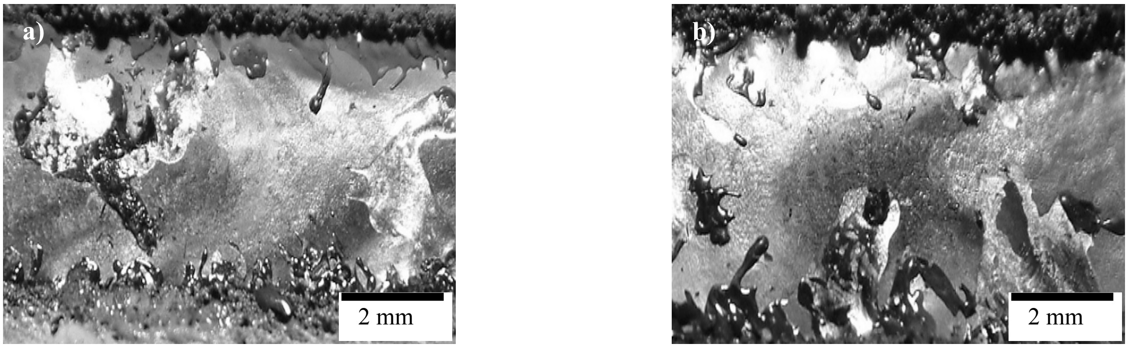

Fig. 4. Surface structure of the laser path of the X40CrMoV5-1 steel after laser remelting with HPDL laser according to the process parameters: a) A1, b) A2, thickness of the put on WC paste coating 0.05 mm

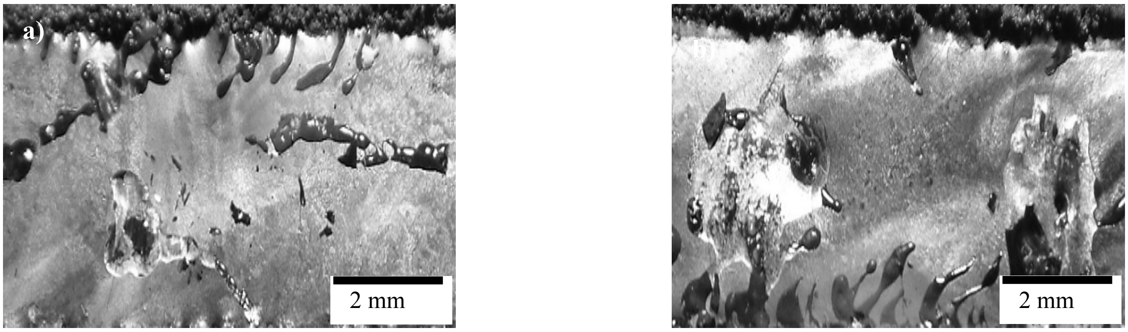

Fig. 5. Surface structure of the laser path of the X40CrMoV5-1 steel after laser remelting with HPDL laser according to the process parameters: a) B3, b) B4, thickness of the put on WC paste coating 0.1 mm

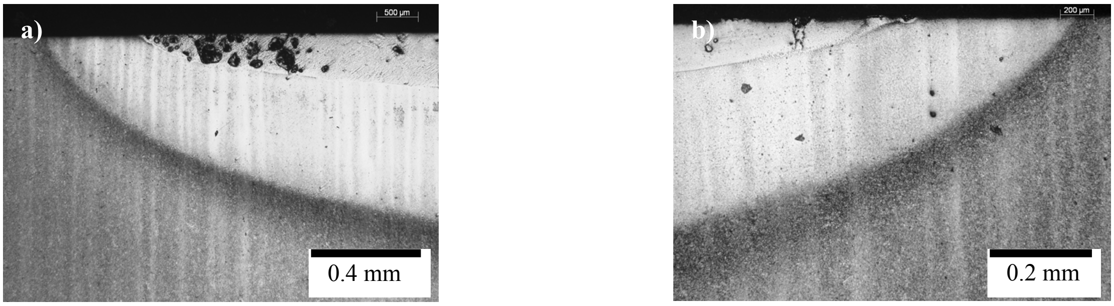

Fig. 6. Structure of the X40CrMoV5-1 steel surface after WC alloying: a) laser power 2.3/2.0 kW, WC layer thickness 0.10 mm, b) laser power 1.6/1.2 kW, WC layer thickness 0.05 mm

