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# Laser modification of surface layer properties of a hot-work tool steel

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**Manufacturing and processing**

## ABSTRACT

**Purpose:** The objective of the present work was to study the modification of the microstructure of hot-work tool steel X40CrMoV5-1 during the surface modifying by means of laser technology.
**Design/methodology/approach:** The initial experiments consisting in alloying the hot work tool steel indicate to the clear influence of the laser power on the run face shape and its depth.
**Findings:** The structure of material solidifying after laser remelting is characteristic of the diversified morphology connected with the repeated changes of the crystals' growth direction, from the small dendrites, whose principal axes are oriented in accordance with the heat removal directions at the boundary between the solid and liquid phases, clusters of carbides arranged in accordance with the swirls caused by the metallic liquid convection motion, and partially non-remelted WC conglomerates as the alloying material in the central area of the remelted zone, to the fine equiaxial grains in the subsurface zone.
**Research limitations/implications:** Laser remelting and alloying with the tungsten carbide results in refinement of the structure in the entire laser power range and in diversification of the grain size in the particular surface layer zones.
**Practical implications:** Laser alloying has the important cognitive significance and gives grounds to the practical employment of these technologies for forming the surfaces of new tools and regeneration of the used ones.
**Originality/value:** The fine grained, dendritic structure occurs in the remelted and alloyed zone with the crystallization direction connected with the dynamical heat abstraction from the laser beam influence zone. The fine grained martensite structure is responsible for hardness increase of the alloyed layer.
**Keywords:** Surface treatment; Tool steel; Alloying; Laser treatment

## 1. Introduction

Tool materials decide many a time the efficiency of the technological processes of metals and other materials, and also reliability of the entire processing lines. Tool reliability becomes the main factor in the face of the progressing mechanization and automation of these processes. Therefore, improvement of the surface layer of the tool steels has to take fully into account the anticipated tool service conditions. On the other hand, it is essential to obtain the required tool properties, with the adequately high reliability, at the possibly lowest costs of tool manufacturing and material used for this purpose [1,2].

The moulding cast allows the performance of a lot of quantity of components with high-level complexity, fulfilling the mechanical specifications required, with a medium-low relative prices. Hot work tool steels are used in many industry branches as the material deciding efficiency, labour demand, and manufacturing process reliability. Tool life is dependant on its quality and, therefore, on the material from which it is made.

Table 1.
Chemical composition of the investigated X40CrMoV5-1 steel

| Average mass concentration of elements, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C | Mn | Si | Cr | W | Mo | V | P | S |
| 0,41 | 0,44 | 1,09 | 5,40 | 0,01 | 1,41 | 0,95 | 0,015 | 0,010 |

Table 2.
Properties of the WC powder

| Average grain diameter, µm | Melting temp., °C | Density, g/cm$^3$ | Hardness, $HV_{30}$ |
|---|---|---|---|
| 20 - 30 | 2730 - 2870 | 15,6 | 1550 |

