Aleksandra PERTEK-OWSIANNA[*]

THE IRON BORIDE WEAR-RESISTANT LAYERS ON CONSTRUCTIONAL C45 STEEL, MODIFIED BY CHROMIUM AND THE LASER PROCESS

PRZECIWZUŻYCIOWE WARSTWY BORKÓW ŻELAZA NA STALI KONSTRUKCYJNEJ C45 MODYFIKOWANE CHROMEM I LASEREM

Key words:

boronizing, borochromizing, laser modification, microstructure, microhardness, frictional wear resistance

Słowa kluczowe:

borowanie, borochromowanie, modyfikacja laserowa, mikrostruktura, mikrotwardość, odporność na zużycie przez tarcie

Abstract

The paper presents the influence of diffusional boronizing, borochromizing processes, and laser modification on microstructure, microhardness, and frictional wear resistance of C45 constructional steel. The borochromizing process consists of two stages: first the boronizing was applied, and then chromizing was carried out as a second step. The boronizing was performed at 900°C for 4h, and then chromizing at 1020°C for 7h using the gas-contact method in powder containing amorphous boron and ferrochrome. Then, the

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[*] State University of Applied Science in Konin, Faculty of Engineering, ul. Przyjaźni 1, 62-510 Konin, Poland, e-mail: aleksandra.pertek-owsianna@konin.edu.pl.

boronized and borochromized layer was modified by remelting it using a TRUMPH CO_2 2600W-power laser. The microstructure after diffusional boronizing and borochromizing consists of needle-like iron borides with a thickness of 80 µm and 100 µm and with a microhardness of 1400 HV0.1–1850 HV0.1. Three zones are formed after laser modification: the remelted zone MZ (eutectic mixture of borides and martensite) with a thickness of 100–120 µm, a martensitic heat affected zone (HAZ), and the core. The microhardness in the remelted zone is approx. 1200 HV0.1, as a result of which there appears a milder hardness gradient between the surface and the core. It was found that the frictional wear resistance of the boride layers modified by chromium and laser is higher than that of the layers after diffusional boronizing.

INTRODUCTION

One of the well-known methods of surface engineering is diffusion boronizing, the purpose of which is to improve the tribological properties of machine parts and tools. Boronized layers can work in extremely difficult conditions where: even high-alloy steels and layers obtained through other kinds of thermo-chemical treatments, such as carburizing or nitriding **[L. 1, 2, 3]**, fail to serve their function.

Diffusion-borided layers are mainly manufactured in the temperature range of 850–950°C within 2-6 hours. As a result of boronizing, borides FeB and Fe_2B are formed, up to 150 µm think, with a needle-like structure, whose hardness reaches 2000 HV. The main advantage of borided layers is an increased hardness and resistance to frictional wear, high heat resistance up to 800°C, corrosion resistance in many acid and alkali solutions, and other advantages not mentioned here. Apart from their numerous advantages, these layers have certain shortcomings: brittleness in the near-surface FeB zone, which can manifest itself in flaking and peeling from the core as well as a large hardness gradient of the transition from the layer to the core **[L. 2, 3]**.

In industry, boronized layers are used for machine parts, tools for cold and hot plastic forming, tools that are subjected to frictional wear, lathing and cutting tools, and moulds for casting metal under pressure. Additionally, applying borides is highly beneficial in hardening components used in caterpillars for tractors, military tanks, construction machinery, pins for bicycle-chain links and timing chains **[L. 2, 3]**. It was found that a borided laser treatment increases the durability of moulds for casting aluminium, zinc, and copper alloys **[L. 2, 3]**. The application of borides in lathing and cutting tools is uncommon because, during the boronizing process, borides FeB tend to be formed with sharp edges of high brittleness, which are prone to chipping.

Contemporary research by many authors is concerned with the modifications of the surface layer aimed at obtaining beneficial properties, like hardness, resistance to frictional wear, corrosion resistance, heat resistance, and a structure free from imperfections (pores, brittleness, and cracks). This purpose can be achieved by layers obtained by multi-component boronizing **[L. 4]** with the use of carbon **[L. 5]**, nickel **[L. 4, 6]**, copper **[L. 7],** and chromium **[L. 7 –11]**. In order to do that, the following methods are used: gas, glow-discharge, powder boronizing, and recently alloying with boron and other chemical elements by means of a laser beam **[L. 6, 11–13]**. Laser technology is becoming more widely used due to the development and an increase in the production of a new generation of lasers.