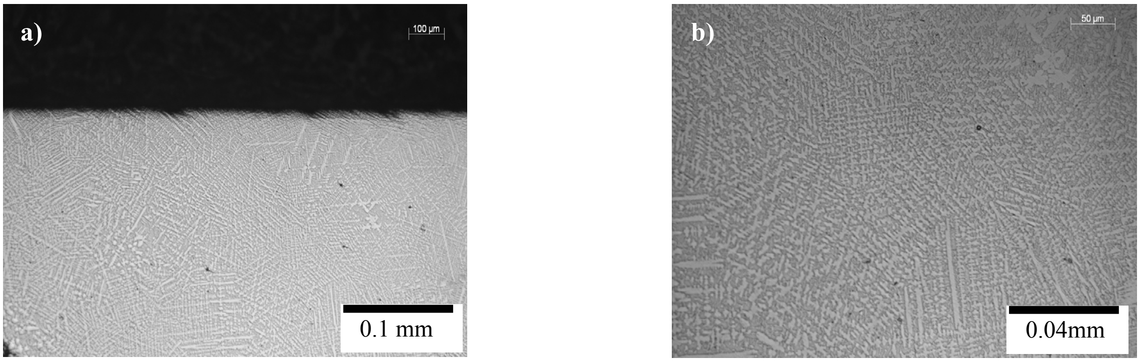

Fig. 7. Structures of the X40CrMoV5-1 steel laser alloyed with WC powder, laser power 2.3/2.0 kW, WC layer thickness 0.10 mm

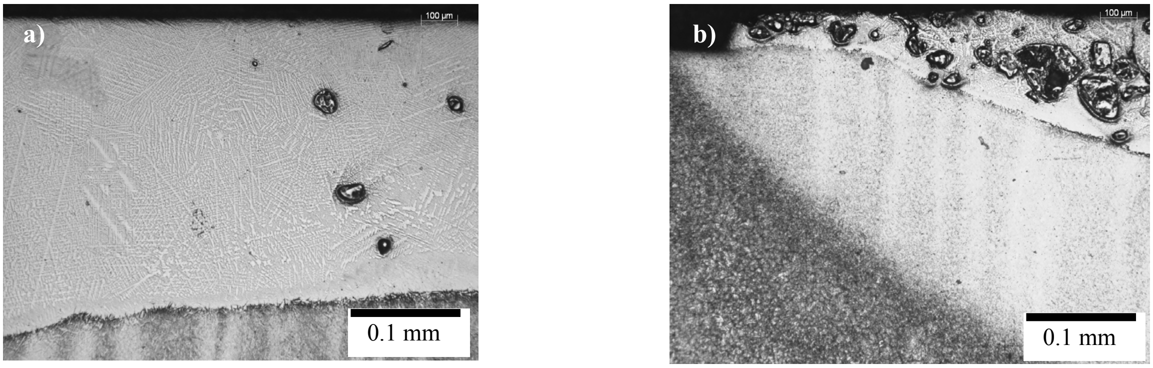

Fig. 8. Structure of the X40CrMoV5-1 steel after laser alloying with WC powder, a) laser power 2.3/2.0 kW, WC laser thickness 0.15 mm, b) laser power 1.6/1.2 kW, WC layer thickness 0.15 mm

The optimal solution in terms of the surface roughness is the appliance of tungsten carbide layer with a paste layer thickness of 0.10 mm and higher laser powers used for the subsequent alloying of the sample. This arrangement results in a laser surface alloying roughness and good quality, what is important, because the increase in surface roughness is a disadvantage of this type of laser treatment, which creates the need for additional finishing of the treated material.

Based on the performed investigations it was found that the hardness of the laser alloyed X40CrMoV5-1 steel surface layer is affected both by the impact of laser power used for alloying, and the thickness of the tungsten carbide film coating put on the surface (Fig. 10). With increasing thickness of the tungsten carbide film there increases the hardness, where the relationship is linear in this case. This is due to the fact that the non-dissolved hard tungsten carbide particles is in the surface layer of the steel, has a huge influence on the hardness.

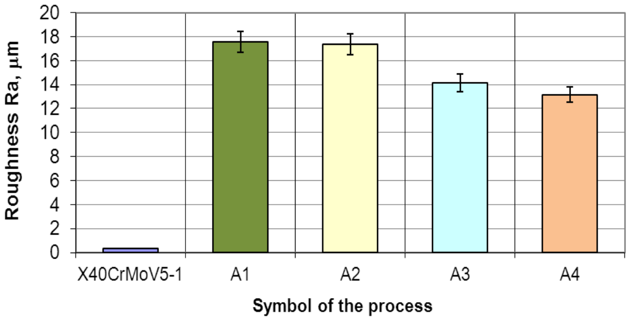

Fig. 9. Comparison of surface roughness of the investigated samples after laser remelting, WC film thickness - 0.05 mm

During the observation of the obtained microstructures it was found that during the remelting of the samples with a laser beam power with sequence respectively 2.3 and 1.2 kW in the steel microstructure there are numerous cracks with a large opening angle as well as microcracks. Such cracks are unacceptable, as they may constitute the beginnings of fatigue cracks.

