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EVALUATION OF THE SURFACE LAYER MIKROSTRUCTURE OF HIGH CARBON ALLOY STEEL AFTER LASER MODIFICATION

Summary

This paper refers to surface layer microstructure of high carbon steel strengthened by laser heat treatment. The aim of this research was to evaluate the influence of the laser heat treatment conditions on microstructure and hardness of the surface layer of high carbon alloy steel. Laser modification consist in alloying the surface layer with boron. Molecular CO_2 *continuous Triumph laser type TLF 2600t with 2,6 kW output power and* $TEM_{0,1}$ *mode was used. Laser beam power density from 160 to 900 W/mm*^{2} *and laser beam velocity from 4,5 to 22,7 mm/s were applied during treatment. The research results allow to state, that boron average atomic concentration in the alloyed zone was 13% and did not exceed 20%. Nevertheless, it is enough for appearing the eutectic mixture (*$\alpha+Fe_2B$*). The alloyed zone was almost entirely homogenous and very fine-crystalline, especially near the surface. Areas with dendritic microstructure were found also. The thickness of the alloyed zone increased from 0,15 to 0,4 mm with increasing laser beam power density from 160 to 850 W/mm*^{2} *and decreased from 0,25 to 0,1 mm with increasing laser beam velocity from 4,5 to 22,7 mm/s. The average hardness of alloyed zone was in range of: 1100÷1600 μHV 65. The average hardness of the hardened zone from the solid state did not exceed 1000 μHV 65. The strengthen of alloyed (boronized) zone by the hardened zone from the solid state in the surface layer of high carbon alloy steel was observed to approx. 1 mm from surface. Existence of the hardened zone from the solid state after laser boronizing (as opposite to diffusion boronizing) should favor gentle changes of the internal stresses in the cross section of the surface layer of treated steel, which has a great importance in case of durability and reliability of the particular machine part.*

***Key words**: surface layer, microstructure, laser alloying*

OCENA MIKROSTRUKTURY WARSTWY WIERZCHNIEJ WYSOKOWĘGLOWEJ STALI STOPOWEJ PO MODYFIKACJI LASEROWEJ

Streszczenie

Artykuł dotyczy umocnionej za pomocą laserowej obróbki cieplnej mikrostruktury warstwy wierzchniej stali wysokowęglowej. Celem tych badań była ocena wpływu warunków laserowej obróbki cieplnej na mikrostrukturę i twardość warstwy wierzchniej wysokowęglowej stali stopowej. Modyfikacja laserowa polegała na stopowaniu warstwy wierzchniej borem. Do badań wykorzystano laser molekularny CO_2 *typ TLF 2600t o maksymalnej mocy 2,6 kW i modzie* $TEM_{0,1}$*. Podczas obróbki zastosowano gęstość mocy wiązki laserowej od 160 do 900 W/mm*^{2} *oraz prędkość jej posuwu od 4,5 do 22,7 mm/s. Wyniki badań pozwoliły stwierdzić, że średnia atomowa zawartość boru w strefie stopowanej wynosiła 13% (zawartość boru nie przekraczała 20%). Niemniej jednak, jest to wystarczająco dużo, aby powstała mieszanina eutektyczna (*$\alpha+Fe_2B$*). Strefa stopowana charakteryzowała się (prawie całkowicie) jednorodną mikrostrukturą i była bardzo drobnokrystaliczna, w szczególności przy powierzchni. Zaobserwowano również obszary z dendrytami. Grubość strefy stopowanej zwiększała się od 0,15 do 0,4 mm wraz ze wzrostem zastosowanej gęstości mocy wiązki laserowej od 160 do 850 W/mm*^{2} *oraz zmniejszała się od 0,25 do 0,1 mm wraz ze zwiększaniem prędkości wiązki laserowej od 4,5 do 22,7 mm/s. Średnia twardość strefy stopowanej była w zakresie od 1100 do 1600 μHV 65. Średnia twardość strefy zahartowanej ze stanu stałego nie przekraczała 1000 μHV 65. Umocnienie strefy stopowanej (borowanej) przez zahartowaną strefę ze stanu stałego w warstwy wierzchniej wysokowęglowej stali stopowe wnosiła ok. 1 mm od powierzchni. Obecność strefy zahartowanej ze stanu stałego po borowaniu laserowym (w przeciwieństwie do borowania dyfuzyjnego) sprzyjać powinna występowaniu łagodnych zmian naprężeń własnych na przekroju poprzecznym warstwy wierzchniej obrabianej stali, co szczególnie jest ważne w przypadku trwałości i niezawodności części maszyn.*

