ALEKSANDRA PERTEK-OWSIANNA*, KAROLINA WIŚNIEWSKA-MLECZKO**, DOMINIKA PANFIL***, ANETA BARTKOWSKA****

TESTING THE STRUCTURE AND PROPERTIES OF STEELS AFTER HARDFACING AND LASER TREATMENT

BADANIA STRUKTURY I WŁAŚCIWOŚCI STALI PO NAPAWANIU I OBRÓBCE LASEROWEJ

Key words: hardfacing, laser alloying with boron, structure, hardness, tribological properties.

Abstract
This paper analyses the structure, hardness, and frictional wear resistance of surface layers formed on steels after hardfacing by means of the SSA arc method with self-shielded flux cored welding wire, with a content of carbon 5% and chromium 30% as well as boron alloying with the CO₂ laser. S355J2 steel after being hardfaced with one up to three layers is characterized by the martensitic structure with chromium carbides and its surface hardness is 50–55 HRC. In the weld deposit zone, with a thickness of up to approx. 2 mm, there is a constant distribution of hardness with the average value of 700 HV0.1, and then the hardness decreases to approx. 160 HV0.1 in the steel substrate. After hardfacing, the carbon content in S355J2 steel (0.23% wt.) increases to a similar content as in steel C90U in the initial state (0.96% wt.). After laser alloying with boron and after rapid cooling, C90U steel obtains distinctive paths with a zone structure and thickness reaching up to approx. 380 μm. In the remelted zone, there is a eutectic structure consisting of a mixture of iron borides and martensite with a hardness of approx. 1200–1800 HV0.1, and beneath it, there is heat affected zone with a martensite-bainite structure with a hardness of approx. 700 HV0.1. Hardfacing and laser heat treatment significantly decrease the frictional wear of the tested steels.

Słowa kluczowe: napawanie, stopowanie laserowe borem, struktura, twardość, właściwości tribologiczne.

Streszczenie
W pracy przeanalizowano strukturę, twardość oraz odporność na zużycie przez tarcie warstw wierzchnich stali po napawaniu metodą łukową SSA drutem proszkowym samoosłonowym o zawartości węgla (5%) i chromu (30%) oraz stopowaniu borem za pomocą lasera CO₂. Stal S355J2 po napawaniu jedną do trzech warstw charakteryzuje się strukturą martensytową z węglikami chromu o twardości powierzchni 50–55 HRC. W strefie napoiny o grubości do ok. 2 mm występuje stały rozkład twardości o średniej wartości 700 HV0.1, po czym twardość spada w rdzeniu stali do ok. 160 HV0.1. Po napawaniu zawartość węgla w stali S355J2 (0.23% mas.) wzrasta do podobnej jak w stali C90U w stanie wyjściowym (0.96% mas.). Stal C90U po stopowaniu laserowym borem i szybkim ochłodzeniu uzyskuje charakterystyczne ścieżki o budowie strefowej i grubości dochodzącej do ok. 380 μm. W strefie przetopionej występuje struktura eutektyki będącej mieszaniną borków żelaza i martenzytu o twardości ok. 1100–1800 HV0.1, a pod nią znajduje się strefa wpływem ciepła o strukturze martensytowo-bainitycznej i twardości ok. 700 HV0.1. Napawanie oraz laserowa obróbka cieplna w sposób istotny zmniejsza zużycie przez tarcie badanych stali.

INTRODUCTION

The resistance of devices, machine parts, and tools to external conditions, such as frictional wear, corrosion, mechanical and thermal fatigue and others, depends on the types of materials used to manufacture the equipment in question and the surface layers of such materials [L. 1]. Steel wear is a serious problem for heavy duty
machinery used in road construction, mining, and agriculture, where elements of some of their subsystems, mainly, grabs, augers, digger buckets, ploughshares, coulters etc., have a direct contact with soil and minerals [L. 2–8].

Steels used in the production of farming equipment working in soil and in coalmines are construction steels which include S45C, S235, S355, 18G2A, and 38GSA [L. 4–10], which demonstrate a larger wear than low-alloyed steels with the addition of boron, for example, HARDOX, B27, and Creusabro, XAR, BRINAR, which are characterized by a better hardenability, high resistance to frictional wear and surface load [L. 5, 7, 9, 14].