The appropriate carbon concentration and alloying elements affect directly the structure and phase transformations, occurring during the metallurgical operations and plastic working or heat treatment. The material of our study is steel used to make a lot of components of mechanized work, as dies for moulding cast for example. These steels are employed in hot working and in casting into the metal moulds as material for tools subjected to periodical temperature changes. Service temperature of tools made from the alloyed hot-work tool steels ranges from 250 to 800ºC. Some forging tools and hot setts work at a lower temperature, whereas the drop forging and extrusion dies, as well as pressure die casting moulds work at a higher temperature [1-4]. The design and the service-behaviour of the steel dies are the most important factors in order to achieve the required specifications in moulding cast. These factors not only control the final dimensions and tolerances but even the surface finish. The thermal stresses produced by hot-cooling cycles promotes little cracks which decrease the life of the die [4]. One die costs almost one million dollar and needs from months to years to be made. Improvements in the steel allows to make better final components, but also a longer life of the die. If the die has a longer life, the costs will be lower and also the energy consumption. Many factors influence the designed element's characteristics. Surface layer, and – in fact – its structure and properties play more and more important role. Service properties of many products depend not only of their capability to carry the mechanical loads by the entire element's transverse section. It happens oftentimes that most of the load is taken by the surface layer. Economical considerations also dictate using surface layers which ensure the required service properties, making it possible to use simultaneously the possibly inexpensive materials for the element's core, when lower service properties are required from it. The investigations of surfacing-alloys reveal that the surface treatments and the surface coatings are very good in order to protect the dies against the thermal fatigue and increase the life of the die too. In fact, the surface coatings increase the resistance to abrasion because it provides higher hardness, toughness and corrosion resistance [5,6]. One of this treatments could be laser surface treatment, which allows to modify the properties of the surface of the material without modifying the core of it. Laser radiation features currently the state-of-the-art source of heat energy, used to form structure and properties of the surface layer. There is an opinion that laser manufacturing techniques belong to the most promising and efficient ones, for ensuring the development in many industrial branches and especially those, in which materials processing dominates. Thanks to the very precise energy delivery laser radiation makes it possible to carry out the technological

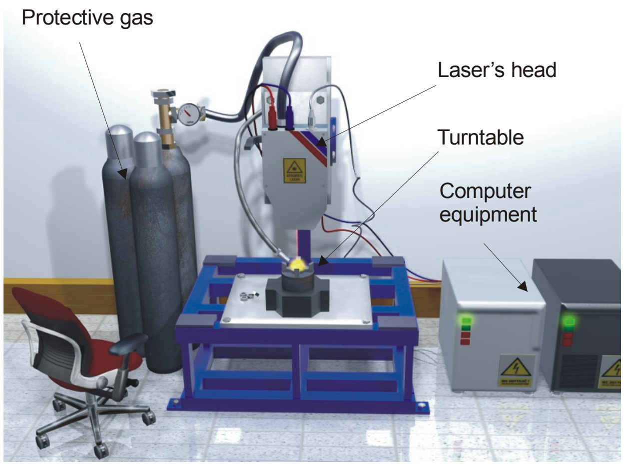


Fig. 1. Schema of the particular parts of the laser alloying laboratory

operations better or faster within the framework of the technologies known to date. It makes also possible introduction of the new technologies whose realisation is impossible when using the conventional power density. These kinds of treatments bring about a very low grain and homogenous microstructure at the surface with a very narrow HAZ (Heat Affected Zone), providing a higher solid solubility of the alloying elements. The resulting surface has very good mechanical properties because the steel is melting and cooling in a very short period of time ($10^4$ – $10^5$ times faster than conventional moulding). The letter bring about composition, distribution of the alloying elements and microstructural changes [3] Employment of the laser surface treatment is justified both from the economical point of view and because the laser treatment, in many cases, ensures obtaining better mechanical properties of the processed surfaces, e.g., teeth of gear wheels or cutting tools edges, which could not be attained using the conventional surface treatment methods. The laser heat treatment includes operations which are conducted using the laser beam as the source of energy needed for heating the surface layer of the processed material, to change its structure for obtaining the relevant mechanical, physical, or chemical properties, improving service life of the processed element [1,2,7-9]. The laser has several unique properties used in heat treatment of materials' surfaces. Part of the absorbed heat energy penetrates inside the material during remelting, which results in a big temperature gradient between the liquid material layer and the matrix. Mixing of the molten metal occurs because of the convection motions during laser treatment with remelting. These motions originate because of the temperature difference between the remelted surface and the bottom of the remelted region, and moreover because of the protective gas blow-in and “pressure” of the laser beam. Quick solidification occurs after remelting and mixing the molten metal due to the big temperature gradient. The obtained results of investigation may be used for the further research on optimisation of the surface layer properties of the hot work tool steels, targeted at obtaining tools with the possibly high mechanical and service properties.

The goal of this work is studying the structural mechanisms and selected properties of the surface layers obtained by the high power diode laser (HPDL) treatment of the hot-work tool steel.