***Słowa kluczowe**: warstwa wierzchnia, mikrostruktura, stopowanie laserowe*

1. Introduction

The agricultural production automation processes which include field of agricultural production and field of machine designing and construction is one of the most significant tendency of development in agricultural technique. Application of new materials and new methods of improving surface layer parts which are exposed i.e. to chemical and tribological loads could cause crucial changes in machines construction [2]. Wear of machine parts depends on the their surface layer microstructure and properties. Therefore, in many cases, the surface layer decides on the durability and reliability of the particular element.

Surface layer modification by laser beam dynamically develops technique of improving materials surface properties. Laser cladding is one of popular methods which could be applied to steel parts of agricultural devices [1]. Laser alloying is another method. The point of this treatment is put on the element (or combination of elements) into the surface of machine part using heating by laser beam. Such element could be boron. In this process laser beam causes melting simultaneously of the cover (paste with the element) with thin layer of covered material (for example steel). Then, those melted materials are mixed and quick chilled. In this way formatted and coagulated alloy is different from material of steel and paste with boron. Commonly, boron is implemented into the surface of steel by diffusion chemical-heat treatment. The point of diffusion boronizing saturates the layer with boron. Such boronized layer improves properties of machine parts like: fatigue surface durability [4, 5], abrasive, fretting and erosive wear resistance [6, 7], corrosion and fatigue corrosive resistance [7], heat-proof (to 800°C in atmosphere) [7]. After diffusion boronizing both kinds of borides (FeB and Fe_2B) usually appear (FeB on surface and Fe_2B under it) [6, 7]. Hardness of Fe_2B borides is approx. 1400-1800 μHV, while FeB is higher (1800-2400 μHV). However FeB borides are more prone to cracking and chipping off [6, 7]. Existence of FeB boride and needle-shaped microstructure of layer increase brittleness of the surface layer.

Laser boronizing is alternative to this method. Previously performed own research [3] proved that it is possible to implement boron into the surface layer by laser alloying and achieve its homogenous microstructure and improve hardness of the surface layer without needle-shaped microstructure of borides. Moreover, it is possible to control the quantity of boron in the melted zone, so FeB forming could be avoided [3, 8]. The thickness of boronized layer could be larger than thickness obtained by diffusion boronizing [3]. In addition, by laser boronizing stable boron distribution in the layer could be achieved [8]. Another advantage of laser boronizing consists in existence of the hardened area below the melted layer (because of high speed of laser treatment process). Therefore, hardness decrease from the surface to the core material is gentle [3].

The aim of the presented research was to evaluate the influence of laser treatment parameters (for example like laser power density or laser beam velocity) on microstructure and hardness of the surface layer of high carbon alloy steel.

2. Methodology

Laser treatment was performed with molecular CO_2 continuous Triumph laser type TLF 2600t with 2,6-kW output power and $TEM_{0,1}$ mode. The covering paste bound an alloying substance and water glass. Thickness of the paste put on samples was approx. 40 μm. Amorphous boron was used as an alloying substance. 100CrMnSi6-4 high carbon alloy steel was used as a test material.

To obtain different conditions of melted zone creation during laser treatment it was necessary to apply an appropriate combination of laser treatment parameters. Such combination should cause different temperature distributions in layer of treating material. Therefore, different temperatures in melted zone during laser treatment generate different temperature gradients, which determine cooling rates. Different temperature distributions could be obtained by following laser treatment parameters combinations: laser beam velocity (laser beam interaction time or laser beam radius) and laser beam power density. In presented research laser beam power density was from 160 to 900 W/mm^2, its velocity was in range: 4,5÷22,7 mm/s, and consequently laser beam fluance was from 40 to 250 J/mm^2. Two series of laser beam parameters were applied: with a change of laser beam power density (and constant laser beam velocity: 5,11 mm/s) and with a change of laser beam velocity (and constant laser beam power density 390 W/mm^2). Parameters were established on the basis of the research performed by Waligóra [8]. The results of the laser treatment were analyzed by means of Neophot optical microscope (zone geometry dimensions evaluation and structure study), Hanemann hardness tester with 65 G of load (microhardness distribution on the section of modified zones determination) and Auger electron spectroscope (boron identification).

