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Functional properties of laser modified surface of tool steel

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ABSTRACT

Purpose: Investigations include alloying the surface of X40CrMoV5-1 hot-work tool steel with tungsten carbide using a 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: The fine grained martensite structure is responsible for hardness increase of the alloyed layer. The dependence is presented of micro-hardness change on the laser beam effect on the treated surface, and especially the hardness increase in the alloyed layer. The tribological wear relationships were determined for laser treated surface layers, determining friction coefficient, mass loss, and wear trace shape developed due to the abrasive wear of the investigated surfaces. The X40CrMoV5-1 conventionally heat treated steel was used as reference material.

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

The basic and most often applied materials for manufacturing hot-work tools and also metal forms used in casting are alloyed hot-work steel. The properties of a surface layer of those steel must protect against the lost of expoitation durability and in particular must be characterised by wear resistance at the higher temperature, load and corrosion resitance of processed material [1-5].

Hot-work tool steel belongs to the group of martensitic steel used in the production of forging tools. The microstructure of hot-work tool steel changes several times during the complex thermo-plastic treatment [5]. The aim of this processing is to obtain high wear and thermal fatigue resistance. Carbides release of two kinds is responsible for high mechanical properties. The primary release - produced in the process of crystallisation and the secondary release – a result of the thermoplastic treatment. The examination of the possibilities of the increase of application properties of tool steels having martensitic matrix by the change of chemical composition in the conventional way is very limited. It may be expected that the wear resistance as well as hardness and chemical stability will be increased in the materials in which additional, more stable and hard molecules were introduced to the native material.

The future direction of research into the improvement of materials properties is a laser modification of the tool surface layer structure either by a laser relmelting or alloying by the use of materials such as tungsten carbides having huge hardness. The effect of the process in which the cooling speed is very high, is the minute-grained structured material with over-cooling phases [7,9]. The difficulty of that method results from two facts. First of all, it is hard to operate the concentrated source of heat and secondly, there is no theoretical data defining expected new structures created under those conditions. Empirical data, on which one usually is based, is not treated precisely as the only source of knowledge because the process is characterised by same deviation from the state of balance, resulting from high increase in temperature as well as great thermal gradients [6-14].

The goal of the work is to determine the technical and technological conditions for alloying the surface layer of the X40CrMoV5-1 hot work alloyed tool steel with the high power diode laser (HPDL), and of the relationship between the parameters of laser treatment and the properties of the surface layer which increase the exploitation durability of hot- work tools.

2. Investigation procedure

The specimens from the X40CrMoV5-1 alloyed hot-work tool steel, obtained from the vacuum melt, and made as O.D. 75 mm bars, featured material for investigation. Specimens of thickness of O.D, 70 mm and 6 mm were turned from the material delivered in the soft annealed state, which were next austenitised in the salt bath furnace and tempered in the chamber furnace with the argon protective atmosphere. The specimens were gradually heated to the austenitising temperature with holding at the temperature of 650°C for 15 min and austenitised for 30 min at temperature of 1060°C. Cooling was made in hot oil. After quenching, the specimens were tempered twice, each time for 2 hours, in the temperature 510°C.

Specimen surfaces were sand blasted and machined on the magnetic grinder. The thickness of the coating applied to the specimens was 0,06 mm and 0,11 mm. The coating contains WC powder and an inorganic binding agent. The laser treatment was carried out with the continuous-wave High Power Diode Laser (HPDL) Rofin DL 020. Samples were mounted on the rotary positioning stage, and the laser beam was focused at the top surface. Two remelting paths were done on each of the face surfaces of the specimens with radii of 12 and 22 mm. The laser spot size was 1,8 x 6,8 mm. Working focal length (measured from a protecting glass surface in a head) equals 92 mm. The multi-mode energy distribution was used.

Remelting of specimens was carried out at the constant remelting rate of 0.5 m/min, changing the laser beam power in the range of 0,5-1,9 kW. It was determined experimentally that the full shielding of the remelting zone is ensured by argon blow-in with the volume flow of 20 l/min through the circular nozzle of the ϕ 12mm diameter, directed in the direction opposite to the remelting one. The specimens' surfaces were ground after remelting to obtain roughness specified by ASTM G99-90 standard.

