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Laser ablation surface layer texturing of selected Fe-C alloys

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ABSTRACT

Purpose: Present the results of their own research on the ablative laser texturing of selected Fe-C alloys.
Design/methodology/approach: This article presents selected examples of the microstructure and stereometry investigations of Fe-C alloys (41Cr4 steel, 41CrAlMo7 acid-resistant steel, steel resistant towards corrosion and low-alloying gray cast iron EN-GJL300) were presented.
Findings: One study found that an increase in the radiation power density q = 0,53 MW/cm^2 significantly affect the efficiency (depth) of ablative laser texturing. After crossing the power density is a significant reduction in the efficiency of laser ablation process. This is probably connected with the phenomenon of plasma shielding generated in the laser pulse.
Research limitations/implications: In the following laboratory tests are proposed in the use of absorbent materials to increase the absorption of the laser radiation and inertial layers to improve the efficiency texturing.
Practical implications: The research results can be used to modify the surface layer of machine components which are wear-resistant in friction conditions.
Originality/value: The novelty in the paper is the use of laser ablation phenomenon to produce surface texture in alloys Fe-C, mainly in terms of tribological.
Keywords: Fe-C alloys; Laser ablation texturing; Microstructure; Surface stereometry

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1. Introduction

There are numerous methods of surface layer modification of Fe-C alloys with high-energy beam technologies, like: electron, plasma, electric discharge and laser beam technologies. The laser beam technology is very attractive because of full automation, full controllability and its recurrence. This technology has gradually increasing field of application in surface engineering, tribology and production engineering of the machines' elements made of various structural materials [1-9].

2. Methods of surface laser texturing

One can distinguish following methods of laser texturing [5]: wastage-less, excess and wastage. Wastage-less laser texturing occurs without materials loss from the area of laser interaction with material. It is connected only with structural changes of the treated material caused by phase transitions, or melting and solidification. This type of texturing takes place during melting and without melting laser hardening [5].

Excess laser texturing occurs with alloying material transportation to the area of laser beam interaction. Here blending and melt applied laser alloying are accounted. Wastage texturing occurs with material's removal from the area of beam interaction with the surface layer as a result of laser ablation process. Here one can include treatments like: marking, engraving, fabrication of "oil pockets" (areas for oil containers), increase of material's surface roughness, laser impact strengthening.

Exemplary cross-sections of the textures are presented in Fig. 1.

The main aim of the laser texturing is [5]:

- Surface layer laser strengthening by: hardening, alloying, shot peening, removal (ablation) of the material, fabrication of oil containers for solid and liquid grease decreasing friction coefficient and abrasive wear
- Giving material's surface layer unique properties e.g.: directional increase of roughness of the sorption coatings for solar cells.

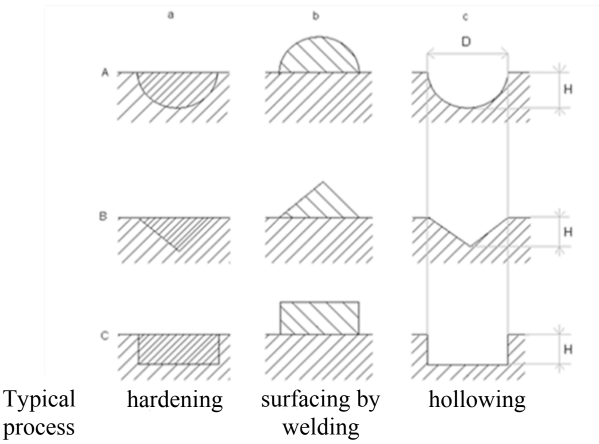

Fig. 1. Perpendicular to the surface theoretical cross-sections of the structure patterns - laser path, a - wastage less, b - excess, c - wastage; A - circular, B - triangular, C - rectangular [5]

3. Studies

This study attempts to determine the effect of the experimental efficiency of the one pulse laser texturing of the investigations of Fe-C alloys.

