Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 28
ISSUE 1
May
2008

# The study of properties of laser modified hot-work tool steel surface layer

**M. Bonek*, M. Piec, L.A. Dobrzański**
Division of Materials Processing Technology, Management and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials,
Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
* Corresponding author: E-mail address: miroslaw.bonek@polsl.pl

Received 28.02.2008; published in revised form 01.05.2008

**Manufacturing and processing**

## ABSTRACT

**Purpose:** The following paper is a synopsis of the fundamentals of laser remelting and alloying, outlining some of its benefits compared with conventional heat treatment techniques of hot-work tool steel X40CrMoV5-1.

**Design/methodology/approach:** A selective review of the experimental research carried out in this area is presented. The aim of such treatment was to harden and alloy the steel surface which had been previously coated with the paste consisting of the tungsten carbide and the inorganic binder.

**Findings:** Development of the surface layer was observed in which one can distinguish the remelted zone, heat-affected zone and the transient zone. Occurrences of the un-melted tungsten carbide grains were observed in the structure and the increased tungsten content compared to the native material, whose variable concentration is connected with the molten metal fluctuation in the pool during alloying. 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.

**Practical implications:** It 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 outcome of the research is an investigation showing the structural mechanisms accompanying laser alloying.

**Keywords:** Heat treatment; Laser; Tool materials; Wear resistance

## 1. Introduction

The number of research centres in the world specialising in materials engineering in which the HPDL high power diode lasers are used grows steadily [1-4]. Until recently, the widespread use of lasers for materials processing has been hindered by the size, complexity and high investment cost of the laser systems. The wavelength of the emitted radiation allows high metallic absorption, which when coupled with favourable spatial and temporal beam profiles allows the HPDL to achieve a high efficiency power density delivered to the surface layer of the heat treated materials is lower for the HPDL lasers compared to the monomode distribution characteristic for other laser types, and the energy is distributed uniformly on the rectangular laser beam focus. Therefore, the HPDL laser is ideally suited for modification of the surface layer of materials. Modification of the tools surface layer structure with laser or its laser alloying with very hard materials, like carbides, feature research directions of the future on improvement of their properties [5, 6]. Laser surface alloying, although possible for a number of years, is a technology which is still in its infancy. The process involves the use of high intensity laser radiation to rapidly heat the surface of steel into the austenitic region. Due to high rates of heat transfer, steep temperature gradients are set up which result in rapid cooling by conduction. This causes the transformation from austenite to martensite without the need for external quenching. Hot work tool steels belong to the martensitic group of steels, used among others for the forging tools [5-7]. The hot work tool steels microstructure changes several times during their complex plastic and heat treatments, whose end effect are obtaining high thermal wear and fatigue resistance. Carbide precipitations are responsible for the high mechanical properties: primary ones originated during crystallization and secondary ones developed in the heat treatment process. One can expect increase of the wear resistance, hardness, and chemical stability from a material with more stable and harder particles introduced in addition into its matrix. However, possibility of improving the martensitic tool steels' functional properties by a conventional change of their chemical composition is very limited already. The advantages of laser treatment in comparison to other surface layer modification methods are: fast treatment, possibility to carry out the treatment without shielding facilities, modification of small – freely selected surface fragments responsible for tool and machine elements life, as well as materials economy. However, its disadvantages are the relatively high purchase cost of the high power lasers and high surface roughness after laser treatment [1, 8-17].

## 2. Investigation procedure

The specimens from the X40CrMoV5-1 alloy hot work tool steel, obtained from the vacuum melt, and made as bars, featured material for investigation. 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. Surfaces of specimens were sand blasted and machined on magnetic grinder. Next, powder layers of the WC tungsten carbide of thicknesses of 0.06 mm bounded with the inorganic binding agent were put down onto the degreased specimens. The siliceous liquid glass consisting of the $Na_4SiO_4$ orthosilicate and $Na_2Si_2O_5$ sodium disilicate was used as a binding agent in the form of the syrup like solution obtained under the increased pressure. Specimens of the X40CrMoV5-1 steel fixed in a turntable were remelted with the Rofin DL 020 high power laser beam (HPDL). 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 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 (Fig. 1).