The research of the structure as well as the measurement of the thickness of proper zones of the surface layer were also conducted by comparison with transverse microsections in the Opton DSM 940 scanning microscope at the magnification of 1000 and 5000x. Examinations of the micro-hardness of surface layers were made on the SHIMADZU DUH 202 ultra-micro-hardness tester. The test of dry wear resistance with the pin-on-disk method were made on the computer controlled CSEM High Temperature Tribometer. Friction force between the ball and the disk was measured during the test run. Basing on the preliminary experiments the following test conditions were assumed: the smallest scatter of results and stable tribological characteristics were obtained for the counter-specimen in the form of the 6 mm diameter ball from the aluminium oxide Al_2O_3. In this test the stationary ball was pressed against the disk rotating in the horizontal plane with the force of 10N. The rubbing speed was 0.5 m/sec, friction radius was from 11 to 22 mm, and the optimum friction distance was determined as 1000 m. The temperature of the environment was assumed as 23°C, and the relative air humidity as 50%. Measurement of the specimens mass loss was made on the Mettler AT 201 electronic weigher, cleaning the specimens form the wear products in the friction zone with the air jet. The analysis of the counter-specimen wear land (Al_2O_3 ball) was made using the light microscope with the Image – Pro Measure Version 1.3 image analysis system at magnification 50x.

Fig. 1. The structure of surface layer after alloying by a HPDL laser; dendrites morphology of alloying area; travel speed – 0,5m/min, laser power – 1,1 kW, thickness of the coating – 0,11mm (500x)

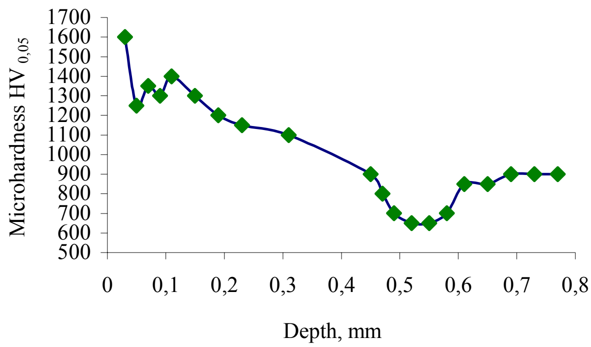

Fig. 2. Hardness profile of laser alloyed surface layer; travel speed – 0,5m/s, laser power – 0,9 kW, thickness of the coating – 0,06mm

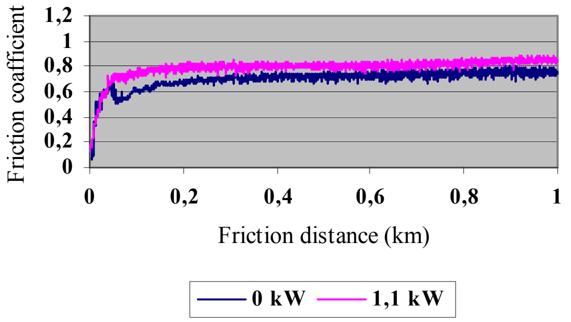

Fig. 3. Friction characteristics of the Al_2O_3 and the X40CrMoV5-1 steel surface layer pair

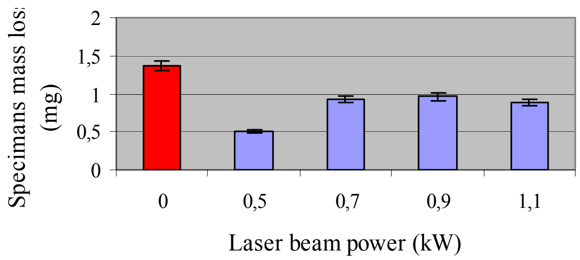

Fig. 4. Measurement results of the average specimen mass loss depending on the laser beam power

3. Discussion of the investigation results

Previous tests of laser remelting and alloying with tungsten carbide WC substrate of alloyed hot-work tool steel X40CrMoV5-1 show distinct influence of process parameters, especially laser power, on the shape of bead face. In the optimal range of laser power regular and flat face of bead without undercuts were observed.