Examples of the microstructure and stereometry investigations obtained by laser surface texturing: 41Cr4 steel, 41CrAlMo7 acid-resistant steel, steel resistant towards corrosion and low-alloying gray cast iron EN-GJL300 were presented.

The study used laser CO_2 and modern ytterbium fiber laser pulse and solid galvo head with wavelength λ = 1064 nm and nanosecond pulse duration (Fig. 2). The geometrical analysis produced microkraters performe dusing an optical microscope with fiber-optic image transmission. One study found that an increase in the radiation power density q = 0.6 MW/cm^2 significantly affect the efficiency (depth) of ablative laser texturing. After crossing the power density is a significant reduction in the efficiency of laser ablation process. This is probably connected with the phenomenon of plasma shielding generated in the laser pulse.

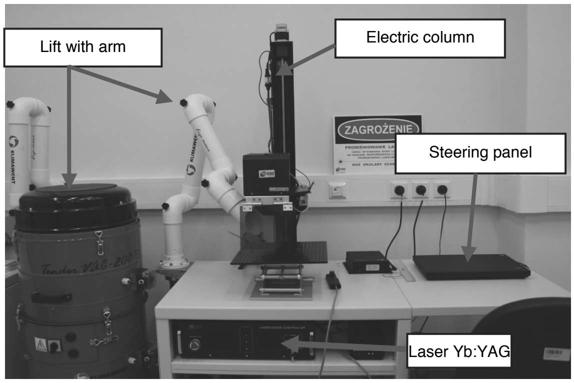

Fig. 2. Laser stand equipped in Yb:YAG fiber ytterbium laser, Galvo head, electric column (for precise beam focusing), steering panel and lift with arm; radiation wavelength and power were λ=1064 nm and P=30 W respectively

Samples of 41Cr4 steel and 41CrAlMo7 acid-resistant steel have been investigated. They are higher-quality structured steels for quenching and tempering used in the production of shafts, sleeves, gear elements.

Melting-less laser texturing with strengthening causes occurrence of phase transitions by heating of the treated area of the element and ultra-fast self-cooling, causing usually hardening of the surface layer. Structural alloying steel dedicated to the heat improvement can be, exemplary, laser hardened with power density of $q \sim 10^2 - 2 \cdot 10^4$ W /cm^2, exposure time of 10^{-2} - 1 s, with CO_2 laser in the continuous mode with power density of $\overline{q} = 1{,}3 \cdot 10^6$ W/cm^2. Numerous experiments concerning this issue were reported by our research group [7].

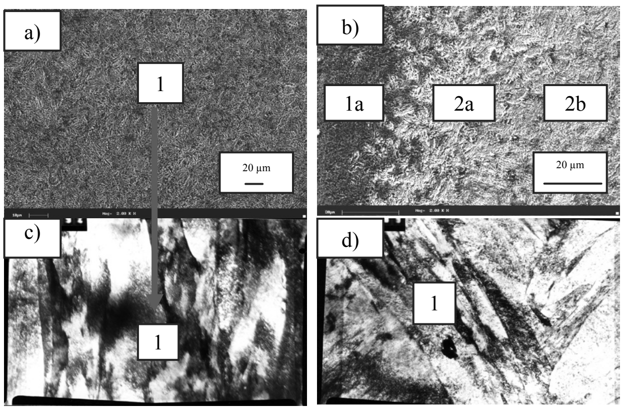

Fig. 3. Microstructure of the 41Cr4 steel laser hardened with materials melt: a) martensite in the surface layer, b) diversed morphology of bainite in the transitional area and packets of the martensite plates in the surface layer on the 0.05 mm depth (c) and 0.1 mm (d) - the middle of the hardened area; CO_2 laser working in the continuous mode with power density equal $q_{śr} = 0.6 \cdot 10^4$ W/cm^2, 1 - laser hardened area, 1a bottom part of the laser hardened area, 2a, 2b - transitional area, thick-plated bainite (2a), bainite+sorbite (2b), SEM - a,b, TEM - c,d magnification of 9000x [7]

For this technology the heating rate is usually of about 10^6 K/s and cooling rate is about 10^4 K/s. during laser heating of e.g. iron-carbon alloys, carbon content increase, increases hardness and thickness of the hardened layer with fixed parameters of the treatment. It is caused mainly by ability of hardening increase and decrease of the austenitization temperature [7].