3. Results and discussion

After laser alloying of high carbon alloy steel in its surface layer could be distinguished the melted zone (which was alloyed with boron) and the hardened zone from the solid state (warmed to temperatures of hardening). The microstructure across those zones is presented in the fig. 1.

] In the first zone from the surface boron was found using AES method. Its average atomic concentration in the melted zone was 13% and did not exceed 20%. Nevertheless, it is enough for appearing the eutectic mixture (α+Fe_2B). In this zone very fine-crystalline, homogenous area (especially near the surface) was found as well as areas with dendritic microstructure. Dendrites during treatment occurred on partly melted grains in the border between the alloyed zone and the hardened zone from the solid state (Fig. 2 a, b).

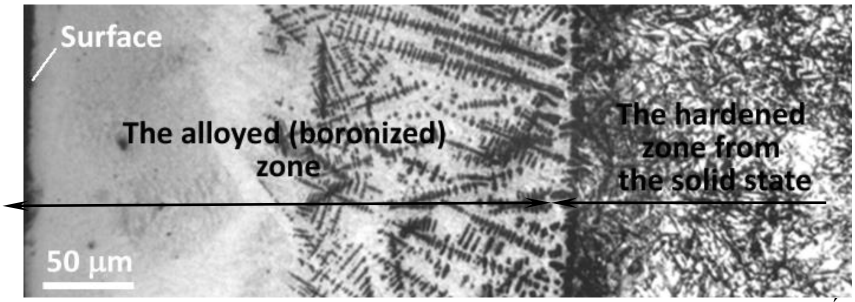

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Fig. 1. The cross-section of the surface layer of high carbon alloy steel after laser boronizing. Etched with nitride acid solution. Magnification 500x

Rys. 1. Przekrój poprzeczny warstwy wierzchniej wysokowęglowej stali stopowej po borowaniu laserowym. Trawione nitalem. Powiększenie 500x

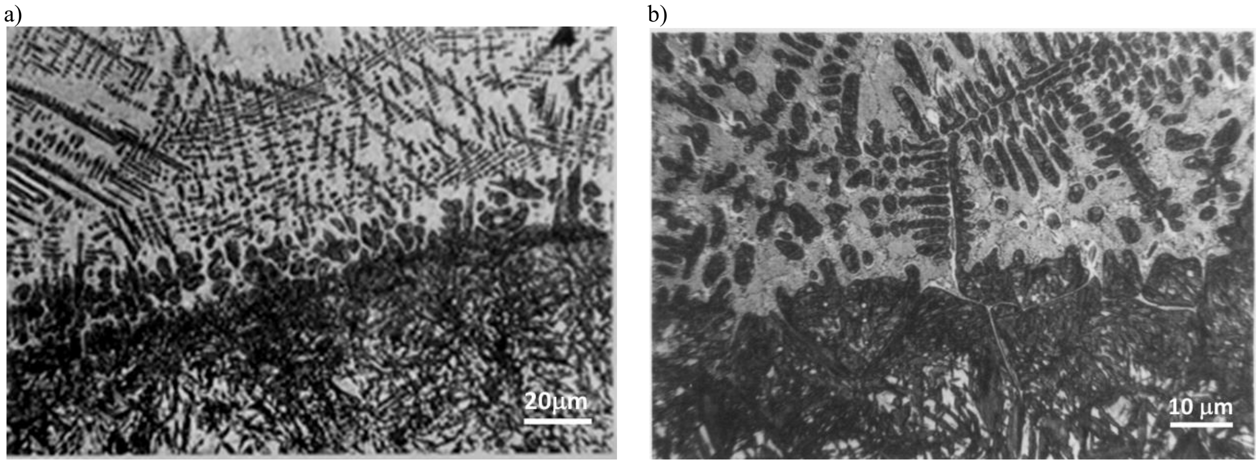

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Fig. 2. The microstructure of the border between alloyed zone and non-melted material observed with magnification of 500x (a) and 1000x (b). Etched with nitride acid solution

Rys. 2. Mikrostruktura obszaru granicy pomiędzy strefą stopowaną a materiałem nieprzetopionym obserwowana z zastosowaniem powiększenia 500x (a) i 1000x (b). Trawione nitalem