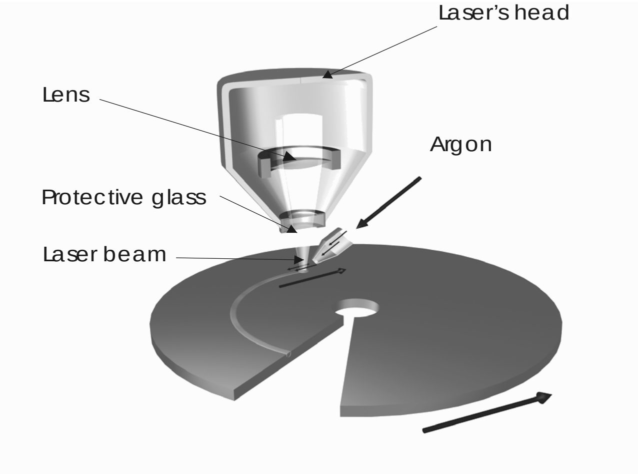

Fig. 1. Experimental setup with high power diode laser HPDL ROFIN DL 020

Metallographic examinations of material structure after laser alloying of its surface layer were made on Leica MEF4A light microscope at magnifications from 100 to 1000x. Structure examinations and thickness measurements of the relevant zones in the surface layer were made also for comparison on the transverse microsections on the Opton DSM 940 scanning electron microscope at magnifications 1000 and 5000x. Diffraction and chemical composition examinations in micro-areas and of the thin foil structures were made on the JEOL 200CX transmission electron microscope at the accelerating voltage of 200 kV, equipped with the Oxford EDS LINK ISIS X-ray energy dispersive spectrometer.

## 3. Discussion of the investigation results

Treatment in the analysed laser power range ensures the regular and flat face shape, without undercuts and with the relatively good surface smoothness. A small number of depressions and surface irregularities, resulting from its intensive heating occur on paths developed during laser alloying of the surface layer. Material transport in the molten metal, caused by surface tension forces features the main factor deciding development of the alloy layers. 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. Protective gas impact on the molten steel surface plays a meaningful role in the 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

Fig. 2. Remelting edge of the steel surface after alloying with parameters: scanning rate – 0.5 m/min, beam power – 1.3 kW, WC coating thickness – 0.06 mm

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 (Fig. 2).

Carbide clusters appear in the central area of the remelted zone, arranged in the characteristic swirls, caused by the convection motion of the material in the liquid state. Size of the crystals depends on the remelting process parameters, and especially on the remelting rate and volume of the remelted material, and also on the non-remelted volume of the heat abstracting material (Fig. 3).

Solidification rate grows along with shortening of the time period of the laser beam impact on the material and with the increase of the treated material volume, and the obtained crystalline structure is more refined. The significant cooling rates, occurring during the laser treatment of the surface layer, which at the initial period of the process flow may reach up to $10^{11}$ °C/s, thanks to the contact of the remelted layer with the non-remelted substrate cause that cooling rate reaches up to 20 m/s. This is the reason for the ultra-fast phase transformations influencing the structural mechanism of forming the surface layers subjected to laser modification. Additions of the alloying elements lower the Ms temperature, affecting morphology of the developing martensite. It is most often the lathe martensite in the hot-work tool steels; and several martensite packets separated with the wide-angle boundaries originate within one austenite grain. Particles of tungsten carbide and the increased tungsten concentration, forming the superfine eutectics, occur in steel alloyed with tungsten carbide. The increased tungsten concentration in the remelted layer results from the tungsten portion in the alloying powder, tungsten carbide melting temperature, and its solubility in the solid solution. Analysis of the plots of linear change of chemical composition, obtained on the transverse surface layer microsections using the EDS system confirms presence of C, W, V, Cr and Fe in the relevant zones of the surface gradient layers.

Occurrences of tungsten both in the steel matrix and also in the alloying material remainders were revealed. The increased concentration of the alloying elements on the dendrite boundaries was confirmed, where the discontinuous carbide lattice develops.

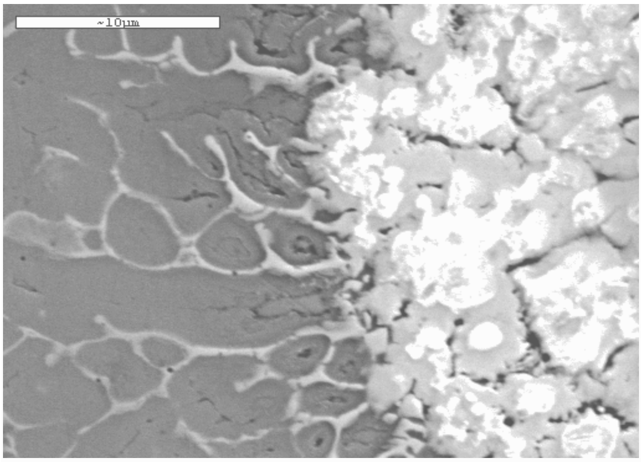

Fig. 3. Alloying material (WC) in surface layer after alloying with parameters: scanning rate – 0.5 m/min, beam power – 0,9 kW, WC coating thickness – 0.06 mm

It was found out in examinations of the surface distribution of elements that in the remelted and alloyed with the tungsten carbide zone the tungsten introduced into the steels is present only in the remelted zone; however, its concentration grows at the dendrite boundaries, like of the other analysed carbide forming elements (Cr, V). Enrichment of the steel surface layer with tungsten is a consequence of using for alloying the commercially available tungsten carbide powder being a mixture of the WC and $W_2C$ interstitial carbides and pure tungsten. Tungsten introduced to steel is present in the remelted zone only; however, its concentration grows at the dendrite boundaries, like of other analysed carbide forming elements (Cr, V). Grouping of the alloying elements was confirmed at dendrite boundaries in the area of the superfine eutectics occurring in the remelted zone due to fluctuation of the chemical composition, especially at the remelting bottom. 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.The maximum average microhardness of M 1220 HV0.05, of all 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. The lowest values of the average microhardness increase occur 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. Conclusions