Application of high power densities in the range of 10^7-10^{11} W/cm^2 and short exposure times one can conduct evaporating laser texturing.

Micro-craters (micro-containers) were fabricated on the specimens with singular laser pulses. Every micro-crater was manufactured with different power density, ranging from 0.32 to 1.06 MW/cm^2.

Experiments with application of absorbent (black ink) and without it and various power densities allowed to obtain diversity of shapes and sizes of the micro-craters. Power density increase from 0.32 to 0.53 MW/cm^2 causes almost linear increase of the micro-crater depth from 3.36 to 5.29 µm. Further power density increase, above 0.53 MW/cm^2, causes slightly noticeable micro-craters depth, up to 5.45 µm. Effect of laser shielding by plasma is a very probable reason of such a laser texturing effectiveness change. During the shielding, the influence of laser radiation on the material's surface layer can be strongly limited (reflect, disperse), or even totally abolished.

Power density increases causes also craters' diameter increase, from 42 to 76 µm. Such a significant increase of the craters' diameter is probably caused by the laser plasma cloud expansion with the radiation intensity increase. The laser plasma interacts directly with the surface of the 41Cr4 steel. Power density increase also causes temperature and pressure amplitude increase.

Characteristic examples of 41Cr4 steel specimens' surface stereometry after laser ablation texturing with power density of 0.32 and 1.06 MW/cm^2 are shown in Fig. 4. Low density of laser radiation (q = 0.32 MW/cm^2) provides regular shapes of the crater (Fig. 4a,b). Depth of the crater was about 3.30 µm and the width was 42.40 µm. Micro-extrusion, around the crater is also noticeable. Observed extrusion effect of the liquid material around the micro-crater is causes by low pressure amplitude of the laser plasma. Greater power densities (1.06 MW/cm^2) provide increase of area with ejected material around the crater (Fig. 4 c,d). Lack of clear boundary between the support and crater was noticed. This option of the laser micro-treatment provides micro-craters with depth ranging from 5.4 to 5.45 µm and diameter ranging from 66.5 to 76.5 µm. Obtained effects are being enhanced with power density increase - temperature and pressure amplitude are increasing then.

Another example of laser ablation texturing of the materials surface is modification of the 41CrAlMo7 steel surface layer applied in production of numerous machines. Laser ablation texturing process can be conducted after heat improvement, or initial mechanical treatment (like grinding) of the mentioned above steel (Fig. 5).

In the laser micro-treatment technology one wants to achieve so-called "cold-ablation" (rapid dissociation of the bond between atoms and sublimation). It can occur at high power densities and pico- or even femtoseconds long exposure. Very shallow area of the evaporated material is obtained then. A little longer time of exposure (nano- and microseconds) triggers on significant heating effect simultaneous with the laser ablation. Side effects like intensive heating, melting and extrusion of the liquefied material are common then. Noticeable influence of heat area is present. Phase and structural transition occurs.

Areas of laser interaction with matter may have various shapes, like dot texture (Fig. 6 a, b - hemispheres), or micro-channels (Fig. 6 c, d) which may serve of a grease containers for the machines working in the various tribological systems.
To obtain precision and recurrence of the laser texturing very precise optics of the laser devices is currently applied, e.g.: Galvo heads. These are very often Yb: YAG laser, providing short exposure time from few nanoseconds. Frequency of the repetition is up to few hundreds kHz (up to 500 kHz and more).

