

M. BONEK\*

## THE INVESTIGATION OF MICROSTRUCTURES AND PROPERTIES OF HIGH SPEED STEEL HS6-5-2-5 AFTER LASER ALLOYING

### BADANIE STRUKTURY I WŁASNOŚCI STOPOWANEJ LASEROWO STALI SZYBKOTNĄCEJ HS6-5-2-5

This paper presents the results of the influence of laser alloying on structure and properties of the surface of HS6-5-2-5 high speed steel, carried out using a high power diode laser (HPDL). WC, VC, TiC, SiC, Si<sub>3</sub>N<sub>4</sub> and Al<sub>2</sub>O<sub>3</sub> particles powder was used for alloying. It was found out that remelting and laser alloying with hard particles result in structure refinement across the entire investigated laser power range. Selection of laser operating conditions is discussed, as well as beam face quality after remelting, hardness, micro hardness test, EDX, X-ray microanalysis results. Fine grained, dendritic structures occur in the remelted and alloyed zone with the crystallization direction related to the dynamical heat movement from the laser beam influence zone. The fine grained martensite structure is responsible for hardness increase of the alloyed layer. Micro-hardness changes depend up in the effects of the laser beam on the treated surface, and especially in the alloyed layer. The outcome of the research provides better understanding of the structural mechanisms accompanying laser remelting and alloying. Laser technique features the especially promising tool for solving the contemporary surface engineering problems thanks to the physical properties of the laser beam, making it possible to focus precisely the delivered energy in the form of heat in the surface layer.

*Keywords:* tool steels, laser heat treatment, laser alloying, surface engineering

W pracy przedstawiono wyniki badań laserowego stopowania na strukturę i własności warstwy wierzchniej stali szybkotnącej HS6-5-2-5, przetapianej za pomocą lasera diodowego dużej mocy (HPDL). Jako materiał stopujący użyto proszków WC, VC, TiC, SiC, Si<sub>3</sub>N<sub>4</sub> i Al<sub>2</sub>O<sub>3</sub>. Stwierdzono, że do przetopienia i stopowanie laserowe twardymi cząstkami powoduje poprawę własności warstwy wierzchniej w całym zakresie mocy lasera. Odpowiedni dobór warunków pracy lasera jak również jakość wiązki ma wpływ na wyniki przetopienia co potwierdzono badaniami twardości, mikrotwardości, mikroanalizy rentgenowskiej i rentgenowskie analizy fazowej. W strefie przetopionej i stopowanej stwierdzono występowanie drobnoziarnistej oraz dendrytycznej struktury z kierunkiem krystalizacji związanym z dynamicznym przepływem ciepła ze strefy oddziaływania wiązki laserowej. Drobnoziarnista struktura martenzytu jest odpowiedzialna za wzrost twardości warstwy stopowanej. Zmiany mikrotwardości ściśle zależą od efektów oddziaływania wiązki laserowej na obrabianą powierzchnię. Wyniki badań pozwalają na lepsze zrozumienie mechanizmów strukturalnych towarzyszących przetapianiu i stopowaniu laserowemu. Laserowa obróbka powierzchniowa stanowi szczególnie obiecujące narzędzie do rozwiązywania problemów inżynierii powierzchni dzięki wykorzystaniu własności fizycznych wiązki lasera umożliwiających precyzyjną obróbkę cieplną w warstwie wierzchniej.