The subject master of this research is to evaluate the structure and properties of borided surface layers modified using chromium and laser.

EXPERIMENTAL

The purpose of this research is to produce wear-resistant borided layers modified using chrome and a laser beam on steel C45. After the processes of diffusion boronizing and chromizing, the remelting of the surface laser was carried out. The microstructure of the obtained layers, microhardness profiles, and resistance to frictional wear were tested.

The tests were carried out on the samples of C45 steel with the following chemical composition [%wt]: 0.42% C, 0.72% Mn, 0.19% Si, 0.30% S, 0.008% P. The samples were ring-shaped 20 mm in external diameter, 12 mm in internal diameter, and 12 mm in height.

The borochromized surface layers were obtained during the two-stage process involving boronizing followed by chromizing, after which laser remelting was performed. The process of gas-contact boronizing was carried out at the temperature of 950°C for 4 hours, in a powder consisting of amorphous boron, KBF_4, as an activator and carbon black. At the next stage, the steel underwent diffusion chromizing at the temperature of 1020°C for 7 hours in a powder containing ferrochromium, ammonium iodide as an activator and clay **[L. 9]**. After being boronized and borochromized, the samples were hardened from the austenitization temperature of 850°C in water and tempered at 560°C for l hour.

For the laser heat treatment (LHT) of the steel, a technological laser TRUMPF TLF 2600 Turbo CO_2 with the nominal power 2600 W was applied. The laser operated with the following parameters: laser power $P = 0.91$ kW, power density $q = 28.98$ kW/cm^2, and laser beam scanning velocity $v = 3.84$ m/min, at a constant beam diameter $d = 2$mm and the distance of the lens optical centre from the surface of the object $\Delta l = 108$ mm. In the test, a helical line pitch $f = 0.5$ mm was applied, as a result of which adjacent laser tracks are obtained on the treated surface **[L. 9, 13]**.

The tests of microstructure were performed using an optical microscope Metaval Carl Zeiss Jena along with a camera 2300 3.0 MP and Live Motic Images Plus 2.0 Resolution software. The metallographic observations of the microstructure were conducted on polished metallographic micro-sections as well as on the ones that were etched in a 2% nitric acid solution. A scanning electron microscope Tescan VEGA 5135 equipped with EDS PGT Avalon spectrometer was used in order to analyse the chemical composition, that is, the content of chromium, boron, and iron.

The microhardness measurements of the samples were carried out by means of Vickers method using a ZWICK 3212 B-microhardness tester under a load of 0.1 kG (0.98 N).

The tests of resistance to frictional wear were carried out by means of a tribometer MBT-01 type Amsler with the following settings: the sample – a rotating ring / plate and the counter-sample-sintered carbide S20S with a hardness of 1430 HV. The tests of resistance to dry friction wear were carried out under a constant load of F = 147 N and at a sample rotation speed of v = 0.26 m/s (n = 250 rev/min).

Wear resistance was determined based on a sample mass loss (Δm [mg]), in relation to friction surface (F [cm^2]) and time (t [h]), with wear intensity assumed as a coefficient and determined by I_w [$mg/cm^2 \cdot h$].

TEST RESULTS AND DISCUSSION

The boronized layer with a thickness of approx. 80 μm, shown in **Figure 1**, has a characteristic needle-like structure of iron borides FeB (with higher porosity) at the surface and borides Fe_2B, which are found deeper. After the two-stage borochromizing process, there are distinctly visible two zones, at the surface there is a constant zone with a thickness of approx. 20–30 μm, enriched with chromium; whereas, deeper, there is a zone consisting of iron borides **(Fig. 2)**. In view of the high temperature of chromizing (1020°C) close to eutectic temperature (1149°C) – according to the equilibrium diagram Fe-B **[L. 2, 3]** and the long time of the process (7 h), the morphology of the layer changed, and the diffusivity of boron increased. In the microstructure at the core, the needles are rounded, and the layer reaches a thickness of approx. 100 μm.