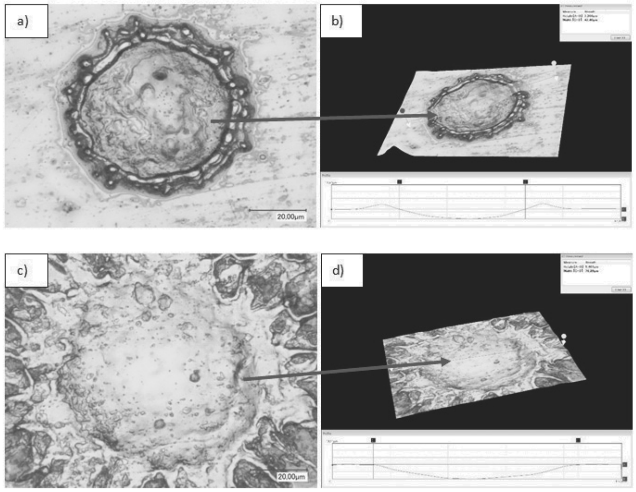

Fig. 4. Stereometry of 41Cr4 steel after laser ablation texturing at various power densities: a,b) q=0.32 MW/cm^2, c,d) q = 1.06 MW/cm^2, a, c) shape of the micro-craters, b,d) micro-craters shape profiles, fiber ytterbium Yb:YAG laser, λ=1064 nm, exposure time t~100 ns

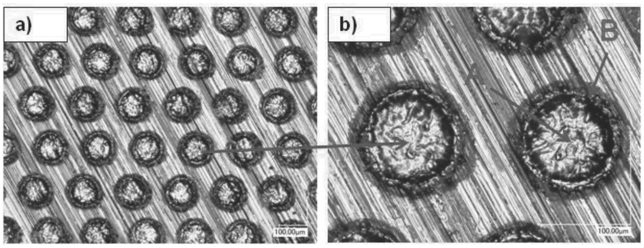

Fig. 5. Surface topography of the 41CrAlMo7 steel after initial honing with oil micro-containers: a,b) dot texture, FE-SEM Philips FEI XL 30, A - area of the laser bream interaction - partially melted and partially evaporated material with effects of laser plasma pressure shaping, B - micro-extrusions of the material around micro-containers

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Example of the application of laser ablation texturing is modification of the low-alloying cast-iron modification - oil micro-containers were fabricated in the shapes of bowls and micro-channels with application of high-power laser ($g \geq 10^5$ - 10^9 W/cm^2) [8]. These patterns are micro-containers for oil or grease (Fig. 7).

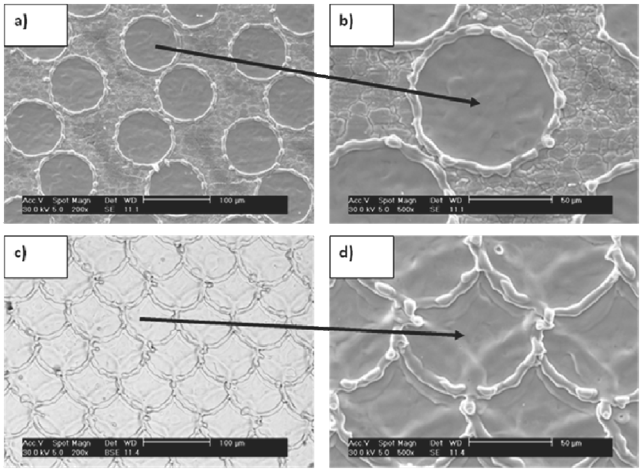

Fig. 6. Exemplary effects of ablation with pulse radiation on the Fe-C alloys (acid resistant steel, resistant towards corrosion): a, b) - dots texture, c, d) - double dot texture with overlapping dots - Author's research

Melting texturing is also a very often applied laser technology. It occurs at power densities in the range of 10^4-10^{12} W/cm^2 and exposure time ranging from nano- to even few miliseconds. In the modified surface layer of the materials, the heat effect is a dominating phenomenon, causing heating and melting of the treated elements. Self-cooling causes phase transitions, causing fragmentation of the materials grains. Application of high power lasers allows to interact deeply with treated material. One obtain then melted surface layer with heat influence area at its bottom (HIA).