Apart from the use of steel displaying good mechanical properties in heavy duty machinery, surface treatment of the materials used can also improve the quality of such equipment. It allows preserving the native properties of the material for the core of the tool and achieving the desired properties exclusively for the surface exposed to wear. One of the methods of changing the properties of the surface layer is modification through introducing additional materials by heating and melting them. These materials can have the form of wire, powder, paste, tape, and they are subjected to partial melting and mixing with the material of the core. This can be achieved by hardfacing, spraying, and alloying. The well-known methods of modification, besides hardfacing and spraying, also include the traditional methods of welding, i.e. flame, arc – MMA, GMA methods [L. 5, 7, 11–13] as well as plasma and laser [L. 4, 9, 14].

Among the first materials to be added during the hardfacing process are cobalt-based hard alloys, called stellite [L. 2, 14, 15] and the ones containing chromium, tungsten, niobium carbides, which are still in use [L. 2–7]. In addition to the above-mentioned materials, other alloys, such as the superalloys, based on Inconel nickel, are used to produce heat-resistant and high-temperature-resistant weld deposits on the heads of marine engines made of 13CrMo4-5 steel [L. 15].

Flux cored arc welding is a widely known method among the many ways used for hardfacing. In the tests described in publications [L. 3], a self-shielded flux cored welding wire containing C, Cr, and Nb was used for hardfacing S235 steel. The following was obtained: chromium carbides Cr<sub>c</sub>C<sub>1</sub>, complex compounds (Cr, Fe)<sub>c</sub>C<sub>1</sub>, and Nb<sub>c</sub>C<sub>2</sub> in the α-Fe matrix. It was demonstrated that the hardness of the weld deposit containing niobium carbides is higher than the hardness of the one containing chromium carbides, and it amounts to 800–900HV30. The results of the tests carried out in paper [L. 12] show that, when the content of chromium in alloy Fe-Cr-C exceeds 35% wt, the weld deposit formed on non-alloy steel S45C by means of the gas tungsten arc welding method (GTAW) contains phase (Cr,Fe)<sub>c</sub>C<sub>1</sub> in its eutectics as an alloy reinforcement, which demonstrates a higher resistance than phase (Cr,Fe)<sub>c</sub>C.<sub>1</sub>

Papers [L. 5–7] present the results of the tests on the wear intensity of samples and ploughshares, in the normal soil conditions, made of new grades of steel, such as XAR, BRINAR, HARDOX, and B27 in comparison to conventional steel 38 GSA. It was demonstrated that the wear intensity of working elements is determined by the properties of the entire working element, not exclusively by the properties of the surface layer.

In the test carried out for paper [L. 5], the cutting surface of steel XAR 600 was covered with a weld deposit by means of an electrode containing chromium carbide and by means of electrode chromium and niobium carbides, and steel 38 GSA covered with sintered tungsten carbide. The highest hardness of surface layers was observed for carbide G10 (1430 HV10) in the following order: XHD 6715 (820 HV10), and XHD 6710 (795 HV10) in comparison to steel XAR 600 (627.2 HV10). On the basis of the results obtained during the in-service testing, it was found that, due to the substantial content of fine chromium carbides, the highest frictional wear resistance was observed in samples hardfaced by means of electrode XHD 6710.

Publication [L. 6] analyses the wear processes of ploughshares made of Hardox 500, B 27, and 38GSA steels, which were hardfaced by means of an electrode containing Cr and electrode containing Cr, Mn, Ni, Mo, and B. The tests carried out during the normal operation demonstrated that the use of hard layers with a ferrite alloy structure containing chromium carbides contributes to a significant reduction in wear intensity in comparison to ploughshares manufactured from steel without a special surface layer. There were no significant differences in the process of the wear of ploughshares hardfaced in the ways that depended on the parent material and additional material.

In paper [L. 7], the results of structural tests of low-alloy steel Brinar referred to abrasion resistance factors obtained by means of the “spinning bowl” method during which different soil abrasive masses were used in comparison to 38GSA steel in the normalized state. The obtained results depend on the phase structure and the level of heat treatment of the tested steels. Brinar steels showed abrasion resistance several times higher than 38GSA steels.

In publications from recent years [L. 11, 16–20], compounds from the following combinations are used to modify the surface by means of which the nanostructure is produced in the surface layer [L. 18]: Fe-Cr-Nb-C, Fe-Cr-B-C, namely, chromium carbides, niobium carbides, and carbides.