The scanning electron microanalysis **(Fig. 3)** indicates that, in the near-surface zone, there is a saturation with chromium from approx. 54.93 wt% ± 6.48 wt%, which gradually decreases; and, at a distance beginning from approx. 30 μm, it assumes the value of approx. 1 wt%. At the same time, in the zone of higher content of chromium, there is a lower concentration of iron, approx. 28%wt% ± 6.48%wt%, which increases with the distance from the surface.

The increased content of boron at the surface up to approx. 25.07 wt% ± 4.34 wt%, shows that, in this zone, there is a possibility of a phase FeB or CrB **[L. 11]**, whose presence can be proven by a X-ray phase analysis. The average surface content of boron, 10.91 wt% ± 4.34 wt%, indicates that borides Fe_2B with the content of 8.83 wt% boron, according to the equilibrium diagram Fe-B **[L. 2, 3]**, predominate deep within the layer.

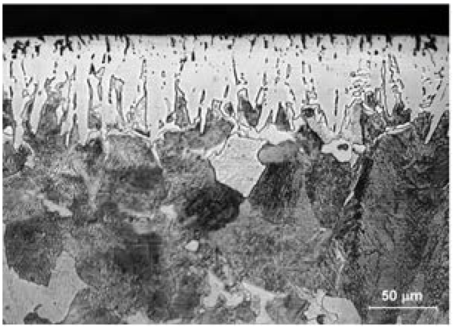

Fig. 1. Microstructure of boronized layer
Rys. 1. Mikrostruktura warstwy borowanej

Fig. 2. Microstructure of borochromized layer
Rys. 2. Mikrostruktura warstwy borochromowanej

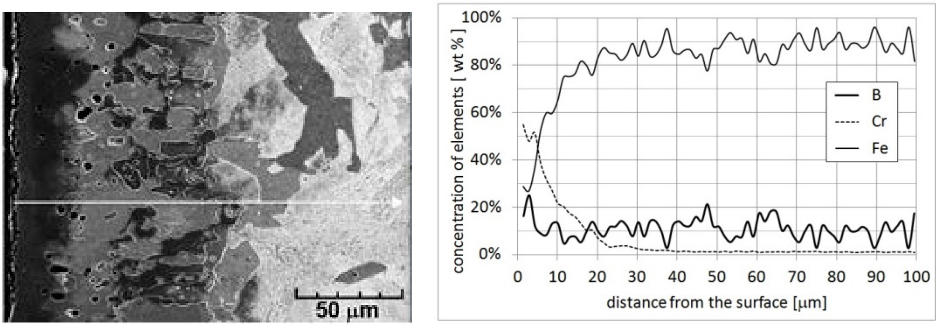

Fig. 3. EDS chemical composition analysis of borochromized layer
Rys. 3. Analiza EDS składu chemicznego warstwy borochromowanej

Figure 4 shows the microstructure obtained after the laser remelting of the boronized layer, and **Figure 5** shows the borochromized one. As a result of remelting, there appeared a fluctuation in the chemical composition of the surface layer material with the core material in the melting pool; after solidification, three zones are visible within the laser track: the melted zone (MZ) and the heat affected zone (HAZ) and the core. The remelted zone, whose depth reaches up to approx. 110 µm, contains boride–martensitic eutectic, whereas the heat-affected zone, whose depth reaches up to approx. 110 µm, is composed of a martensitic structure **[L. 11, 13].**

At the border of the laser tracks that overlap each other partially with the heat-affected zones, unmelted borides can be seen for the applied power and laser beam scanning velocity **(Figs. 4, 5)**.

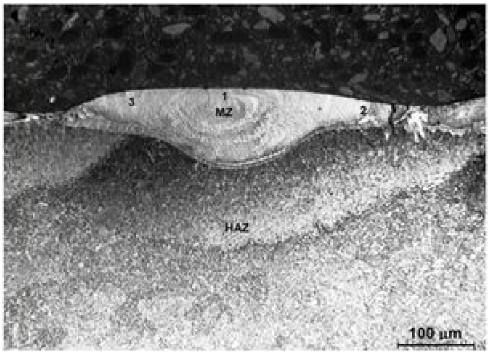

Fig. 4. Microstructure of boronized C45 steel after laser surface modification
Rys. 4. Mikrostruktura stali C45 borowanej modyfikowanej laserem