### 1. Introduction

Surface treatment of manufactured elements with the application of such means as laser is nowadays a very common and innovative technology due to its seemingly unlimited potential, as e.g. large material savings, treatment accuracy, considerable improvement of the properties of the treated materials, applicability of full automation processes, etc. [1-4]. Such a treatment can also contribute to better resistance to corrosion and wear. It can raise hardness and afford better resistance to abrasion between surfaces of relatively small size. The cost of laser treatment is the only limitation when considering the application of this method on large surfaces. Covering a large surface for decorative reasons or to protect it against

corrosion with the use of laser techniques is more expensive than traditional methods, e.g. painting or electrolytic coating. The application of laser surface treatment is grounded both from the economical viewpoint and due to the fact that laser treatment in many cases ensures the acquisition of higher mechanical properties of the treated surfaces e.g. gear teeth or cutting bits, which would be impossible to achieve using conventional methods of surface treatment [5-8]. The material behavior during the HPDL processing has been found to be different from the other high-power lasers in the following aspects: fewer cracks and more uniform melt/heating zones, smoother surface, better beam absorption for metallic materials, more consistent and repeatable [3]. It is a well-known fact that the same laser processing parameters may not necessarily

\* SILESIA UNIVERSITY OF TECHNOLOGY, DIVISION OF MATERIALS PROCESSING TECHNOLOGY AND COMPUTER TECHNIQUES IN MATERIALS SCIENCE, INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS, 18A KONARSKIEGO STR., 44-100 GLIWICE, POLAND

produce the same results in laser materials processing. It has already been noticed that HPDL can produce more consistent materials-processing results than Nd:YAG lasers. This feature, together with the lower maintenance costs and longer service life would make HPDL suitable for mass production applications such as the soldering of telephone connectors [5]. Other advantages of the HPDL are: lower running cost, higher energy efficiency (up to 35% wall plug efficiency) thus the cooling requirement is low and the size of laser and cooling unit is small, flexible beam shaping by controlling the intensity of individual beams, theoretically unlimited average power, portable and longer service life (typically 4000-5000 up to 10000 h). This type of surface treatment is used for improvement of hardness by changing the structure, and for improvement of the abrasion wear resistance, mostly by introduction of carbide or ceramic particles to the material matrix.

## 2. Materials and methodology

Investigations were carried out on test pieces from the HS6-5-2-5 high speed steel with the composition according to PN-EN ISO 4957:200 standard. Chemical composition of the steel is given in Table 1. The investigated steel was melted in a vacuum induction furnace at a pressure of about 1 Pa, and cast into ingots weighing about 250 kg, with were roughed at the temperature range 1100-900°C into the O.D. 75 mm bars, which were soft annealed. After machining, the specimens were heat treated. The specimens were austenitized in a salt bath furnace and tempered in a chamber furnace in a protective atmosphere of argon. The specimens were gradually heated to the austenitizing temperature with the isothermal arrests at 650 and 850°C for 15 min. They were austenitized for 30 min at the temperature of 1210°C and then cooled in hot oil. The specimens were tempered twice after quenching, each time for 2 hours, at a temperature of 575°C and next at 560°C. Surfaces of specimens were sand blasted and machined on magnetic grinder.

TABLE 1  
Chemical composition of the HS6-5-2-5 high speed steel

Average mass concentration of elements, %								
Steel type	C	Cr	W	Mo	V	Si	P	S
HS6-5-2-5	0.91	4.2	6.3	5.0	1.9	1.09	0.015	0.010

Particular attention was paid to prevent development of micro-cracks that might disqualify the specimen from further examination. Sample size was 10×10×55 mm. On specimen surface two parallel grooves, deep for 0.5 mm of triangular shape (with angle of 45°) were machined. The grooves were located along sample axis and distance between them was ca. 1.0 mm. Such prepared grooves were filled with WC, VC, TiC, SiC, Si<sub>3</sub>N<sub>4</sub> and Al<sub>2</sub>O<sub>3</sub> particles. It was found in the preliminary investigations made using the HPDL Rofin DL 020 high power diode laser, that the maximum feed rate at which the process was stable is  $v=0.5$  m/min. Therefore all experiments were made varying the laser beam power in the range from 0.7 to 2.1 kW. At low laser power values, i.e., 0.4 to 0.7 kW, no remelting was observed for powders mentioned above. It was