## 2. Experimental procedure

The experiments were made on specimens made from the X40CrMoV5-1 alloyed hot work tool steel (Tab. 1). The investigated steel was molten in the electric vacuum furnace at the pressure of about 1 Pa, cast into ingots weighing about 250 kg, and were roughed at the temperature range 1100-900ºC into the bars 75 O.D. mm, which were soft annealed. After making by machining the O.D. 70 mm and 6 mm thick specimens they were heat treated. The specimens were austenitized on the salt bath furnace and tempered in the chamber furnace in the protective atmosphere – argon. The specimens were gradually heated to the austenitizing temperature with the isothermic stops at 650 and 850°C for 15 min. Further they were austenized for 30 min at the temperature of 1060°C and cooled in hot oil. The specimens were tempered twice for 2 hours at the temperature of 510°C after quenching. Next, powder layers of the WC tungsten carbide (Tab. 2) of two different thicknesses of 0.06 mm and 0.11 mm bounded with the inorganic binding agent were put down onto the degreased specimens. Specimens of the X40CrMoV5-1 steel fixed in a turntable were remelted with the Rofin DL 020 high power laser beam (HPDL) (Fig. 1 and 2). The dimensions of the laser beam focused on the material surface are 1.8 x 6.8 mm. Remelting was carried out perpendicularly to the longer side of the focused beam with the multimode energy distribution, which makes it possible to obtain the wide run face. The working focal length (measured from the protective glass in the head) is 92 mm. The multimode energy distribution was used. It was found out in the preliminary investigations that the maximum feed rate at which the process is stable is 0.5 m/min. Further experiments were carried out at the constant remelting rate, changing the laser beam power in the 0.5-2.5 kW range during alloying the surface layer of the test pieces. It was established experimentally that the argon blow-in with the flow rate of 20 l/min through the ϕ 12mm circular nozzle oppositely directed in respect to the remelting direction provides full remelting zone protection.

## 3. Analysis of experimental results

The initial experiments consisting in alloying the X40CrMoV5-1 hot work steel indicate the clear influence of the laser power on the run face shape and its depth.

Material transport in the molten metal, caused by surface tension forces, features the main factor deciding development of the alloy layers. The uneven heating of material because of the laser beam influence causes that a big surface tension gradient occurs on the liquid surface. The force directed outwards from the beam centre, where the temperature has its maximum, causes movement of the molten metal to the remelting path edges and putting the allying material away in the axis and on the remelting path edges. Increase of the laser power and of the thickness of the tungsten carbide coating put down onto the steel surface before remelting at the constant feed rate of the laser beam causes increase of roughness and irregularity of the beam face shape. This effect is connected with the increase of the absorption of laser radiation absorption by the test piece surface, thanks to the higher value of the tungsten carbide absorption coefficient compared to the steel surface absorption coefficient. Growth of absorption causes increase of the steel surface layer remelting process intensity. Obtaining various thicknes of the alloyed zones is connected with the laser radiation absorption effect by the surface of test pieces covered with the paste consisting of the tungsten carbide and the inorganic binder.

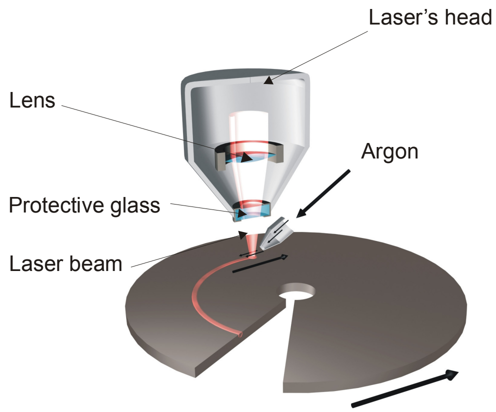


Fig. 2. Experimental setup with high power diode laser HPDL ROFIN DL 020

The investigated steel displays in the softened state the ferritic structure with carbides distributed uniformly in the matrix. The lathe martensite structure is obtained after quenching, which is saturated with alloying elements and with carbon, which is confirmed by the results of chemical composition analysis performed by means of EDX method. The anticipated hardenability of these steels was attained at the austenitizing time long enough, which ensures dissolving most alloying carbides in the austenite. Structural examinations consist in comparing the effect of parameters of heat treatment and remelting of the hot work tool steel with the diode laser on the run shape and remelting depth.