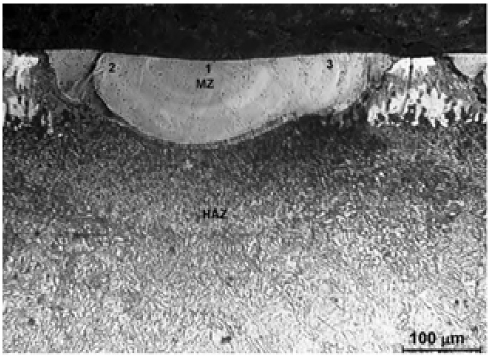

Fig. 5. Microstructure of borochromized C45 steel modified by laser
Rys. 5. Mikrostruktura stali C45 borochromowanej modyfikowanej laserem

Mircoanalyse tests **(Fig. 6)** showed that, within the whole area of the remelted zone, chromium is evenly spread in the quantity of approx. 4.69 wt% ± 0.59 wt%. The concentration of iron is also stable within the area of the remelted zone.

Figures 7, 8, and **9** show the measurement results of microhardness tests of steel C45 after boronizing, borochromizing, and laser remelting. The boronized steel has a microhardness of approx. 1400–1850 HV0.1 in the FeB phase and approx. 1400 HV0.1 in the Fe_2B phase, which rapidly decreases towards the core with the microhardness of approx. 190 HV0.1 without heat treatment **(Fig. 7)** and approx. 280 HV0.1 after the heat treatment of the steel **(Fig. 8)**.

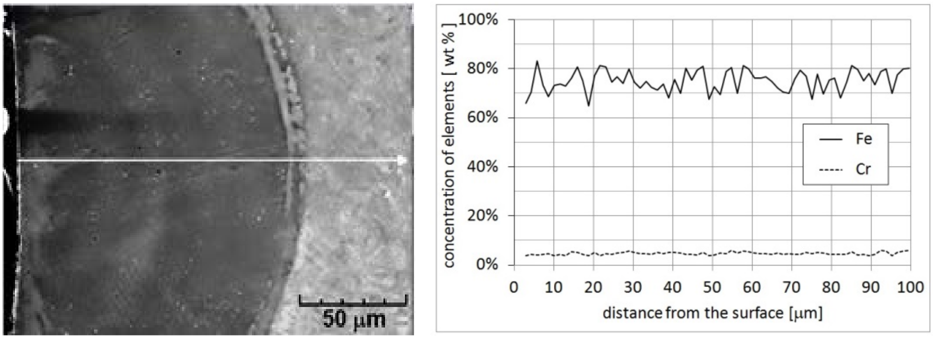

Fig. 6. EDS chemical composition analysis of borochromized layer after laser surface modification
Rys. 6. Analiza EDS składu chemicznego warstwy borochromowanej modyfikowanej laserem

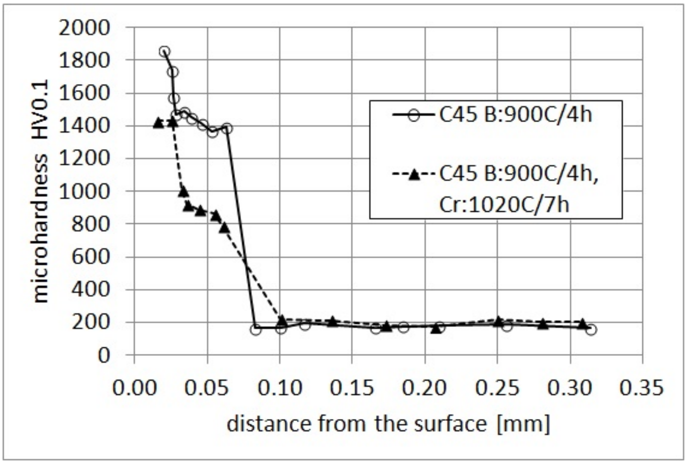

Fig. 7. Microhardness profiles in boronized and borochromized layer
Rys. 7. Profile mikrotwardości w warstwie borowanej i borochromowanej

After the borochromizing process in the near-surface zone, the microhardness is lower than after boronizing and amounts to approx. 1400 HV0.1, and deeper within the layer, it falls within the range of 800–1000 HV0.1, after which it decreases towards the core **(Fig. 7)**.

