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Tribological properties of the surface layer of the X40CrMoV5-1 steel remelted using the high power diode laser (HPDL)

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The paper presents the effect of remelting parameters on the tribological properties of the surface layer of the X40CrMoV5-1 steel, using the high power diode laser (HPDL). Influence of the remelting parameters is discussed on the friction coefficient measurement results, and the quantitative measurement of wear using the gravimetric method, using the counter-specimen wear area analysis and with the surface profilography method.

1. INTRODUCTION

The phenomenon of wear of the working surface of tools due to friction features an important aspect of the contemporary surface engineering. The friction process between two surface leads to their wear and is connected with energy losses. It is disadvantageous especially when it occurs along with other factors deteriorating properties of surface layer, like corrosion, erosion, mechanical and thermal fatigue.

Hot work alloy steels used for casting moulds and for forging dies and punches are the materials that have to meet more and more stringent requirements pertaining their reliability and life. Properties of the surface layer of these steels, and especially their wear resistance at elevated temperature, resistance to high surface load and to cyclic mechanical loads have to protect hot work tools from losing their stability.

The strive to make the tool surface more resistant to action of the external conditions, induces research on improvement of their surface layers. One of the methods of improving the surface layers of materials operating in harsh conditions is laser modification of their

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structure. Currently much attention is being paid in the world to using the high power diode lasers HPDL in materials engineering. They feature the most modern, used worldwide, heat energy source, characterized – other than in the continuous operation CO_2 gas lasers and impulse operation Nd:YAG ones – by a very high radiation absorption coefficient (about 20-40% for steel), high watt-hour efficiency, and reliability. Their specific advantage used in surface engineering are the possibility of obtaining remelting in a form of a path up to 6.8 mm wide, and close to linear, energy density distribution within the laser light spot. The main goal of remelting the surface layers is modification of structure resulting in an increase of their wear, erosion, and corrosion resistance. It is a consequence of the quick crystallization due to solidification of a metal at a rate up to 10^6 °C/s. This causes development of a chemically homogeneous, fine grained surface layer without change of the chemical composition of the material.

The goal of the work is determining the technical and technological conditions for remelting 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 obtained tribological properties.

2. EXPERIMENTAL PROCEDURE

The specimens from the X40CrMoV5-1 alloy hot work tool steel, obtained from the vacuum melt, and made as O.D. 75 mm bars, featured material for investigation. The chemical composition of the steel is given in Table 1. Specimens with the O.D, 70 mm and 6 mm thick were turned from the material delivered in the soft annealed state, which were next austenitized in the salt bath furnace and tempered in the chamber furnace with the argon protective atmosphere. The specimens were gradually heated to the austenitizing temperature with holding at the temperature of 650°C for 15 min and austenitized for 30 min at a 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 range from 510 to 660°C with gradation every 30°C.

Table 1
Chemical composition of the investigated X40CrMoV5-1 steel

Steel type	Average mass concentration of elements, %								
	C	Mn	Si	Cr	W	Mo	V	P	S
X40CrMoV5-1	0,41	0,44	1,09	5,40	0,01	1,41	0,95	0,015	0,010

Specimen surfaces were sand blasted and machined on the magnetic grinder. Specimens of the X40CrMoV5-1 steel fixed to the computer controlled welding positioner were remelted with the high power laser beam (HPDL) Rofin DL 020 with parameters given in Table 2.

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 1.4-2.5 kW. Two remelting paths were done on each of the face surfaces of the specimens with radii of 12 and 22 mm.

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.

Table 2
Specification of the HPDL ROFIN DL 020 diode laser

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

Test of dry wear resistance with the pin-on-disk method were made on the computer controlled CSEM High Temperature Tribometer. Schematic diagram of the tester ball – disk operation is shown in Figure 1. The test friction spot consists of the disk – specimen rotating at the *n* rotating speed and ball pressed against this disk with a load *F* at a distance *R* from the disk centre. 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. Environment temperature 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.

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.