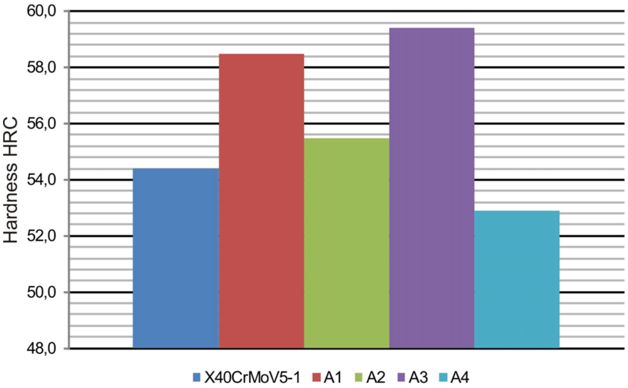

Fig. 10. Comparison of hardness of the surface layer, obtained after laser alloying as well as after standard heat treatment of the X40CrMoV5-1 steel

These cracks can be caused by not properly chosen parameters for the remelting process, discontinuity of the applied protective argon atmosphere, or become due to rapid cooling of the material. In the so carried out melting process, there was also found a decrease of hardness below the typical value for the X40CrMoV5-1 steel achieved by the conventional heat treatment (Fig. 10). In the other microstructures there are also present microcracks and cracks, but their number, size and range are small.

The impact of external positive factors and negative factors (difficulties) on the specific technologies is crucial for the environment influence, in consistency with the proposed concept, each of the processes illustrates the most favourable external situation ensuring the future success. It can provide a chance for steady progress, corresponds to a neutral environment where the success of a technology is risky but feasible. There are some expectations that technology development is difficult or unachievable, however the results of positive or negative environment influence on the individual groups of technologies show that the environment for all the investigated multiple alloying processes is very supportive, bringing diverse opportunities and few difficulties, hence all the analysed groups of processes were classified according to their development. Again, the group of technologies was given the highest rank and the lowest was given to the group of technologies corresponding to laser treatment in the process.

The strategy consists in developing, strengthening and implementing an attractive technology with a large potential in the industrial practice to achieve a spectacular success. The results reveals very good development prospects for the technologies of laser surface treatment of tool steels using tungsten carbide and the technologies are discussed in other works of the authors [1-12].

4. Expected applications of laser treated hot work tool steel

The investigated hot work tool steel and their treatment technology, also alternatively for the surface layers ensuring the most favourable quasi-gradient properties on the surface of products, can be used in the industrial practice, especially in the foundry industry where a small product weight is required, higher wear resistance, enhanced strength properties of components as well as ability to repair finished parts. As legislation on restricting environmental pollution made it mandatory to reduce the weight of forging tools, this has spurred an intensive interest in tool steel It is essential to reduce the wear resistance and increase to tool life more and more but also functional attractiveness. Steel has been applied in the foundry industry more and more widely in the recent decade for such parts as dies, stamps, moulds.

The optimisation of chemical composition and manufacturing conditions of production, casting and heat treatment of tool steels, due to the most favourable set of mechanical properties and resistance to corrosion based on an analysis of precipitation processes and phase changes occurring in the tested materials while cooling them are the measures improving their mechanical and functional properties. Harder surface more corrosive to resistance are usually produced by obtaining a fine-crystalline structure in the conditions largely deviating from balance. It should be stressed though that the advantages of surface laser treatment including shorter process duration, flexibility and precision of manufacturing operations due to a possibility of fine-tuning the process conditions including scanning rate and laser beam power, the type and thickness of the remelting material and the volume of shield gas, are decisive for its effective application and for achieving, gradually, competitive edge over alternative technologies to improve the casting properties of hot work tool steels.

5. Conclusions

The outcomes of the materials science research made show the positive impact of laser surface treatment on the quality and microstructure of the investigated tool steel and a promising improvement in the mechanical and functional properties of the tested material, especially hardness, microhardness and porosity. Laser remelting and alloying with tungsten carbide powders influences the fining of the structure within the entire range of laser power and the different grain size in specific zones of the investigated alloys surface layer. The investigations conducted with the experts' opinions used as reference data point out a very good current strategic position of the technology for the laser surface treatment of tool steel and its extensive development prospects. The expected range of applications for tool steels surface treatment using the high performance diode laser encompasses especially the foundry industry where small product weight is required, wear resistance, good strength properties of components and ability to repair finished parts.

The performed investigations aloud to conclude, that as a result of heat-treatment as well as remelting of the hot work steel X40CrMoV5-1 with WC powder can be possible to obtain high-quality top layer without cracks and defects as well as considerably higher hardness value compared to the non remelted material. In such kind of laser coating, a fine powder, is putting with a carrier paste to the surface of the material to be coated. The powder absorbs energy from the laser beam, starts heating and melting, deposits on the surface of the base 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 the increasing laser power, also the depth of remelting material grows up. Also the surface of the remelted area is more regular less rough and more flat with increasing laser power. In case of

WC alloyed samples there are found some cracks in the surface layer, so this kind of feeding seems to need to extend the investigations, because it cannot be recommended for surface properties improvement, a possible solution of this problem can appear in the appliance of other type of alloying material, addition of some solvents or special surface preparation of the investigated steel, which can lead to obtain more regular smooth surface without crack and discontinuities over the entire laser alloyed tray face.

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