Performed research showed, that the thickness of the zone containing boron (the alloyed zone) of high carbon alloy steel could be controlled by laser beam parameters. The thickness of this zone increased with quantity of laser beam power density delivered to the steel during warming by laser beam. The thickness increased from 0,15 to 0,4 mm with increasing laser beam power density from 160 to 850 W/mm^2 with applying constant laser beam velocity 5,1 mm/s (Fig. 3). This dependence was described by logarithmic function (the r_{xy} correlation rate was 0,97). Furthermore, it was noticed that the thickness of the alloyed zone changed with changing laser beam velocity. For constant laser beam power density 390 W/mm^2 the thickness of the alloyed zone for treated steel decreased from 0,25 to 0,1 mm with increasing laser beam velocity from 4,5 to 22,7 mm/s (Fig. 4). This dependence was also described by logarithmic function (nevertheless, the r_{xy} correlation rate was lower than in the previous dependence).

The average hardness of the alloyed (boronized) zone in all cases was at least 1100 µHV 65. In comparison to the core material (hardened high carbon alloyed steel) it was at least approx. 2-times increase of hardness. In the first series of laser treatment with constant laser beam velocity: 5,1 mm/s and laser beam power density from 160 to 850 W/mm^2 the average hardness was between 1100 and 1200 µHV 65 (Fig. 5). This hardness was higher than hardness in the hardened zone from the solid state. The average hardness of the hardened zone from the solid state did not exceed 1000 µHV 65. In the second series of laser treatment with constant laser beam density 390 W/mm^2 and laser beam velocity from 4,5 to 22,7 mm/s the average hardness of alloyed (boronized) zone was higher than in case of alloyed (boronized) zones obtained in the previous series of laser treatment. The average hardness was in range of: 1100-1600 µHV 65.

The strengthen of alloyed (boronized) zone by the hardened zone from the solid state in the surface layer of high carbon alloy steel was observed to approx. 1 mm form the surface. The thickness of this zone is at least 0,7 mm. The hardness changes from the surface to the core material for all performed variants of laser treatment as shown in fig 7 a and b.

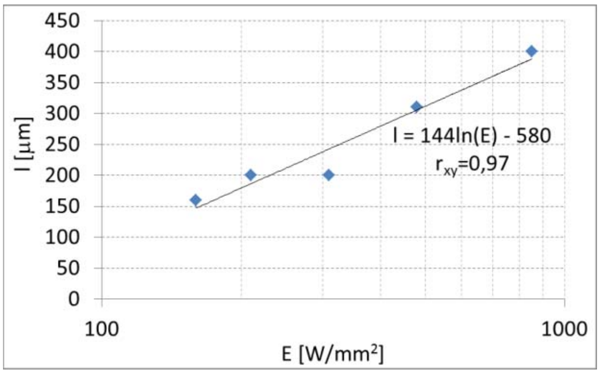

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Fig. 3. The influence of laser beam power density on the thickness of alloyed zone for high carbon alloy steel (using constant laser beam velocity: 5,1 mm/s)

Rys. 3. Wpływ gęstości mocy wiązki laserowej na grubość strefy stopowanej dla wysokowęglowej stopowej stali (przy zastosowaniu stałej prędkości mocy wiązki laserowej: 5,1 mm/s)

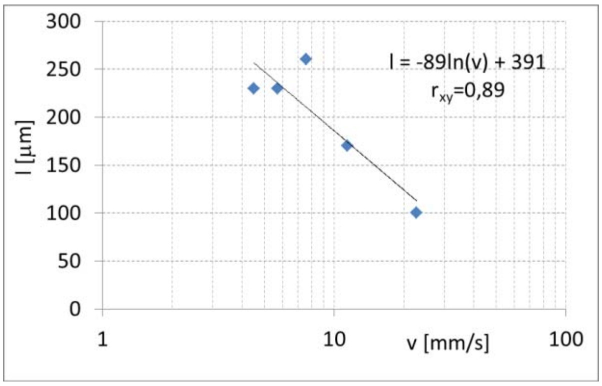

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Fig. 4. The influence of laser beam velocity on the thickness of alloyed zone for high carbon alloy steel (for laser beam power density: 390 W/mm^2)

Rys. 4. Wpływ prędkości mocy wiązki laserowej na grubość strefy stopowanej dla wysokowęglowej stopowej stali (przy zastosowaniu stałej gęstości mocy wiązki laserowej: 390 W/mm^2)

