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Structure and properties of hot-work tool steel alloyed by WC carbides by a use of high power diode laser

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ABSTRACT

Purpose: The paper presents the effect of alloying with tungsten carbide on properties of the X40CrMoV5-1 steel surface layer, using the high power diode laser (HPDL).

Design/methodology/approach: The structural mechanism of surface layer development was determined and the effect of alloying parameters, gas protection method, and thickness of paste layer applied onto the steel surface on structure refinement and influence of these factors on the mechanical properties of surface layer was studied.

Findings: Selection of laser operating conditions is discussed, as well as thickness of the alloying layer, and their influence on structure and chemical composition of the steel. Analysis of the process conditions influence on thicknesses of the alloyed layer and heat-affected zone is presented.

Practical implications: Laser surface modification 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

Improvement of surface properties of materials used to date features one of the goals set to the research institutions active in the materials engineering area. Possibilities of increasing the functional properties of the hot-work alloy tool steels by modification of their chemical composition in a conventional way are very limited already. 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. Moreover, methods which are not based on partial melting of surface alone, but on partial melting with the simultaneous introduction of the alloying elements with high hardness, like carbides, are being employed more and more widely for modification of the surface layer. High cooling rates are obtained in this process and its end result is the fine-grained material with the super-cooled phases. Material transport in the liquid metal, caused by the surface tension forces, features the main factor deciding development of the alloyed layers. The non-uniform material heating resulting from the laser beam impact causes development of a big surface tension gradient on the surface of the liquid. The force is directed outside from the beam centre where is the highest temperature value to its edge and causes movement of the molten material [1-5, 12-15].

Density of power delivered to the surface layer of the processed materials is lower for the more and more often used HPDL type lasers compared to its single mode distribution characteristic for other laser types; however, the energy is distributed more uniformly across the rectangular area of the laser beam focus [6]. Therefore, the HPDL laser is ideally suited for modification of the surface layer of materials. Moreover, employment of the appropriate shielding gases and correctly selected nozzle shape, and its position in respect to the processed material, have the objective to ensure the high quality of weld face and repeatability of the obtained results. The advantages of laser treatment compared to other surface layer modification methods are: high processing rate, possibility to carry out treatment without protective guards, modification of small, arbitrarily selected fragments of the processed surfaces responsible for tools and machine elements life, as well as its material economy [7-11].

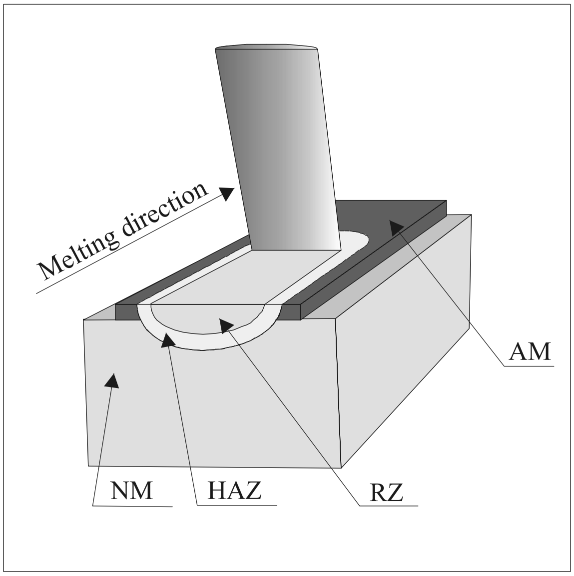

Fig. 1. Experimental setup with high power diode laser HPDL ROFIN DL 020, NM – native material, HAZ - heat effected zone, RZ – remelted zone, AM – alloying material

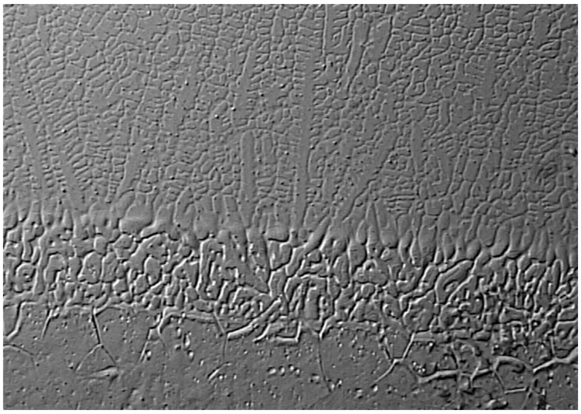

Fig. 2. Boundary of the remelted steel surface layer after alloying with the parameters: scanning rate – 0.5 m/min, beam power – 1.1 kW, WC layer thickness – 0.06 mm

The goals of this work were: determining the technological conditions for alloying with the tungsten carbide the hot-work alloy steel surface layer using the high power diode laser (HPDL) and determining the relationship between the laser treatment parameters and structure and chemical composition of the steel.