Metallographic examinations carried out on the light microscope and on the scanning microscope confirm that the structure of the material solidifying after laser remelting is diversified and is dependant on the solidification rate of the investigated steels. Occurrence of structure with big dendrites was revealed in areas at the interface between the solid and liquid phases (Fig. 3). Protective gas impact on the molten steel surface plays a meaningful role in the remelting and alloying process, as it is flowing in the area of the developing surface layer and protecting steel in the liquid state from exposure to air and removing the decay products of the inorganic binder, used as a binding agent for the tungsten carbide powder, and also participating in forming the crystallizing bead face and in transporting the alloying material remaining on the remelting surface. In case of alloying with the tungsten carbide powder, whose melting temperature is much higher than the steel melting temperature, penetration occurs of the undissolved tungsten carbide powder grains into the molten steel substrate. Strong circulation of the molten metal occurs then, followed by sudden solidification when the laser beam has passed. Packing of the solidified crystals' bands is consistent with the schema of convection motions in the molten metal pool. The chemical composition of the steel and conditions of its crystallisation affect phase transformations occurring during the solidification and cooling processes. Due to the quick crystallisation of the hot-work tool steels after their laser remelting precipitation of the high-temperature ferrite from the liquid solution is observed most often. Next, the peritectic reaction occurs, which leads to origination of austenite. Concentrations of carbide and alloying elements, which – depending on their portion - may precipitate directly from liquid, demonstrating clear segregation at the dendrite boundaries, have a significant effect on austenite nucleation. As expected, precipitation of the $M_{23}C_6$ and $M_7C_3$ carbides and of the retained austenite occurs in the remelted zone. Moreover, WC tungsten carbide occurs in the steel after its alloying (Fig. 4). Tungsten carbides and products of its high-temperature decomposition accumulate also at the remelting path edges and in flashes. This mechanism is most surely connected with the difference of the surface tensions of the molten steel and of the alloying material, as well as with the impact of the strong protective gas stream.

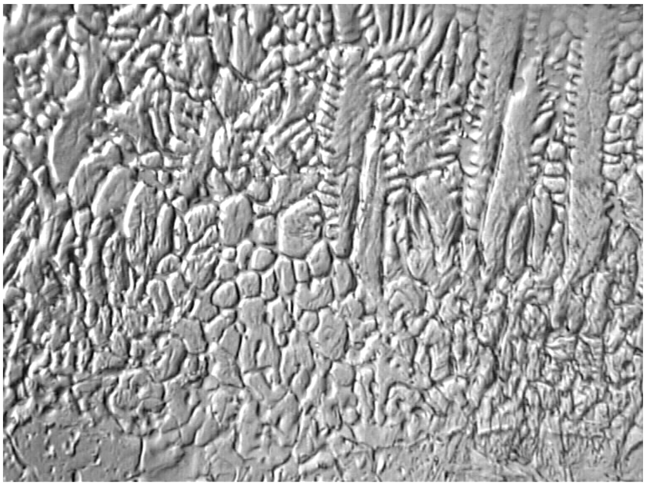

Fig. 3. The structure of surface layer after alloying by a HPDL laser; dendrites morphology of alloyed area; travel speed – 0,5m/min, laser power – 1,1 kW, thickness of the coating – 0,11mm (1000x)