The strong circulation of liquid metal was observed and after the transition of laser beam, rapid solidification leading to surface freezing took place. Rapid crystallisation leads to diversification of morphology in the intersection of the remelted area. Increasing the laser power, thickness of the replaced coating of tungsten carbide WC and decrease of the travel speed cause increase of roughness and irregular shape of the bead. The effect is connected in the increase in radiation absorption of the laser by the surface of the steel sample. It is possible because of high absorption coefficient of tungsten carbide. The increase is responsible for the growth of in intensity of the process of surface layer alloying.

On the basis of metallographic research, it was stated that the structure of material solidified after laser remelting is characterised by diverse morphology, connected with steel crystallisation speed (Fig. 1). In the initial stage of solidification crystals increase epitaxially, take the structure and the orientation of partially melted grains of native materials being on the boundry between the solid and liquid phases. Because the process of solidification has begun on carbides and small matrix grains, the size of crystals at the bottom of remelted layer is much smaller than in the central part of that sphere. The intermediate stage of crystal growth is cellular and arborescent with proviledged orientation (the direction of aborescent growth equals the direction of the biggest temperature gradient). The final stage of crystal growth in the central part of the remelted sphere is charcterised by a huge segregation. The carbide clusters creating characteristic spins caused by convectional movement of remelted material was noticed (Fig. 1).

The research proves that at constant speed laser beam scanning, the change of beam power scanning, are strictly connected with the size area of the surface layer in which structural changes take place. It has been stated that the increase in power beams is followed by the increase in the thickness of the remelted area. The change goes from 0,02 mm for 0,5 kW laser beam to about 0,47 mm when the 1,9 kW laser beam is used. The thickness of the area in which the laser beam has been applied rises proportionally to all values of laser beam and change from 0,15 mm to 0,80 mm.

In Figure 2 the distribution of surface layer microhardness in the function of the distance from remelting surface is presented. The microhardeness measurements confirm stratified structure of the remelting sphere. The scatter of results of microhardness on the section of the remelted sphere, which is connected with the presence of numerous fluctuations of the chemical composition in the remelted sphere, was observed. Hardness of the remelted sphere is significantly higher (ca. 1400 $HV_{0,05}$) than the sphere of warm influence (ca. 800 $HV_{0,05}$). Together with the distance growth from the surface microhardness grows again achieving the value of native material microhardness equalled ca. 900 $HV_{0,05}$.

The examined specimens were tribologically damaged due to action of the counter-specimen with the load of 10 N, along the friction distance of 1000 m. To analyse changes of the friction coefficient, plots of friction coefficient μ as function of friction distance were made. The comparison of the transient part of the friction coefficient plot for the surface layer of steel after heat treatment and after the laser alloying is presented in Figure 10. The value of the friction coefficient was evaluated as the average from the instantaneous values obtained for the part of the characteristics relevant for the stabilised friction (Fig. 3). The significant effect of laser alloying of the surface layer on decrease of friction coefficient, compared to the standard heattreatment only was observed. The tests with the gravimetric method were carried out weighing each specimen three times before the experiment and after the test and their results were statistically analysed. Confidence intervals calculated with the probability of 95% are marked in the plots. Test results of the average specimens mass loss due to friction in the ball – disk pair for the surface layer obtained at various laser beam power values are presented in figure 4. It turns out from the analysis of the mass loss of specimens, depending on the laser beam power used for alloying of the surface layer that the mass wear of the alloyed specimens was 50% smaller and was from 0.5 mg to 0.9 mg in comparison with the material that was not subjected to laserremelting, for which this value was 1.4 mg. The laser beam power does not have any clear effect on the mass wear of the

investigated specimens. Increase in the counter-specimen wear land area was observed (0,20 to 0,27 mm^2) in the contact with the laser alloyed surface layer. The counter-specimen land wear after the contact with the X40CrMoV5-1 steel after the standard heat treatment is about three times smaller (about 0,094mm^2). The laser beam power during melting does not have a meaningful influence on the wear land of the counter-specimen from Al_2O_3.
For the tribological assessment of the examined surface layer the linear wear was measured using the wear profiles. The influence of laser alloying was found out on the depth of the transverse section of the wear path, which for the non-remelted material was about 4 µm, whereas for the surface layer alloyed by tungsten carbides with the laser beam with the 0,5 kW power it achieved value of 2,0 µm.