After the laser remelting, due to the zonal structure of the tracks and the change in the microstructure **(Figs. 4, 5)** as well as a higher thickness of the layer, the microhardness is lower, but it is spread more evenly within the whole area of the remelted zone with a value of approx. 1100–1300 HV0.1 **(Figs. 8, 9)**. On the tracks where: borides were not remelted, microhardness may be locally higher **(Fig. 9)**. In the heat-affected zone, microhardness reaches

700–800 HV0.1, and it gradually decreases towards the core to approx. 280 HV0.1. Therefore, microhardness gradient between the surface and the core is smaller and milder, and more beneficial than in the boronized zone.

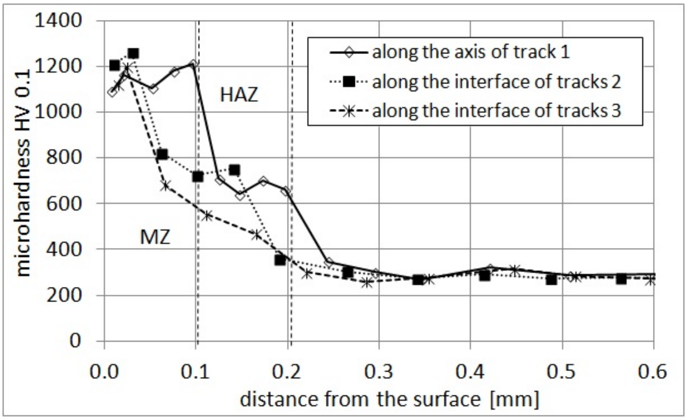

Fig. 8. Microhardness profiles in boronized layer after laser surface modification
Rys. 8. Profile mikrotwardości w warstwie borowanej po laserowej modyfikacji

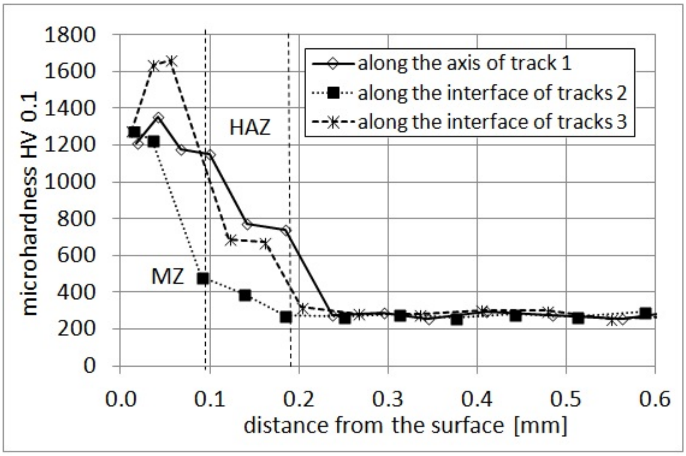

Fig. 9. Microhardness profiles in the borochromized layer after laser modification
Rys. 9. Profile mikrotwardości w warstwie borochromowanej po laserowej modyfikacji

The results of tests on frictional wear resistance are show in **Figure 10**. Boronized layers exhibit good frictional wear resistance, which is recognized and confirmed in earlier research **[L. 3, 13]**. Their wear intensity coefficient is 1.65 [mg/cm^2·h**]**, but the mass loss in the near-surface zone is higher than in the remaining zones because of **the surface** caused by the occurrence of brittle FeB boride zone during running-in **[L. 2, 3, 13]**. The wear resistance of layers after diffusion borochromizing is lower than that of boronized ones, because the boride structure was noticeably changed after chromizing at a high temperature and after a long period of time, i.e. microhardness of layers is lower, and grains in the core are oversized. After laser modification, both the boronized layer and the borochromized layer have improved tribological properties.

Due to the chromium occurrence, the borochromized layer after laser modification exhibits a lower wear intensity coefficient $I_w = 0.78$ [mg/cm^2·h] than the boronized layer after laser remelting, for which $I_w = 1.52$ [mg/cm^2·h].

