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Mechanical and tribological properties of the laser alloyed surface coatings

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Properties

ABSTRACT

Purpose: Improvement of surface properties of X38CrMoV5-3 is one of the goals set to the research institutions active in this paper.
Design/methodology/approach: Remelting and alloying of surface layers were made using the HPDL high power diode laser Rofin DL 020 in the laser power range of 1.2÷2.3 kW. Abrasion wear resistance tests were made in the metal-ceramic material arrangement (ASTM-G65), and also in the metal-metal one.
Findings: All employed carbides cause hardness and microhardness increase of the surface layer of the investigated steel, and in most cases abrasion wear resistance increase. The investigations carried out indicate that the best mechanical properties are displayed by the surface layers of steel alloyed with carbides: TaC, NbC, and VC; whereas, the best tribological properties are displayed by surface layers alloyed with vanadium carbide, compared to the conventionally heat treated steel. Improvement of mechanical properties and abrasion wear resistance grow with the increase of the laser power.
Research limitations/implications: The material behavior for the HPDL processing has been found to be different from the other high-power lasers in the following aspects: fewer cracks and less spallation for surface glazing/sealing, more uniform melt/heating zones, smoother surface, better beam absorption for metallic materials, more consistent and repeatable.
Practical implications: 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 for manufacturing and regeneration of various tools from the X38CrMoV5-3 hot-work tool steel.
Originality/value: Possibilities of increasing the functional properties of hot-work alloy tool steels by modification of their chemical composition additional of ceramic particles in a conventional way are very limited already.
Keywords: Mechanical properties, HPDL laser; Alloying; Carbides

1. Introduction

The technology consisting in laser alloying is enjoying more and more interest in many centres in the world. This type of surface treatment is used for improvement of hardness and abrasion wear resistance by influencing the structure change, mostly by introduction of carbide particles into matrix on the material surface. Violent mixing of constituents in the laser pool, into which carbide powder is introduced; takes place during alloying process employing laser with the sufficiently high power and the surface layer develops after solidifying from the remelted materials. Convection motions in the laser pool decide the final distribution of the alloying element in the remelted zone. The intensity of the convection motions, velocity of liquid transition, is caused also by a big temperature gradient, which is the bigger the bigger is the energy portion delivered in the unit time by the laser beam [1-8]. Entering of powder is done using the conveyor directly during alloying, or else the powder is being applied as paste which dries up on the specimen surface, and only next is subjected to alloying. This makes it possible developing the alloy with the bi- or multi-component structure, and also of the composite or gradient type with the intermetallic phases. Thanks to the rapid cooling because of heat removal to the cold substrate an advantageous, fine-grained structure develops, which displays also the gradient morphology [9-15].

2. Experimental procedure

Investigations were carried out on test pieces from the X38CrMoV5-3 hot work high-speed tool steel with the composition according to PN-EN ISO 4957:2002U standard. Chemical composition of the steel is given in Table 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 O.D. 76 mm bars 3 m long, which were soft annealed. Test pieces for structural and tribological tests were made using the test pieces with the following dimensions: 65 x 25 x 5 mm. Specimens prepared like that were subjected to heat treatment consisting in quenching and tempering twice. Austenitising was carried out in vacuum furnace at the temperature of 1040ºC, at the holding time of 0.5 h. Two isothermal stops were used during heating to the austenitising temperature were used - at temperatures of 585ºC and 850ºC. The specimens were tempered twice after quenching, each time for 2 hours, at the temperature of 575°C and next at 560 ºC. Surfaces of specimens were ground on magnetic grinder after heat treatment. Particular attention was paid to prevent development of micro-cracks that might disqualify the specimen from further examination.

Remelting and alloying of surface layers were made using the HPDL high power diode laser Rofin DL 020 in the laser power range of 1.2÷2.3 kW. The following carbides were used as the alloying material: TaC, NbC, WC, VC, and TiC with the average grain size showed in table 2. Remelting and alloying 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 surface.

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 1.2-2.3 kW range during remelting the surface layer of the test pieces. It was revealed that the argon blow-in with the flow rate of 20 l/min through the 12 mm circular nozzle oppositely directed in respect to the remelting direction provides full remelting zone protection. Abrasion wear resistance tests of the surface layers were carried out in the metal-ceramic material arrangement according to the ASTM standard (Figure 1).