4. Conclusions

The outcarried tests of laser alloying of surface layers of X40CrMoV5-1 steel into tungsten carbide by melting initially coated WC coatings show that it is possible to melt having high face quality. At correctly chosen melting parameters regular and flat melting shape can be achieved.
Alloying of the tested steel causes the appearance of the surface layer in which remelted, heat affected and transient zones can be distinguished. The research on microhardness confirms the fact that the surface layer consists of several zones. It has also been proved that the hardness of the alloyed area rose to 80% in comparison with the hardness of the native material in the conventional heat treatment. The surface layer remelting experiments of the X40CrMoV5-1 steel carried out with the high power diode laser (HPDL) indicate that it is possible to obtain the friction coefficient smaller than about 15% in the pair of Al_2O_3 with the laser remelted surface layer of the steel. Employment of laser remelting leads to decrease in the mass wear of specimens during the test, due to the slower release of the wear products. The analysis of the wear profiles of the surface layer revealed decrease in the profile depths for the laser remelted materials. No meaningful effect of the laser beam power during remelting was found on the tribological properties of the surface layer of the X40CrMoV5-1 alloyed hot-work alloy steel. Obtained results confirmed the applicability of the used method of the modification of the surface layer for the improvement of its tribological properties.

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References

[1] L. Lin, Materials processing with a high power diode laser, ICALEO 1996 – Section E, 1996, 38-47
[2] J. Mateos, J.M. Cuetos, E. Fernandez, R. Vijande, Tribological behaviour of plasma sprayed WC coatings with and without laser remelting, Wear, vol. 239, 2000, 274-281
[3] T.R. Jervis and all, Tribological effects of excimer laser processing of tool steel, Surface and Coatings Technology, vol. 89, 1997, 158-164
[4] J. Kusiński, Lasers and their employment in materials engineering, Publisher „Akapit", Kraków, 2000, (in Polish)
[5] L.A. Dobrzański, Fundamentals of Materials Science and Metallurgy. Engineering with fundamentals of Materials Design, WNT, Warsaw, 2002, (in Polish)
[6] L.A. Dobrzański, M. Bonek, E. Hajduczek, A. Klimpel, Application of high power diode laser (HPDL) for alloying of X40CrMoV5-1 steel surface layer by tungsten carbides, Journal of Mat. Proc. Tech. 155-156, 2004, 1956-1963
[7] L.A. Dobrzański, M. Bonek, A. Klimpel, A. Lisiecki, Surface layer's structure of X40CrMoV5-1 steel remelted and/or WC alloyed with HPDL laser, Mat. Sci. Forum, 3(140), 2003, 69-72
[8] L.A. Dobrzański, M. Bonek, A. Klimpel, A. Lisiecki, S. Bugliosi, Tribological properties of the surface layer of the X40CrMoV5-1 steel remelted using the high power diode laser (HPDL), Proceedings of the 11th Scientific International Conference „Achievements in Mechanical and Materials Engineering" AMME'2002, Gliwice – Zakopane, 2002, 77-82
[9] A. Klimpel, High power diode laser in surfacing by welding", Welding review, Vol.6, 200, 1-6 (in Polish)
[10] L.A. Dobrzański, M. Bonek, A. Klimpel, A. Lisiecki, Effect of laser HPDL surface alloying of X40CrMoV5-1 hot-work tool steel, 4th International Conference on Industrial Tools, Bled-Celje, 2003, 723-728
[11] J. Kusiński, Microstructure, chemical composition and properties of the surface layer of M2 steel after laser melting under different conditions", Applied Surface Science, vol. 86, 1995, 317-322
[12] J. Kusiński, Wear properties of T15 PM HSS made indexable inserts after laser surface melting, Journal of Materials Processing Technology, vol. 64, 1997, 239-246
[13] A. Klimpel, High Power Diode Laser Application for Welding and Surfacing, JOM-10 International-Jubilee Conference N The Joining of Materials, Helsingor – Denmark, 2001
[14] L.A. Dobrzański, E. Jonda, M. Bonek, K. Labisz, M. Piec, A. Polok, Properties and structures of gradient layer surface of 32CrMoV12-28 hot work steel alloyed using high power diode laser, International Conference on Manufacturing and Materials Processing 2006 (ICMM 2006), Kuala Lumpur, Malaysia, 2006, 171-174