Basing on the research carried 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). Alloying the investigated steel with tungsten carbide causes development of the surface layer, in which one can point out the melted zone, heat affected zone, and interface zones. A fine-grained, dendritic structure was obtained in the fused zone, with the crystallographic orientation connected with the dynamical heat abstraction from the laser beam impact zone. Occurrences of the un-melted tungsten carbide grains were observed in the structure and the increased tungsten content compared to the native material, whose variable concentration is connected with the molten metal fluctuation in the pool during alloying. Size of the crystals depends on the remelting process parameters, and especially on the remelting rate and volume of the remelted material, and also on the non-remelted volume of the heat abstracting material. Solidification rate grows along with shortening of the time period of the laser beam impact on the material and with the increase of the treated material volume, and the obtained crystalline structure is more refined. 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.

## Acknowledgements

Investigations were partially financed within the framework of the Scholarships from the International Visegrad Fund for Dr. M. Bonek and Dr M. Piec

## References

[1] T.R. Jervis, Tribological effects of excimer laser processing of tool steel, Surface and Coatings Technology 89 (1997) 158-164.
[2] J. Kusiński, Lasers and their employment in materials engineering, Publisher „Akapit”, Kraków, 2000, (in Polish).
[3] R. Colaco, R. Vilar, Development of New Coating Materials Using a Laser Rapid-alloy-prototyping-technique, Materials Science Forum 414-415 (2003) 164-70.
[4] E. Gemelli, A. Galerie, M. Caillet, Thermal Oxidation Resistant Surface Alloys Processed by Laser Alloying on Z38CDV5 Ferritic Steel, Materials Science Forum 251-254 (1997) 291-296.
[5] T.R. Jervis, Tribological effects of excimer laser processing of tool steel, Surface and Coatings Technology 89 (1997) 158-164.
[6] J. Kusiński, Microstructure, chemical composition and properties of the surface layer of M2 steel after laser melting under different conditions, Applied Surface Science 86 (1995) 317-322.
[7] J. Kusiński, Wear properties of T15 PM HSS made indexable inserts after laser surface melting, Journal of Materials Processing Technology 64 (1997) 239-246.
[8] A. Klimpel, High Power Diode Laser Application for Welding and Surfacing, JOM-10 International-Jubilee Conference “The Joining of Materials”, Helsingor – Denmark, 2001, 276-281.
[9] L.A. Dobrzański, M Piec, A. Klimpel, Z. Trojanowa: Surface modification of hot work tool steel by high-power diode laser, International Journal of Machine Tools and Manufacture 47/5 (2007) 773-778
[10] M. Bonek, L.A. Dobrzański, M. Piec, E. Hajduczek, A. Klimpel, Crystallisation mechanism of laser alloyed gradient layer on tool steel, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 411-414.
[11] R. Colaco, R. Vilar, Phase selection during laser surface melting of martensitic stainless tool steels, Scripta Materialia 36 (1997) 199-205.
[12] L.A. Dobrzański, M. Bonek, M. Piec, E. Jonda, Diode laser modification of surface gradient layer properties of a hot-work tool steel, Materials Science Forum 532-533 (2006) 657-660.
[13] M. Piec, L.A. Dobrzański, K. Labisz, E. Jonda, A. Klimpel, Laser Alloying with WC Ceramic Powder in Hot Work Tool Steel using a High Power Diode Laser (HPDL), Advanced Materials Research 15-17 (2007) 193-198
[14] L.A. Dobrzański, K. Labisz, A. Klimpel, J. Lelątko, Modelling of gradient layer properties of the 32CrMoV12-27 surface layer alloyed with WC powder Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 343-346.
[15] L.A. Dobrzański, M. Piec, K. Labisz, M. Bonek, A. Klimpel, Functional properties of surface layers of X38CrMoV5-3 hot work tool steel alloyed with HPDL laser, Journal of Achievements in Materials and Manufacturing Engineering 24/2 (2007) 191-194.
[16] L.A. Dobrzański, E. Jonda, A. Križ, K. Lukaszkowicz, Mechanical and tribological properties of the surface layer of the hot work tool steel obtained by laser alloying, Archives of Materials Science and Engineering 28/7 (2007) 389-396.
[17] L.A. Dobrzański, E. Jonda, A. Polok, A. Klimpel, Comparison of the thermal fatigue surface layers of the X40CrMoV5-1 hot work tool steels laser alloyed, Journal of Achievements in Materials and Manufacturing Engineering, 24/2 (2007) 135-138.