Laser modification of surface layers results in the steel surface hardness increase. This effect is achieved thanks to occurrences of phase transformations connected closely with the heat removal rate from the remelted zone. The factor controlling in great measure the cooling rate is thickness of the remelted layer, dependant on the absorbed radiation energy and the time period of the laser beam impact on the material. Only the laser power affects the energy delivered to the surface layer with the constant remelting rate. At the low power of the laser beam the remelting depth is small, therefore heat removal rate is the highest. High cooling rate causes occurrences of the super-fast phase transformations; therefore, the fine-grained martensite structure occurs in the material, responsible for growth of its hardness. The highest hardness value of the X40CrMoV5-1 steel surface layer subjected to laser remelting was 61.1 HRC and it occurred after remelting with the laser beam at the power of 1.4 kW. The steel surface layer alloyed with tungsten carbide with the alloying coating thickness of 0.06 mm demonstrates the maximum hardness growth of up to 64.5 HRC at the laser beam power equal to 1.9 kW. The comparable hardness is characteristic for most of the laser beam power values used with this alloying coating thickness.

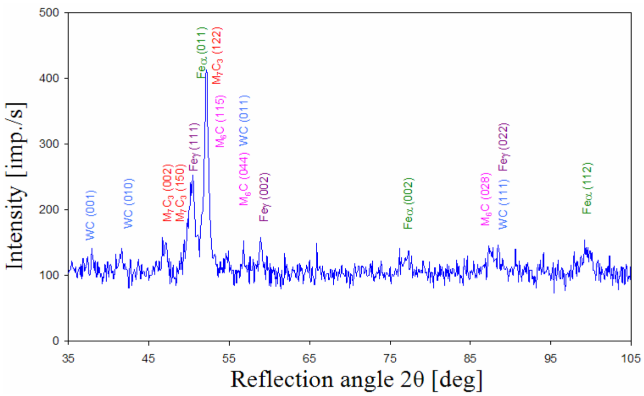


Fig. 4. Diffraction patterns of the X40CrMoV5-1 hot-work steel after alloying of the HPDL laser. Travel speed – 0,5m/s, laser power – 0,9 kW and thickness of the coating – 0,06mm

The maximum average microhardness number 1220 HV0.05 of all X40CrMoV5-1 steel test pieces subjected to laser modification is ensured at the laser power of 1.7 kW for steel alloyed with tungsten carbide with the 0.11 mm coating thickness (Fig. 9). The lowest values of the average microhardness increase occurred in the investigated steel after laser remelting. Occurrences of the tungsten carbide and lattice of carbides at dendrites' boundaries, demonstrating hardness different from the substrate, feature the reason of the microhardness measurement results discrepancy for the remelted zone and the alloyed one on the transverse section of the laser paths versus distance from the surface.

## 4. Summary

On the base of the research carried out it was found out, that it is feasible to develop the surface layers on the X40CrMoV5-1 hot-work tool steel by remelting and alloying with the tungsten carbide using the high power diode laser (HPDL). The structure of material solidifying after laser remelting is characteristic of the diversified morphology connected with the repeated changes of the crystals' growth direction, from the small dendrites, whose principal axes are oriented in accordance with the heat removal directions at the boundary between the solid and liquid phases, clusters of carbides arranged in accordance with the swirls caused by the metallic liquid convection motion and partially non-remelted WC conglomerates as the alloying material in the central area of the remelted zone, to the fine equiaxial grains in the subsurface zone. The very fast heat removal from the remelted zone by the core material ofmuch greater thermal capacity, is crucial for the martensitic transformation of the austenite originated due to crystallization and the lathe martensite developed in this process, partially twinned, is characteristic of the significant refinement of the martensite with the martensite lathes' length several times smaller than that of the ones of the martensite developed during the conventional quenching. Laser remelting and alloying with the tungsten carbide results in refinement of the structure in the entire laser power range and in diversification of the grain size in the particular surface layer zones. The research results indicate to the feasibility and purposefulness of the practical use of remelting and alloying with the tungsten carbide using the high power diode laser, e.g., for making new tools or for regeneration of the used ones from the X40CrMoV5-1 hot-work tool steel.

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