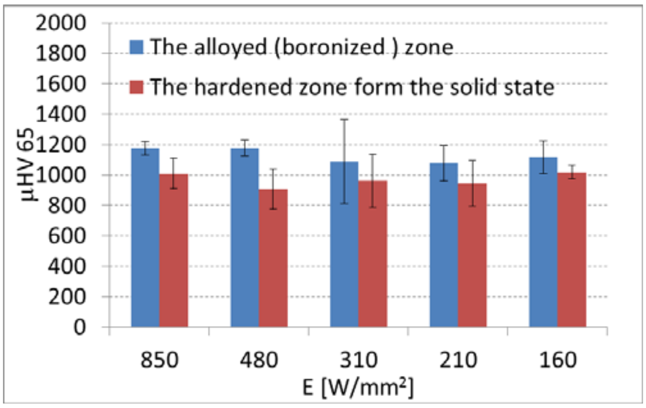

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Fig. 5. The average hardness of alloyed (boronized) zone of high carbon alloy steel after laser treatment with constant laser beam velocity (5,1 mm/s)

Rys. 5. Średnia twardość strefy stopowanej (borowanej) wysokowęglowej stali stopowej po obróbce laserowej z zastosowaniem stałej prędkości wiązki laserowej (5,1 mm/s)

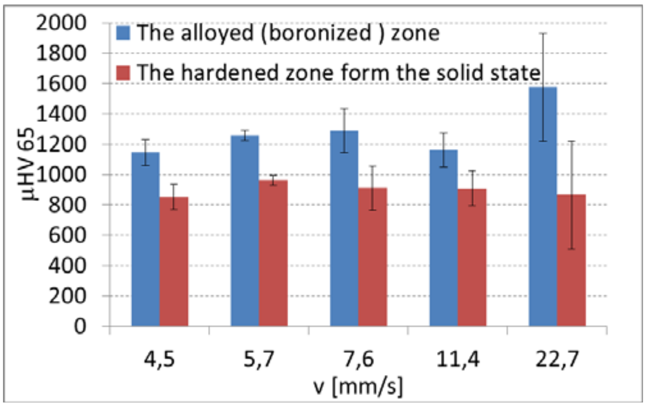

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Fig. 6. The average hardness of alloyed (boronized) zone of high carbon alloy steel after laser treatment with constant laser beam power density (390 W/mm^2)

Rys. 6. Średnia twardość strefy stopowanej (borowanej) wysokowęglowej stali stopowej po obróbce laserowej z zastosowaniem stałej gęstości mocy wiązki laserowej (390 W/mm^2)

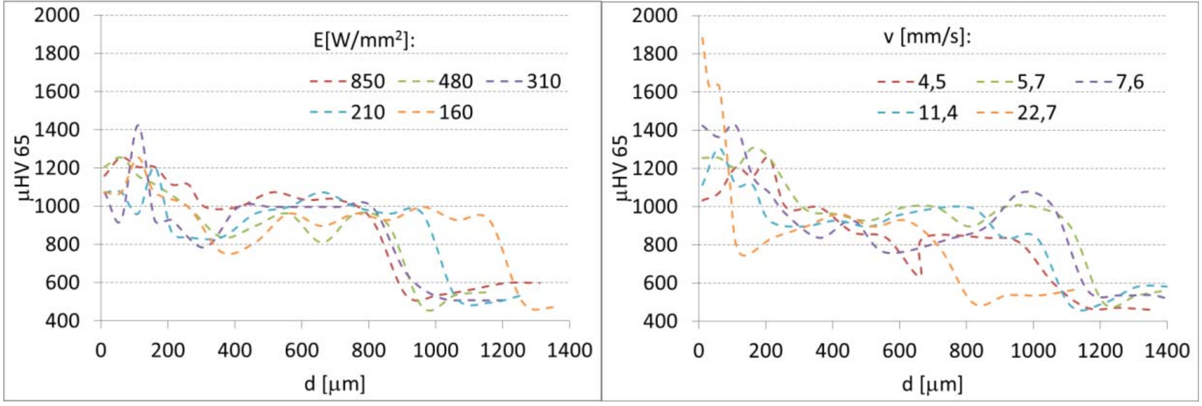

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Fig. 7. Hardness changes on the section of modified surface layer of high carbon alloy steel after laser boronizing with constant laser beam velocity: 5,1 mm/s (a) and constant laser beam power density 390 W/mm^2 (b) of high carbon alloy steel