established experimentally that argon purging with flow rate of 20 l/min through a 12 mm circular nozzle oppositely directed in respect to the remelting direction provided full remelting zone protection. Metallographic examination of the material structures after surface laser alloying were made on a Zeiss LEICA MEF4A light microscope with magnifications from 50 to 500x. A Leica-Qwin computer image analysis system was used for thickness examination of the particular zones of the surface layer. Structure of the developed coatings were examined with SUPRA 25 scanning electron microscope (SEM) equipped with X-ray energy dispersive spectrometer (EDS). Hardness tests were made using Rockwell method in C scale on specimens subjected to the standard heat treatment 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 bead face of specimens. Coating microhardness was tested on the FM-700 microhardness tester. The tests were carried out at 0.01 N load, making the necessary number of indents on the section of each examined specimen, correspondingly to the structural changes depth in the material surface layer. The microhardness tests were made along the lines perpendicular to specimens' surfaces, along the run face axis.

## 3. Results

The investigated steel displays in the softened state a ferritic structure with carbides distributed uniformly in the matrix. A lath martensite structure is obtained after quenching, which is saturated with alloying elements, which is confirmed by the EDX chemical composition analysis, and with carbon. The anticipated hardenability of these steels was attained at an austenitizing time long enough, to ensure solubility of most alloy carbides in the austenite. Structural examinations compared the effect of parameters of heat treatment and remelting of the high speed steel with the diode laser on the run face shape and remelting depth. The initial experiments indicated the clear influence of the laser power of 0.7, 1.7, 2.1kW respectively on the run face shape and its depth. It was observed that the remelting depth increased with the laser power increase. It was found, that thickness of the analysed layers, evaluated supported on the computer image analysis made on pictures from the light microscope and confirmed by examinations on the scanning electron microscope, falls within the broad range and is a function of laser beam power. The average remelted layer thickness was proportional to the laser power increase. It was found that the remelted layer thickness changes from 0.26 mm, with the 0.7 kW laser beam, to about 1.07 mm, with the 2.1 kW laser beam power. The remelted zone thickness also increases in proportion to the laser power in the case of alloying the steel with carbides and ceramic particles such that the average alloyed layer thickness varied from 0.13 mm (laser beam power 0.7 kW), to about 0.93 mm (laser beam power 2.1 kW). Roughness of the surface layers obtained by remelting the steel with the laser beam with power ranging from 0.7 to 2.1 kW is within the range of  $R_a = 0.39-0.79$   $\mu\text{m}$  and incised in proportion to the laser beam power. The surface layer obtained by alloying with carbides and ceramic particles

did not demonstrate proportional dependence of the surface roughness with the laser beam power. The maximum surface roughness of  $R_a = 21.4 \mu\text{m}$  occurs at the surface of the layer obtained with the laser beam with the power of 1.7 kW; whereas, the minimum surface roughness of  $R_a = 5.9 \mu\text{m}$  was obtained on the surface layer developed of 2.1 kW. No dependence of surface roughness with laser beam power in the case of alloying with the carbides and ceramic particles is caused by the mechanism of the hard particles powder inundation into the surface layer of steel. At low laser beam power some of the carbide grains remain at the surface, causing high roughness; whereas, at the higher laser beam power the steel surface is formed in a very characteristic shape, resulting from the fast crystallization in the heat transfer direction and from interaction with the flow of protective gas (Fig. 1-2).

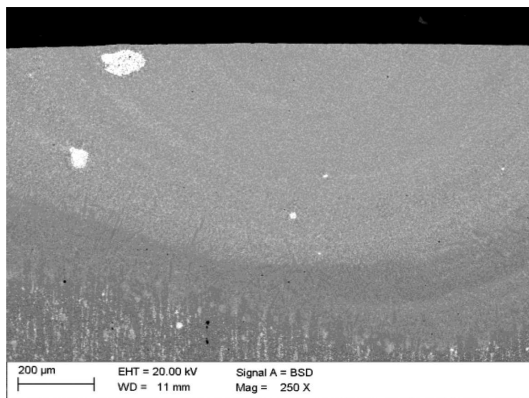


Fig. 1. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the WC particles with laser power value 2.1 kW