In the tests carried out in publication [L. 11], welding electrodes were used in the SMAW method for the formation of a boron coating on low-carbon SAE 1020 steel (0.18% C), 17–31% of ferroboron was used as a source of boron in the electrode shield. It was found that, with the increase in the amount of boron (2.4–7.2% wt.), which was transferred from the electrode shield onto
the coating, various levels of the boron content caused the microstructure to change from the eutectic one (α-Fe + Fe₂B) to the one (Fe₇B), and then to the eutectic one (Fe₇B + martensite). Microhardness in the coatings up to 500 μm thick had a variable hardness between 1450 HV and 1700 HV and depended on the boron content and structure. This higher microhardness was obtained with a higher boron content and the structure of (Fe₇B + martensite).

The authors of publication [L. 16] selected SAE 950C low carbon steel (0.17% C) for samples and ploughshares. They were subjected to boronizing and carburizing in comparison to non-thermally treated steel. Boronized steel with the structure containing Fe₂B borides and a hardness of 1892 HV0.05 showed the lowest wear in the laboratory tests when being subjected to abrasive papers with aluminium oxide, and they had a higher wear than the carburized one for abrasive papers with silicon carbide. It was observed that, while the surface hardness of ploughshares increases along with the increase in the degree of boronizing, the wear resistance of ploughshares under field conditions does not improve to the same extent.

Publication [L. 18] examined the microstructure, hardness, and frictional wear resistance of weld deposits containing Cr, Nb, and B formed on the iron alloy substrate (0.11% C), deposited in the FCAW process (flux cored arc welding). It was found that a double-layer weld deposits demonstrated the highest content (flux cored arc welding). It was found that a double-substrate (0.11% C), deposited in the FCAW process containing Cr, Nb, and B formed on the iron alloy hardness, and frictional wear resistance of weld deposits one (Fe₂B + martensite). Microhardness in the coatings varied from around 900 HV0.1 to 1400 HV0.1, depending on the boron content and the coating structure. The tests demonstrate that the surface hardness of the coating changes the microstructure of the surface, thus improving its hardness by 1.5 to 3 times, which translates into a 2 to 6-fold improvement in wear resistance per the hectare of the field being cultivated. The conclusion was that surface modification by means of a laser is more economical than flame spraying.

The tests presented in publications [L. 4, 6, 16] showed that there are a number of already-applied or ready-to-use technologies that improve the properties of the material and delay its wear. Such technologies can be used in agriculture, mining industry, and mineral processing. These include surface modification methods involving electric arc, plasma arc, and laser. The presented tests show that the most effective coatings can be made from materials in the following arrangements: Fe-Cr-C-Nb and Fe-B-C.

The paper presents tests carried out on coatings containing two hardening materials, namely chromium carbides and iron borides. The influence of the conditions of surface layer production on the material structure with the SSA arc and LHT methods as well as hardness and frictional wear resistance were tested.

**METHODOLOGY**

The chemical compositions of the tested steels are presented in Table 1. S355J2 high strength structural steel of general use was hardfaced. The SSA arc method was applied for hardfacing by means of self-shielded flux cored welding wire with a high content of Cr-C alloy, with the chemical composition shown in Table 2 and with a hardness of 58HRC. The high number of phases containing hypereutectic carbides of the M₇C₃ type makes the alloy suitable to be hardfaced on elements that are exposed both to strong friction by mineral substances and to rusting. A non-alloyed C90U tool steel was used for remelting and boron laser alloying (Table 1).

**Table 1. Chemical composition of steels, % wt.**

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355J2</td>
<td>0.23</td>
<td>0.60</td>
<td>1.70</td>
<td>0.35</td>
<td>0.35</td>
<td>&lt;0.04</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>C90U</td>
<td>0.96</td>
<td>0.22</td>
<td>0.25</td>
<td>-</td>
<td>-</td>
<td>0.025</td>
<td>0.025</td>
</tr>
</tbody>
</table>

**Table 2. Chemical composition of self shielded cored wire, % wt.**

<table>
<thead>
<tr>
<th>Concentration of elements [% wt.]</th>
<th>C</th>
<th>Cr</th>
<th>Si</th>
<th>Mn</th>
<th>B</th>
<th>Mo, Ni, Co, V, W, Al</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.25</td>
<td>30.20</td>
<td>1.45</td>
<td>0.20</td>
<td>0.30</td>
<td>additions</td>
<td>remaining</td>
</tr>
</tbody>
</table>

A technological laser TRUMPF TLF 2600 Turbo CO₂ with the nominal power 2.6 kW was used for the laser modification (LHT). The above mentioned laser is located at Laser Technology Laboratory of Machining Treatment Institute of Poznań Technical University.
Before proceeding with the laser heat treatment (LHT), amorphous boron with water glass in the form of paste with a thickness of approx. 0.04–0.12 mm was applied. The samples prepared in this way were subjected to a laser irradiation with a power \( P = 0.78 \text{–} 1.82 \text{ kW} \) with a constant laser beam scanning velocity of \( v = 2.88 \text{ m/min} \) and a distance between the laser tracks of \( f = 0.50 \text{ mm} \), at a constant beam diameter \( d = 2 \text{ mm} \) in the argon shield.