Rys. 7. Zmiana twardości na przekroju poprzecznym warstwy wierzchniej wysokowęglowej stali stopowej po borowaniu laserowym z zastosowaniem stałej prędkości wiązki laserowej 5,1 mm/s (a) oraz stałej gęstości mocy wiązki laserowej: 390 W/mm^2 (b)

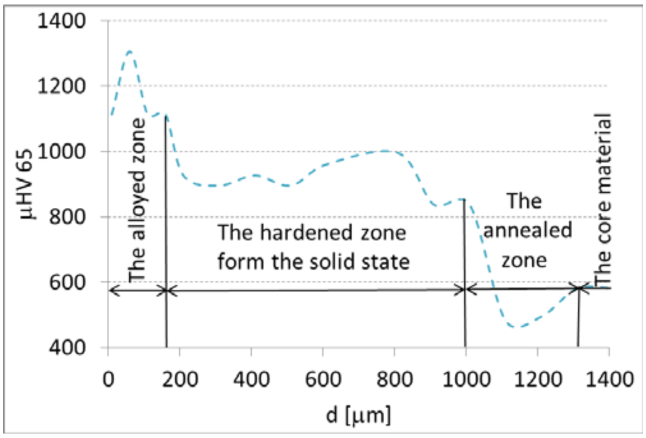

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Fig. 8. The example of hardness changes on the section of modified surface layer of high carbon alloy steel after laser boronizing with marked three zones: the alloyed zone, the hardened zone form the solid state and the annealed zone

Rys. 8. Przykład zmiany twardości na przekroju zmodyfikowanej warstwy wierzchniej wysokowęglowej stali stopowej po borowaniu laserowym z zaznaczanymi trzema strefami: stopowaną, zahartowaną ze stanu stałego i odpuszczoną

Existence of the hardened zone from the solid state after laser boronizing (as opposite to diffusion boronizing) should favor gentle changes of the internal stresses in the cross section of the surface layer of treated steel. It is worthy emphasizing, that it has a great importance in case of durability and reliability of the particular machine part.

Below the hardened zone from the solid state a thin area of lowered hardness could be observed. Fig. 8 presents the example of hardness changes obtained after one of variants of laser treatment where this area with lowered hardness was clearly visible. This area is annealed zone. In case of laser treatment consisting in hardening, melting or alloying of previously hardened steel during treatment in the surface layer area where temperature is not exceeded, hardening temperature occurs. Consequently, if the time of treatment is sufficient, annealing processes could appear.

4. Conclusion

The following conclusions can be drawn based on the carried out research:

1. Three different zones in the surface layer of high carbon alloy steel after laser alloying (boronizing) could be distinguished: the alloyed (boronized) zone, the hardened zone from the solid state, and the annealed zone.
2. Boron average atomic concentration in the alloyed zone was 13% and did not exceed 20%. Nevertheless, it is enough for appearing the eutectic mixture (α+Fe_2B).
3. The alloyed zone was almost entirely homogenous and very fine-crystalline, especially near the surface. However, areas with dendritic microstructure were found.
4. The thickness of the alloyed zone in the surface layer of high carbon alloy steel increased from 0,15 to 0,4 mm with increasing laser beam power density from 160 to 850 W/mm^2 with applying constant laser beam velocity 5,1 mm/s and decreased from 0,25 to 0,1 mm with increasing laser beam velocity from 4,5 to 22,7 mm/s with applying constant laser beam power density 390 W/mm^2.
5. The average hardness of alloyed zone was in range of: 1100÷1600 μHV 65. Thus, at least approx. 2-times increase of hardness was obtained as a result of laser treatment (in comparison to the hardness of the core material).
6. The average hardness of the hardened zone from the solid state did not exceed 1000 μHV 65. The strengthen of alloyed (boronized) zone by the hardened zone from the solid state in the surface layer of high carbon alloy steel was observed to approx. 1 mm from the surface.
7. Existence of the hardened zone from the solid state after laser boronizing (as opposite to diffusion boronizing) should favor gentle changes of the internal stresses in the cross section of the surface layer of treated steel, which has a great importance in case of durability and reliability of the particular machine part.

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