Wear profiles of the specimens were made on the Taylor – Hobson Form Talysurf 120L laser profile measurement gauge in the depth range from 5 μm to 20 μ and the measurement length from 500 μm to 1755 μm in three planes every 120°.

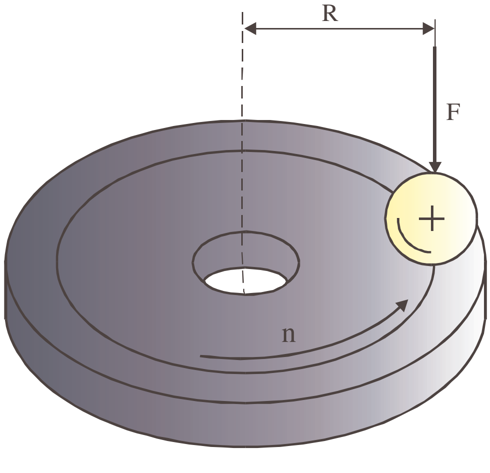

Fig. 1. Operation principle of the sphere-disk type tester

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. Comparison of the transient part of the friction coefficient plot for the surface layer of steel after heat treatment and after the laser remelting is presented in Figure 2. 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 stabilized friction (Fig. 3). The significant effect of laser remelting of the surface layer on decrease of friction coefficient, compared to

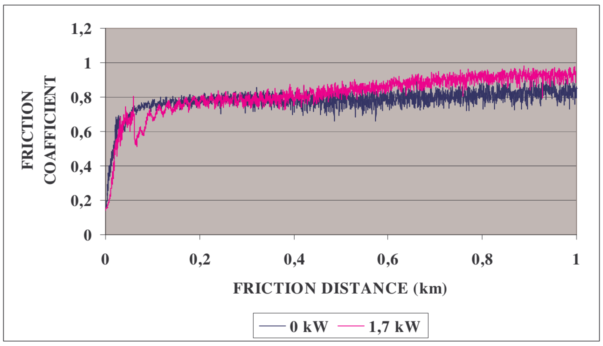

Fig. 2. Friction characterystics of the Al_2O_3 and the X40CrMoV5-1 steel surface layer pair

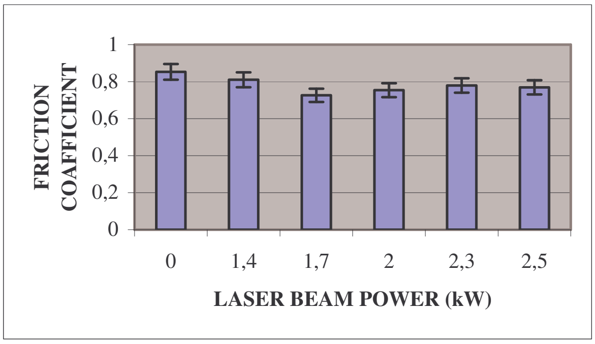

Fig. 3. Comparizon of the friction coefficient measurement results depending on the laser beam power used for remelting the steel

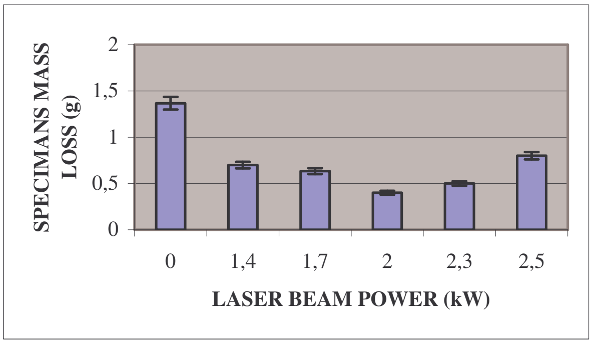

Fig. 4. Measurement results of the average specimen mass loss depending on the laser beam power