The observation of microstructure and the thickness measurements were made by means of a Metaval light microscope produced by Carl Zeiss Jena and equipped with a Moticam camera as well as a Tescan VEGA 5135 scanning electron microscope.

A Spectrotest JRF Micoline 182 was used in order to analyse the chemical composition of the hardfaced steel S355J2.

The microhardness measurements of the samples were carried out by means of a Vickers method using a ZWICK 3212 B microhardness tester under a load of 100 G (HV0.1).

The tests of resistance to frictional wear were carried out by means of a tribometer MBT-01 type AMSLER with the following settings: the counter-sample (plate) – the sample, and a rotating ring with the dimensions: \( D = 20 \text{ mm} \), \( d = 12 \text{ mm} \) and \( h = 12 \text{ mm} \). The counter-sample was made of 100Cr6 steel (for tests on weld deposits) with a hardness of 62 HRC or S20S sintered carbide (for tests on layers after LHT) with a hardness of 1430HV. The tests were carried out under the following conditions: load placed on the sample-counter-sample arrangement – \( P = 49 \text{ N} \) (tests on weld deposits) or \( P = 147 \text{ N} \) (tests on layers after LHT), and a rotational speed of the sample – \( n = 0.26 \text{ m/s} \). Frictional wear resistance was determined on the basis of the wear intensity factor \( I_w \): \( I_w = \Delta m / S \cdot t \left[ \text{mg/cm}^2 \cdot \text{h} \right] \), in which: \( \Delta m \) – a mass loss [mg], \( S \) – a friction surface [cm²], and \( t \) – a friction time [h]. Friction surface \( S \) is the surface of wear scar measured every 0.5 hour.

**TEST RESULTS**

**S355J2 steel after hardfacing**

Figures 1–5 present the results of tests on the hardfaced steel S355J2. The weld deposit contains 1, 2, or 3 layers with an initial thickness of 8 mm to a maximum thickness of approx. 13 mm and a hardness of 50 – 58 HRC (Fig. 1).

The average chemical composition of steel after hardfacing is shown in Table 3. The analysis shows that, after remelting and mixing of the additional material and steel substrate, the carbon content decreases from approx. 5% C in the wire and settles in all weld deposits at the level of 0.9%. In a two-layer weld deposit, the concentration of chromium increases considerably to approx. 47%, with other alloying elements not showing significant changes (except for the increase of the Ni content in the three-layer weld deposit). For this reason, as well as because of the highest surface hardness, the steel with a two-layer weld deposit was used for further testing. A larger number of weld deposits also causes cracks in the surface layer.

On the basis of the conducted tests of microstructure presented in Fig. 2, it can be concluded that, in the weld deposit zone, with a thickness of up to approx. 2 mm, there are chromium carbides based on bainitic ferrite, and in the narrow transition zone with a thickness of approx. 0.5 mm between the weld deposit layer and the substrate, there is martensite with the increased hardness in comparison to the weld deposit and the substrate, and then the structure changes into a ferritic one with a small amount of pearlite in the surface of the steel.

![Fig. 1. Samples after hardfacing: a) hardfaced one-layer, b) hardfaced two-layer, c) hardfaced thirty-layer](image)