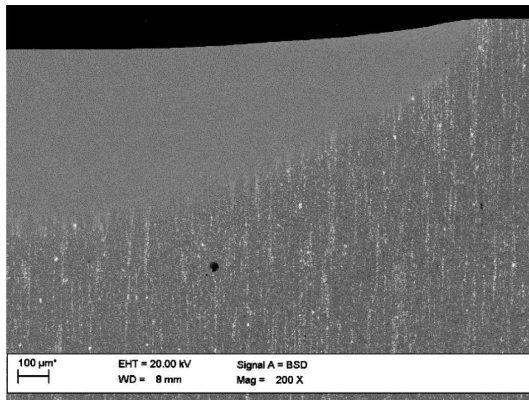


Fig. 2. Surface shape and remelting depth of the high speed steel HS6-5-2-5 test piece transverse sections with the VC particles with laser power value 2.1 kW

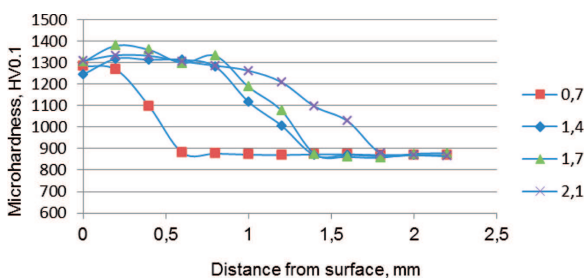


Fig. 3. Change in microhardness of the high speed steel HS6-5-2-5 surface layer after alloying with TiC carbide

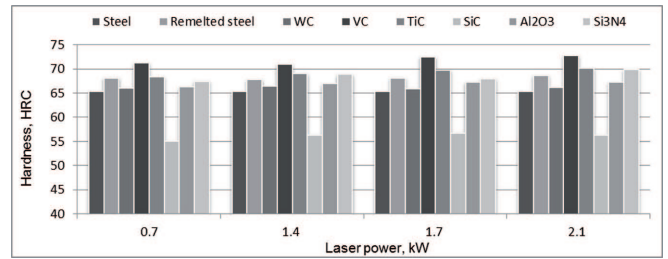


Fig. 4. Average hardness for the high speed steel HS6-5-2-5 remelted and alloyed with the WC, VC, TiC, SiC, Si<sub>3</sub>N<sub>4</sub> and Al<sub>2</sub>O<sub>3</sub> particles with the scanning rate of 0.5 m/min and laser beam power of 0.7, 1.4, 1.7 and 2.1 kW

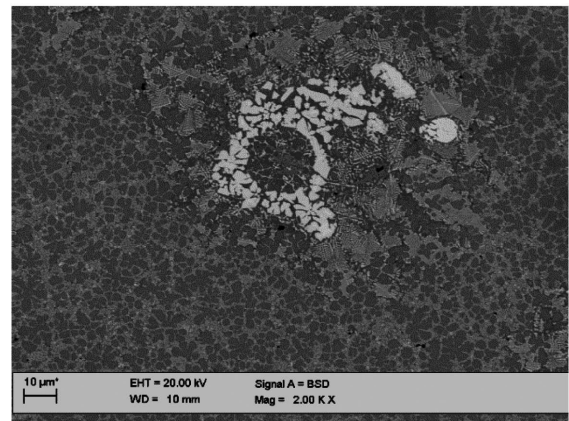


Fig. 5. Surface layer of the high speed steel HS6-5-2-5 steel after laser remelting with the WC particles with the scanning rate of 0.5 m/min and laser beam power of 1.7 kW, remelted zone – visible particles of tungsten carbide in the surface layer