2. Investigation procedure

The material under investigation were specimens from the X40CrMoV5-1 hot-work alloy tool steel, obtained from the vacuum cast, delivered in the form of bars with O.D. 75 mm. The chemical composition of the steel is given below in table 1. Specimens of O.D. 70 mm and 6 mm thick were turned from the material delivered in a softened state, further they were austenitized in a salt bath furnace and tempered in the chamber furnace with argon protective atmosphere.

The specimens were heated gradually to the austenitizing temperature with holding at 650°C for 15 min and were austenitized for 30 min at the temperature of 1060°C. Cooling was carried out in the hot oil. The specimens were tempered twice after quenching, each time for 2 hours, at the temperature of 510°C.

Table 1
Chemical composition of X40CrMoV5-1 steel

Steel type	Weight, (%)								
	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

Table 2
Properties of the WC powder

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

Table 3
Technical date for the HPDL ROFIN DL 020

Wavelength of the laser radiation, nm	808 ± 5
Maximum output power of the laser beam (continuous wave), W	2500
Power range, W	100-2500
Focal length of the laser beam, mm	82 / 32
Laser spot size, mm	1.8 × 6.8 / 1.8 × 3.8
Power density range in the laser beam focal plane, kW/cm^2	0.8-36.5

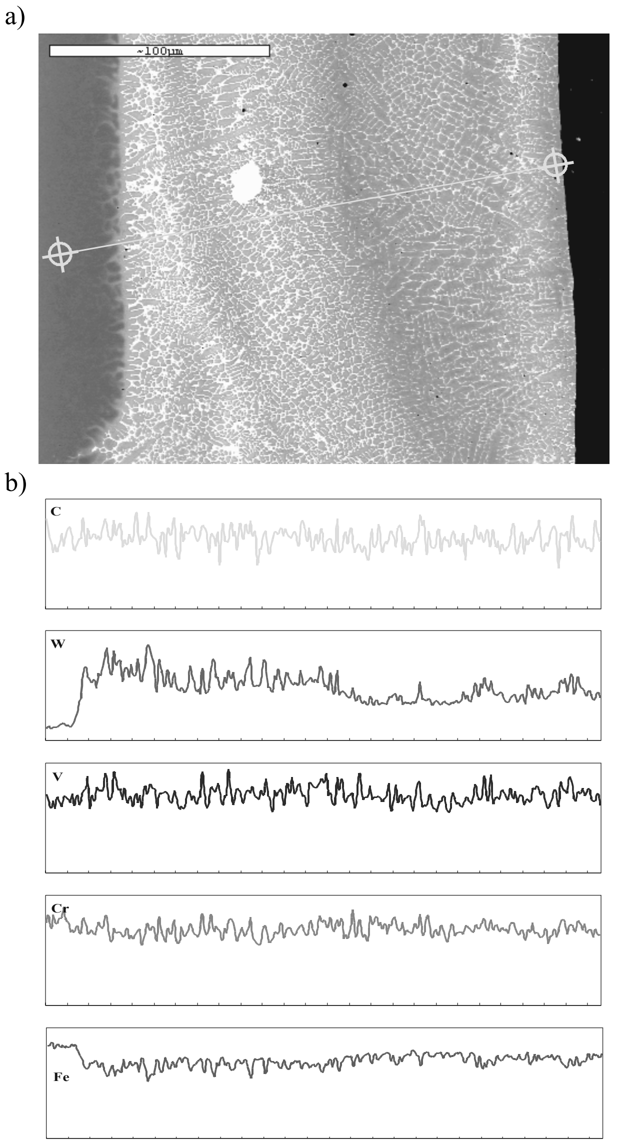

Fig. 3. Surface layer of the X40CrMoV5-1 steel after alloying with the following parameters: beam power – 1.3 kW, layer thickness – 0.11 mm; a) SEM structure, b) linear analysis of the chemical composition changes

The specimens' surfaces were sand blasted and ground on a surface grinder with the magnetic holder. The paste containing the WC tungsten carbide powder with the inorganic binder was applied on the degreased specimens as 0.06 mm and 0.11 mm thick layers, which properties can be seen in table 2. The specimens from the X40CrMoV5-1 steel, mounted on a turntable, were penetrated with the Rofin DL 020 high power diode laser (HPDL) beam. The technical parameters of the laser can be seen in table 3. Two fusion tracks were made on each specimen face with radii of 12 mm and 22 mm. Dimensions of the laser beam focused on the material surface are 1.8 x 6.8 mm. The working focal distance (measured from the head protective glass) is 92 mm.