**Table 3. Chemical composition of S355J2 steel after hardfacing, % wt.**

<table>
<thead>
<tr>
<th>Weld deposit number</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Al</th>
<th>Ti</th>
<th>V</th>
<th>Ni</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.096</td>
<td>0.673</td>
<td>0.199</td>
<td>25.91</td>
<td>0.043</td>
<td>&lt;0.0008</td>
<td>0.0394</td>
<td>&lt;0.001</td>
<td>&lt;72.17</td>
</tr>
<tr>
<td>2</td>
<td>0.871</td>
<td>0.491</td>
<td>0.079</td>
<td>&lt;47.28</td>
<td>0.013</td>
<td>0.0123</td>
<td>0.057</td>
<td>&lt;0.001</td>
<td>&lt;51.19</td>
</tr>
<tr>
<td>3</td>
<td>0.901</td>
<td>0.641</td>
<td>0.143</td>
<td>&lt;35.84</td>
<td>0.072</td>
<td>0.0485</td>
<td>0.101</td>
<td>3.67</td>
<td>&lt;57.81</td>
</tr>
</tbody>
</table>
These changes in the structure correspond to the hardness profile in the hardfaced steel shown in Fig. 3. Within the weld deposit, the microhardness oscillates around the value of 700 HV0.1. In the transition zone it increases locally to approx. 1000 HV0.1, after which, it decreases sharply to the approx. 160 HV0.1 in the substrate.

A mass wear resistance of S355J2 steel before and after hardfacing is shown in Figs. 4 and 5. On the basis of the obtained results, which have a linear character, it can be concluded that S355J2 steel in the initial state is approximately 5 times less resistant to friction than 100Cr6 bearing steel. The presence of a double-layer weld deposit increases the frictional wear resistance of S355J2 steel by approximately 3 times. Under the conditions of the test (load force P = 47 N), the frictional wear of S355J2 steel with the weld deposit formed on it is similar to the wear of bearing steel 100Cr6 in the hardened and tempered condition [mass wear intensity factor for both samples $I_w \approx 1.16 \text{ mg/(cm}^2\cdot\text{h})$].
C90U steel after laser modification

C90U steel was subjected to laser re-melting with boron with a carbon content similar to that of the weld deposit formed on S355J2 steel, obtaining the microstructure shown in Fig. 6. Three zones are visible: remelted (MZ), heat effect (HAZ), and substrate. In the remelted zone, there is a eutectic structure containing iron borides and martensite \([L. 19, 20]\). The dimensions of the laser tracks in relation to the parameters of the treatment are shown in Fig. 7. Regardless of the laser power and the thickness of the paste alloying with boron, the width of the MZ zone settles approximately at a constant level of, on average, 600 \(\mu\)m (Fig. 7a). The depth of the remelted zone MZ increases along with the laser power and the thickness of the boronizing paste from approx. 50 to 380 \(\mu\)m (Fig. 7b). The thickness of heat affected zone HAZ reaches approx. 100 \(\mu\)m (Fig. 6a).

Figure 8 shows the measurement results of the microhardness of C90U steel after laser alloying with boron. In the remelted zone, microhardness falls within the range 1100–1800 HV0.1 and then it decreases gradually in the heat affected zone to approx. 700 HV0.1 towards the substrate whose microhardness is approx. 220 HV0.1.

The most advantageous microhardness in the whole range of the melted zone was obtained for 1.04kW power, because the laser tracks are compact and without pores (Fig. 6). The tests of friction wear resistance carried out for this power are shown in Fig. 9. Under the conditions of the test (load force \(P = 147\)N), the mass wear acquires a linear character, expressed as an factor \(I_w = 1.11\) mg/(cm\(^2\)·h). For comparison, after diffusional boronizing, which is one of the most well-known and effective technologies that increase frictional wear resistance of steels, a slightly more favourable factor is obtained, namely, \(I_w = 0.98\) mg/(cm\(^2\)·h) \([L. 19]\).
The analysis of the results of the tests on the wear of the surface layer formed on the hardfaced steel (Figs. 4 and 5) and modified by laser alloying with boron (Fig. 9) shows that the layers obtained by laser treatment have a level of frictional wear resistance similar to that of the hardfaced ones, but with approx. three times higher loads.

CONCLUSIONS

The types of material and technology used for surface layer modification have an influence on the properties of the item according to the principle of synergy.

Hardfacing with the use of classical welding methods as well as laser surface modification causes that the applied material simultaneously melts along with the metal of the substrate, which is also melted at a small depth, resulting in a high-quality connection of the layer with the substrate.

For laser treatment, a very high power density of the beam and a high cooling rate results in minor deformations and a lower tendency of the item to crack.

After boron laser alloying, the layers obtained are thinner, with a very fine-grained structure, which are harder than those formed by means of hardfacing, and the desired effect is achieved after the first exposure.

The laser-modified surface layers are characterized by a gradual transition to the substrate due to the small thickness of the HAZ transitional zone with a lower hardness than the surface layer.

Laser heat treatment of steels is an alternative and more economical method than conventional welding methods.
REFERENCES