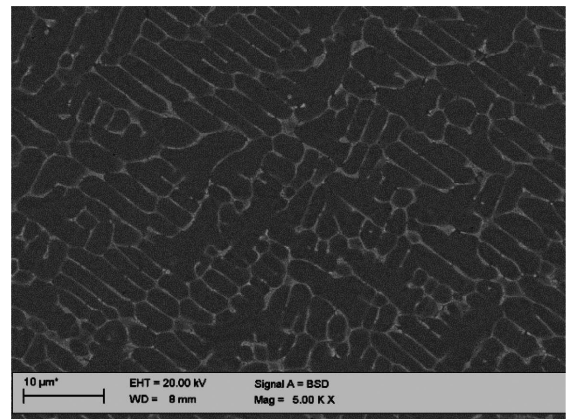


Fig. 6. Surface layer of the high speed steel HS6-5-2-5 steel after laser remelting with the VC particles with the scanning rate of 0.5 m/min and laser beam power of 1.7 kW, remelted zone

Microhardness growth was revealed, based on microhardness tests on the transverse section of laser runs versus distance from the surface of the examined steel test pieces showed hardness increases (Fig. 3). The high average microhardness increase in the remelted zone surface layer was observed for laser beam power of 2.1 kW. In the case of alloying, the highest microhardness was obtained for the steel surface layer alloyed with the VC particles, for which the average microhardness increase is 1398 HV<sub>0,1</sub>, when the laser power used for alloying was 2.1 kW. Figure 4 presents the HRC hardness tests



results of the surface layer after remelting with the HPDL high power diode laser using the carbide and ceramic particles. It was observed that increase of the laser power causes inundation of a larger amount of the carbide and ceramic particles; and therefore, increased the surface layer hardness, which was confirmed by examination on the light microscope with the Leica-Qwin computer image analysis system, and also by observations on the scanning microscope. Hardness for the native material after heat treatment is about 65 HRC, whereas after alloying with vanadium carbide it is about 73 HRC.

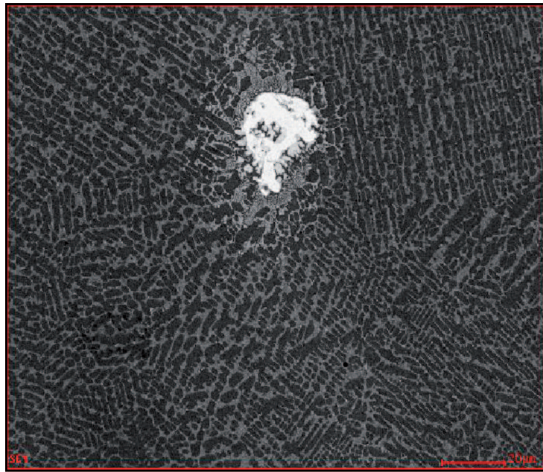


Fig. 7. Surface layer of the high speed steel HS6-5-2-5 alloyed with the WC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW – remelted zone

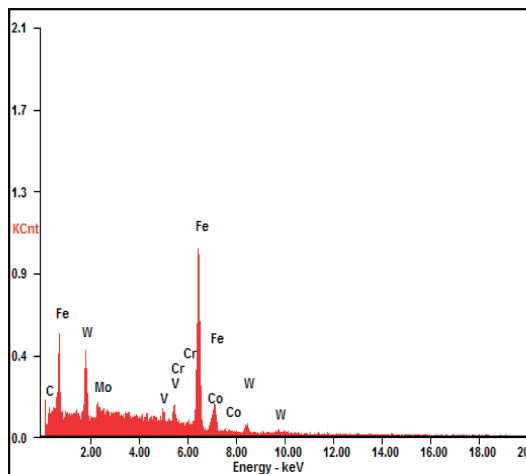


Fig. 8. Surface layer of the high speed steel HS6-5-2-5 alloyed with the WC particles with the scanning rate of 0.5 m/min and laser beam power of 2.1 kW. – spectrum of the pointwise chemical composition analysis