The surface layer obtained consists of four adjacent welding sequences remelted or alloyed. Two test pieces of each type of the investigated surface coatings were examined according to the requirements of the standard. The schematic diagram of the device is presented in Figure 1; whereas the test conditions are specified by the requirements of the ASTM standard.

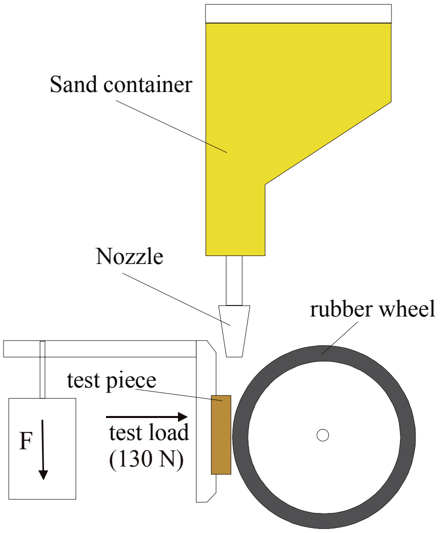

Fig. 1. Schematic diagram of the device for abrasion wear resistance tests of the surface layers in the metal-ceramic material arrangement according to the ASTM standard

The ceramic material - quartz sand with the granularity of 212-300 µm - is delivered by the nozzle with the flow rate of about 350 g/min during the test. The nozzle is between the examined test piece and the rubber circle with the diameter of 229 mm. The test piece is loaded with the constant force of 130 N and is pressed down to the rotating rubber wheel. This wheel, rotating at the constant speed of 200 rpm, makes 6000 rotations during the test. The test pieces before and after the grindability examinations were weighed on the analytical balance with the accuracy of 0.0001g to check the mass loss, depending on the used particles and laser power. The X38CrMoV5-3 conventionally heat treated steel was used as reference material. The mass loss of the investigated layers was determined using the following relationship:

$$\text{Mass loss} = \frac{\Delta\text{m specimen with carbide [g]}}{\Delta\text{m heat treated specimen [g]}} \times 100\ \% \quad (1)$$

Abrasion resistance wear tests of the surface layers in the metal-metal arrangement were carried out using the device designed at the Faculty of Mechanical Engineering of the Silesian University of Technology. The test piece was examined on which two remelting or alloying paths were made for each of the surface layers. Preparation of the test pieces for examinations consists in grinding the surface with the 1200 grit abrasive papers, to remove the remains of the non-remelted powder. Particular attention was paid to prevent removal of the remelted zone. Tests were carried out on surfaces prepared in this way using the steel ball with 8.7 mm diameter as the counter-specimen. The load of 10 N and the constant number of cycles of 1000 were determined in the preliminary tests. Test pieces were rinsed in the ultrasonic washer to clean them before and after the test. Wear profiles were registered for the investigated surface layer, and also the wear trace of the counter-specimen to compare the test results for each type of the test pieces coated with various alloying particles at various laser power values.

Table 1.
Chemical composition of X38CrMoV5-3 steel

The mass concentration of main elements, %							
C	Si	Mn	P	S	Cr	Mo	V
0,372	0,42	0,43	0,022	0,002	4,95	2,72	0,42

Table 2.
Chemical composition of applied powders

Powder	Grain sice, µm	Melting temperature,°C	Density g/cm^3	Hardness, HV
Niobium carbide	10	3500	7,6	2100
Tantalum carbide	10	3880	15,03	1725
Vanadium carbide	1,5	2830	5,36	2850
Titanium carbide	3	3140	4,25	2800
Tungsten carbide	5	2770	15,6	2600

3. Discussion of experimantal results

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 mostly 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 steel surface. 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 hardness growth. The highest hardness of the steel surface layer subjected to laser remelting of 61.7 HRC, occurs after remelting with the laser beam with power of 1.2 kW. The steel surface layer alloyed with carbides demonstrates the maximum hardness growth of up to 67.4 HRC for tantalum carbide at the laser beam power equal to 2.3 kW.

The clear microhardness growth in the remelting zone was revealed also in case of the microhardness test. The maximum average microhardness of 1412 HV$_{0.01}$, of all steel test pieces subjected to laser modification, is ensured at the laser power of 2.3 kW for steel alloyed with tantalum carbide.

Microhardness growth was revealed, basing on microhardness tests on the transverse section of laser runs versus distance from the surface of the examined steel test pieces, in case of remelting and alloying with all used particles.