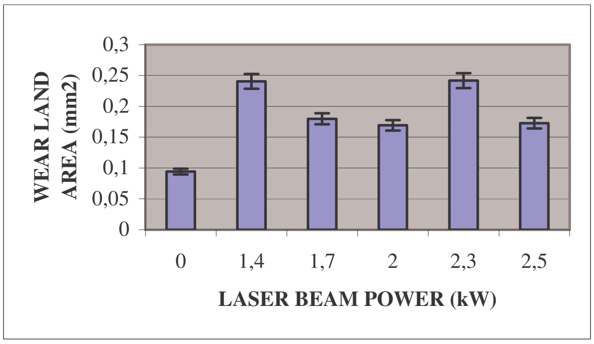

Fig. 5. Comparizon of the surface area of the Al_2O_3 counter-specimen wear

the standard heat treatment 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 analyzed. 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 remelting of the surface layer, that the mass wear of the remelted specimens was two times smaller and was from 0.4 mg to 0.8 mg in comparison with the material that was not subjected to laser remelting, 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.

The results of the counter-specimen (Al_2O_3 ball, Fig. 6) wear land area analysis during the tests of the tribological properties of the ball – disk pair are shown in Figure 5. Increase of the counter-specimen wear land area was observed (0,170 to 0,240 mm^2) in the contact with the laser remelted surface layer. The counter-specimen land wear after the contact with the X40CrMoV5-1 steel after the standard heat treatment is about two 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.

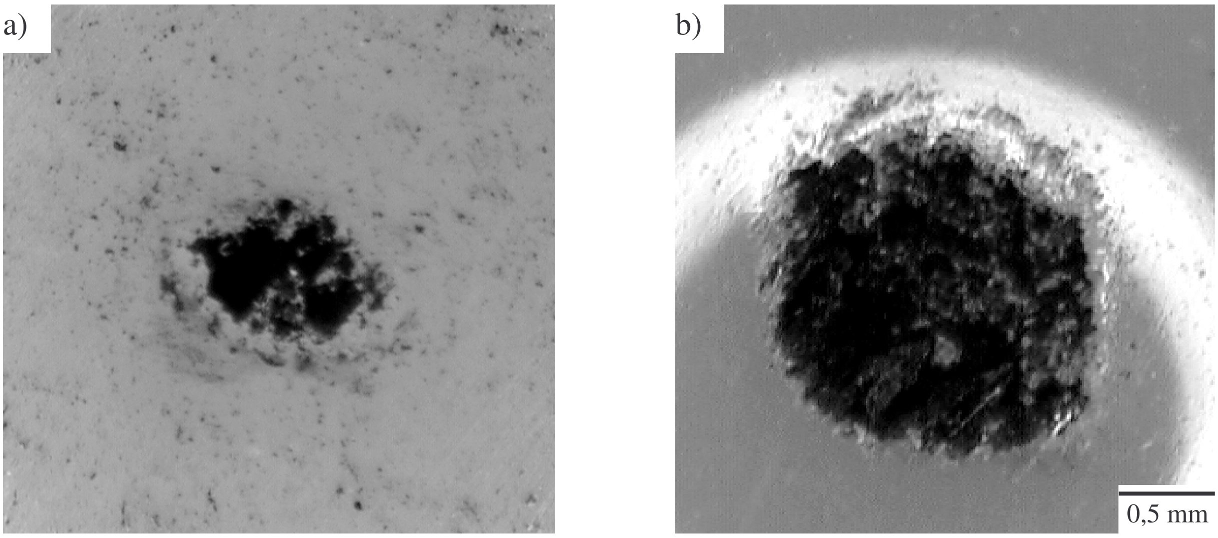

Fig. 6. The Al_2O_3 counter-specimen wear after 1000 m of friction distance: a) with the surface layer of the steel after the standard heat treatment, b) with the surface layer of the steel after remelting wiht the 2. kW laser beam