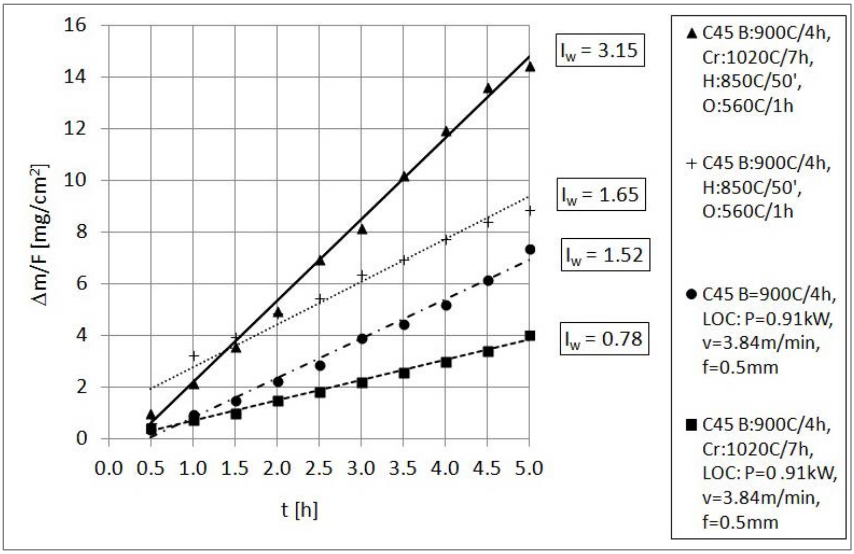

Fig. 10. Frictional wear resistance of boronized and borochromized layers
Rys. 10. Odporność na zużycie przez tarcie warstw borowanych i borochromowanych

CONCLUSION

Wear resistance properties of surface layers produced on C45 steel can be shaped by diffusional saturation with boron and chromium and then by laser remelting. The test results indicate that the morphology of boronized and borochromized layers after laser treatment changes from a needle-like structure into adjacent tracks consisting of remelted zones partially overlapping heat affected zones. Located in the boronized zone at the surface, the zone of iron borides FeB, characterized by high microhardness and brittleness, disappears. The eutectic boride–martensitic structure is formed in the remelted zone, the microhardness of the layers decreases, and the gradient between the surface and the core is milder. As a result of laser modification, the boronized layer is saturated with chromium (the borochromized one), thanks to which it obtains higher frictional wear resistance from the boronized layer.

ACKNOWLEDGEMENTS

Research work was conducted within the period from 2013 to 2015 in the Institute of Material Science and Engineering, Poznan Technical University. The author would like to thank the following people for cooperation during laser surface modification: prof. Mieczysław Kawalec, PhD. Eng. Marian Jankowiak and Ireneusz Nowak from Institute of Mechanical Technology, Poznań Technical University.

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Streszczenie

W pracy przedstawiono wpływ procesu borowania i borochromowania dyfuzyjnego oraz laserowej modyfikacji na mikrostrukturę, mikrotwardość i odporność na zużycie przez tarcie stali konstrukcyjnej C45. Proces borochromowania składa się z dwóch etapów: borowania, a następnie chromowania. Borowanie przeprowadzono w temperaturze i czasie wynoszącym 900°C i 4 h, a chromowanie w 1020°C i 7 h w mieszaninie proszkowej zawierającej bor amorficzny i żelazo-chrom. Warstwy borowane i borochromowane następnie poddano modyfikacji przez przetopienie laserem CO_2 firmy TRUMPH o mocy 2600 W. Mikrostruktura warstw borowanych i borochromowanych dyfuzyjnie zawiera iglaste borki żelaza o grubości ok. 80 µm i 100 µm oraz mikrotwardości 1400–1850 HV0.1. Po laserowej modyfikacji otrzymuje się trzy strefy: przetopioną MZ o grubości 100–120 µm (mieszanina eutektyczna borków i martenzytu), martenzytyczną strefę wpływu ciepła HAZ, a następnie rdzeń. Mikrotwardość w strefie przetopionej wynosi ok. 1200 HV0.1, stąd wynika łagodniejszy gradient twardości między powierzchnią a rdzeniem. Stwierdzono, że warstwy borków modyfikowane chromem i laserem wykazują wyższą odporność na zużycie przez tarcie od borowanych dyfuzyjnie.