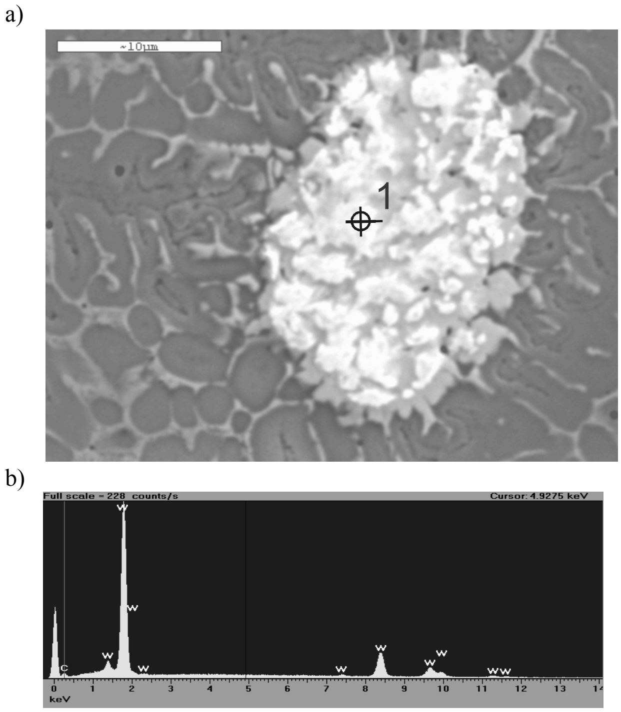

Fig. 4. a) Microstructure of the X40CrMoV5-1 steel (SEM) after alloying with the following parameters: beam power – 0.9 kW, layer thickness – 0.11 mm b) the plot of intensity versus energy dispersive X-ray radiation, representing the pointwise WC carbide chemical composition analysis

Fusion was carried out in the direction perpendicular to the longer side of the focused beam with the multi-mode energy distribution, which ensures obtaining the wide weld face in the statement (fig. 1).

Metallographic examinations of the material structures after laser alloying its surface layer were made on LEICA MEF4A light microscope with magnifications from 100 to 1000x. Structure examinations and thickness measurement of the relevant zones in the surface layer were made also on the transverse micro-sections on the OPTON DSM 940 scanning electron microscope with magnifications from 1000 do 5000x. Examinations of the chemical composition in micro-zones and analyses of the linear distribution of alloying elements in specimens from the investigated steel were made on the OPTON DSM-940 scanning electron microscope with the Oxford EDS LINK ISIS energy dispersive X-ray spectrometer with the 20 kV accelerating voltage.

3. Discussion of investigation results

Basing on metallographic examinations, occurrences of two zones in the surface layer of the investigated steel were found out: the remelted zone and the heat-affected zone, whose thicknesses are dependant on the employed laser treatment parameters (laser treatment type, laser beam power, thickness of the alloying layer).

In case of alloying with the tungsten carbide powder, whose melting point is much higher than the melting point of steel, with the initially specified laser power, inundation occurs of the un-molten WC powder grains into the molten steel substrate. Strong circulation of the liquid metal was discovered with rapid solidification after the laser beam has passed, leading to freezing of the structure (fig. 2). It was found out, basing on metallographic examinations, that the structure of the material solidifying after laser fusion is characterized by occurrences of areas with the diversified morphology (fig. 3a) connected with crystallization of the steel. Depending on the processing parameters used various material mixing mechanisms were observed. At low laser material penetration energy values the capillary lines are not connected and the fusion structure is relatively hogeneous. Along with the laser power growth the occurrences of capillary lines' swirls were observed. Big dendrites occur in the boundary zone between the solid and liquid phases, whose main axes are oriented according to the heat abstraction directions. Repeated crystal growth direction changes are observed, characteristic for these zones. Structure of fine equiaxial crystals with the carbide lattice develops in the central zone of the fused area where heat abstraction takes place in all directions. Linear analysis of the chemical composition revealed tungsten presence in the fused zone only (fig. 3b). No tungsten presence was found in the heat affected zone. Undissolved tungsten carbides were revealed surrounded by the dense lattices of the superfine eutectic mixture (fig. 4). It was found out that laser fusion results in refinement of structure in the entire laser power range. Different grain size was revealed during examinations in the particular zones of the surface layer after laser alloying. Matrix grains shape and size does not change during fusion. Only at the crystallization front, between the fused and heat affected zones, the elongated and smaller grains were found, which are subjected to partial melting and re-crystallization during laser modification in the statement.

4. Conclusions

Alloying the investigated steel with tungsten carbide causes development of the surface layer, in which one can point out the fused zone, heat affected zone, and interface zones. Their thickness is closely connected with the fusion parameters, and thickness of the fused layer changes significantly along with the laser beam power increase. 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-fused 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.

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