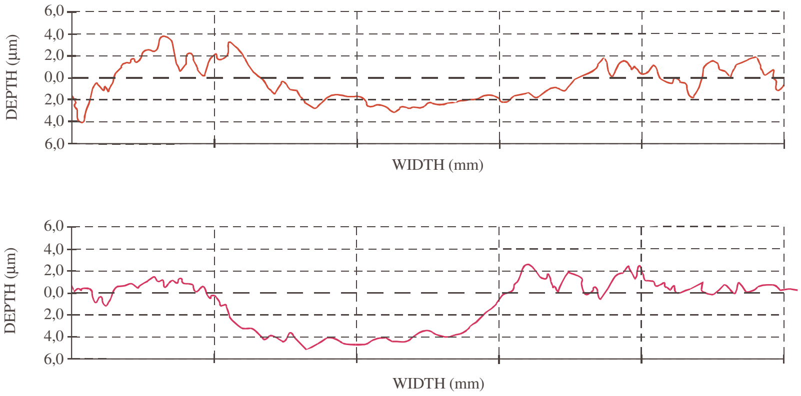

Fig. 7. Exemplary wear profile: a) steel surface layer after the standard heat treatment, b) steel surface layer after remelting with the 1.7 kW laser beam

For the tribological assessment of the examined surface layer the linear wear was measured using the wear profiles. The exemplary surface layer wear profiles of the steel are shown in Figure 7. The influence of laser remelting 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 remelted with the laser beam with the 1.7 kW power it achieved value of 1.8 µm.

The microsection surfaces were ground on the diamond discs and then polished using the diamond abrasive compounds on STRUERS equipment.

The metallographic examinations of structures and the deposited coatings were made on the LEICA MEF4A light microscope with magnifications of 100 and 1000x.

Laser remelting of alloy hot-work tool steel X40CrMoV5-1 resulted in structural changes in the surface layer: producing dendrite fusion zone, heat affected zone, distinct border between fusion zone and heat affected zone, and also border between heat affected zone and native material (Fig. 8).

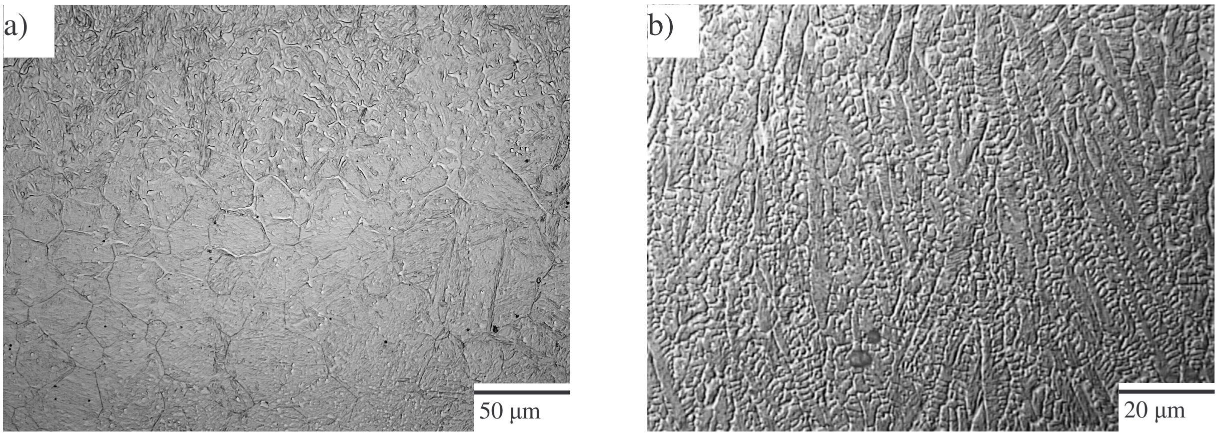

Fig. 8. The structure of surface layer after remelting: a) heat affected zone and native material; b) dendrites morphology of remelted area, travel speed – 0,5m/s, laser power – 1,0 kW

3. SUMMARY

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 by about 20% in the pair of Al_2O_3 with the laser remelted surface layer of the steel. Employment of laser remelting leads to decrease of the mass wear of specimens during the test, due to slower releasing of the wear products. Analysis of the wear profiles of the surface layer revealed decrease of 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 hot work alloy steel. Surface layer melting cause that fine-grained dendritic structure and sphere of warm influence appear. Obtained results confirmed the applicability of the used method of modification of the surface layer for improvement of its tribological properties.

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