The highest average microhardness growth in the remelted zone in the remelted surface layer was observed in case of the laser beam power of 1.2 kW. In case of alloying, the highest microhardness growth compared to the material after the standard heat treatment was revealed for the steel surface layer alloyed with the TaC particles, for which the average microhardness growth is 712 HV$_{0,01}$, when the laser power used for alloying is 2.3 kW. For other particles used the average microhardness growth in the surface layer is: 521 HV$_{0,01}$ for vanadium carbide and laser power 2.0 kW, 546 HV$_{0,01}$ for niobium carbide and laser power 2.3 kW, 217 HV$_{0,01}$ for titanium carbide and laser power 2.3 kW.

Moreover, microhardness tests reveal occurrence of the hardness drop area to the value of about 550 HV$_{0,01}$ in the analysed steel, both after remelting and after alloying. The hardness drop occurs over the entire width of the border between the heat-affected zone and native material. Such hardness drop was revealed in all examined specimens. The hardness drop attests to development of the tempered material zone during laser treatment, heated to the temperature higher than the tempering temperature, i.e., 560ºC.

It turns out from the analysis of plots registered during the microhardness tests (loading an unloading versus indenter penetration into the native material) that the depth to which the indenter reaches decreases along with hardness growth. Moreover, the depth to which the indenter reaches in the native material and at the boundary of the heat affected zone of the native material in all analysed states of laser treatment is the same.

The hardness changes of the surface layers obtained by remelting and alloying with carbides using the high power diode laser are accompanied by the improved tribological properties in comparison with the conventionally heat treated steel.

To determine the abrasion wear resistance the surface layers of steel obtained with laser treatment were subjected to the abrasion wear resistance test according to the American ASTM standard. The mass loss increase was revealed along with the laser beam power increase in case of steel test pieces subjected to laser remelting.

However, in case of alloying the mass loss decrease was observed in proportion to the laser power increase, the smallest mass loss occurs in case of the surface layers subjected to alloying with vanadium carbide, among which the minimum mass loss determined according to formula 1 is 47.4085 % for laser power of 2.0 kW. Whereas the biggest mass loss of about 152.3511 % was observed, among all particles used, in the surface laser of steel alloyed with tungsten carbide at laser beam power of 1.2 kW. One can also notice, basing on the abrasion wear resistance test, that the smallest average mass loss in proportion to the laser beam power employed occurs during alloying with the niobium carbide and vanadium carbide. The biggest mass loss for the majority of the analysed cases was observed for the alloyed surface layers obtained using the laser beam power of 1.2 kW.

The biggest mass loss was revealed for the laser beam power of 2.3 kW only in case of the surface layer alloyed with the vanadium carbide which may result from the fact that this layer is not free from defects like numerous cracks and micro-cracks.

The results presented above are also confirmed by research carried out on the device designed in the Institute of Engineering Materials and Biomaterials in which the steel ball features the abrasive material. This test was intended to compare the abrasion wear resistance of the obtained surface layers with the service condition, therefore the test was made in the metal-metal setup. The steel ball suffers the significant wear for surface layer alloyed with the VC and TiC particles; whereas, the wear profile of the surface layers is minimum.

These layers are characteristic of the best tribological properties among all the used particles. Both observations of the steel counter-specimen wear and the surface layers' wear profiles confirm the best tribological properties compared to the conventionally heat treated steel.

4. Conclusions

Due to the martensitic transformation of the hot work tool steel subjected to remelting and alloying with carbides steel hardness growth occurs usually compared to hardness of about 51.8 HRC after the conventional heat treatment. The maximum hardness of 67.4 HRC the investigated steel achieves in case of alloying with the tantalum 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 100% higher in case of the tantalum carbide than in case of the native material. The hardness changes of the surface layers obtained by remelting and alloying with carbides using the high power diode laser are accompanied with the improved tribological properties compared to the conventionally heat treated steel. Only in case of the surface layer alloyed with the vanadium carbide the abrasion wear resistance deteriorates, which may result from the fact that these layers are not free from defects like numerous cracks and micro-cracks. The highest abrasion wear resistance, more than 2.5 times higher than that of the native material, was revealed in case the steel alloyed with vanadium carbide.

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 for manufacturing and regeneration of various tools from the X38CrMoV5-3 hot-work tool steel.

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