Metallographic examination confirmed that the structure of the material solidifying after laser remelting is different, which is dependent on the solidification rate of the investigated steel. Occurrence of structure with dendrites was revealed in areas on the boundary between the remelted and heat affected zone (Fig. 5-7). Examination of the chemical composition (Fig. 8) with the surface and pointwise methods reveal occurrences of the inundated particles in conglomerates (Fig. 7). Moreover, using the X-ray microanalysis it was found out also

that titanium occurs not only in the form of conglomerated but also the remelted layer. X-ray diffraction were also made of the remelted steels and alloyed with the carbides. According to the assumptions, on surface of the investigated test pieces alloyed with the NbC, VC, WC and TiC powders, occurrences of the NbC, VC, WC and TiC carbides were observed using the X-ray qualitative phase analysis methods.

#### 4. Summary

The investigations carried out made it possible to state that due to the heat treatment and remelting of the HS6-5-2-5 tool steel with the carbides powders it is possible to obtain the high quality of the surface layer with no cracks and defects and with hardness significantly higher than the substrate metal. Remelting experiments made it possible to demonstrate the effect of the HPDL high power diode laser alloying parameters on properties and structure of the tool steels. Remelting depth grows along with the laser power increase and the remelted surface is more regular, less rough and more flat along with the laser power increase. Due to the martensitic transformation of the HS6-5-2-5 high speed steel subjected to remelting and alloying with carbides steel hardness growth occurs usually compared to hardness of about 65.1 HRC after the conventional heat treatment. The maximum hardness of 73.2 HRC the investigated steel achieves in case of alloying with the vanadium carbide with the laser power of 2.3 kW. The average micro-hardness of the surface layers subjected to laser treatment is up to about 80% higher in case of the tantalum carbide than in case of the native material. A very fast process of the heat abstraction from the remelted zone through the core of a material with a multiply bigger heat capacity decides about the martensite transformation of the austenite arisen as a result of crystallization, and the partially twined lath martensite, formed this way, is characterized by big lathes' dispersion with their length several times shorter in comparison to martensite lathes after a conventional heat treatment. Metallographic examinations on the scanning microscope with the EDX attachment and also with the X-ray qualitative phase analysis method confirm the occurrence of the NbC, VC, WC and TiC carbides in the surface layer of the investigated steel. It was found out that the vanadium and titanium occurs in the remelted layers mainly in the form of conglomerates.

The research results indicate to the feasibility and purposefulness of the practical use of remelting and alloying with carbides using the high power diode laser for manufacturing and regeneration of various tools from the HS6-5-2-5 high speed tool steel.

#### REFERENCES

- [1] M. B o n e k, Laser Surface Alloying. In: Wang Q., Chung Y. (Ed.) Encyclopedia of Tribology: SpringerReference, Springer-Verlag Berlin Heidelberg, 1938-1948 (2013).
- [2] M. B o n e k, Effect of high power diode laser surface alloying of tool steels, Chiang Mai Journal of Science 40(5), 849-856 (2013).

- [3] M. Bonek, G. Matula, L.A. Dobrzański, Effect of laser surface melting on structure and properties of a high speed tool steel, *Advanced Materials Research* **291-294**, 1365-1368 (2011).
- [4] A. Lisiecki, Welding of titanium alloy by Disk laser. *Proceedings of SPIE* **8703**, Laser Technology 2012.
- [5] A. Lisiecki, Diode laser welding of high yield steel. *Proceedings of SPIE* **8703**, Laser Technology 2012.
- [6] 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**, 1056-1061 (2005).
- [7] L.A. Dobrzański, R. Maniara, J. Sokolowski, W. Kasprzak, M. Krupinski, Z. Brytan, Applications of the artificial intelligence methods for modeling of the ACAISi7Cu alloy crystallization process, *Journal of Materials Processing Technology* **192**, 582-587 (2007).
- [8] E. Torres, D. Ugues, Z. Brytan, M. Perucca, Development of multilayer coatings for forming dies and tools of aluminium alloy from liquid state, *Journal of Physics, Applied Physics* **42**, 10, 105306 (2009).

*Received: 20 October 2013.*