Recent technological processes, mainly micro - and nanoscale treatments can be applied as a finishing treatments. Very short impulses (micro-, nano-, pico- and femtoseconds long), heat interaction is very short and ablation is the dominating process. Short time of interaction and proper focusing of the laser beam one can obtain high power densities, and phase transitions are close to the amorphization. Such a treatment is known as glazing and occurs from few ten of nano- to even few tens of microns towards material's bulk. It can reach even few hundrets of microns down to the material's bulk. Micro-melting is one of the process of laser texturing (Fig. 8).

Laser technologies have found application in the surface engineering in the wastage texturing e.g. engraving of the surface layer of materials and machine elements. Fabrication of permanent and even aesthetic pattern is related to the laser ablation with heat effect and ridding of, with particular evaporation of the treated material.

Modern laser systems (fiber laser with Galvo head) allow to obtain patterns with precision and recurrence.

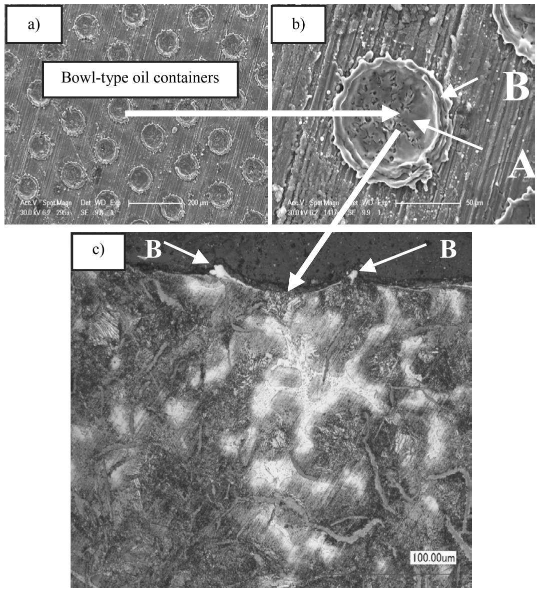

Fig. 7. Stereometry and microstructure of the grey cast iron EN - GJL300 after laser ablation: a, b) bowl-type oil containers, c) microstructure of the material with noticeable oil micro-container, A - area of the laser beam interaction - melted, partially evaporated and shaped by laser plasma pressure, B - area of the micro-extrusion around the micro-container

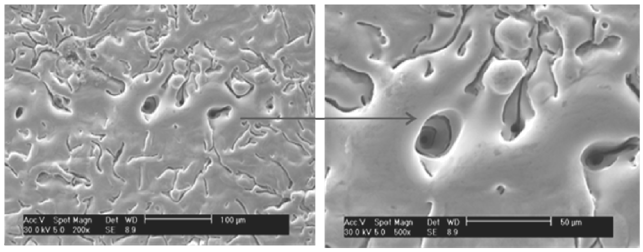

Fig. 8. Cast iron surface topography (EN-GJL300) after micro-texturing with laser melting; fiber ytterbium laser working in the pulse mode Nd:YAG (λ = 1064 nm), exposure time 25 nm, repetition frequency 3 kHz, (SEM)

4. Summary

To choose proper technological application of the laser texturing for a given machine elements (made of e.g. Fe-C alloy) conditions of the working and wear should be well-known. One has to be aware that for the first wavelength has to be properly adjusted, because it influences significantly on the radiation absorption, ablation and phase transitions. The shorter wave, the shallower penetration of the material's surface layer caused by physical phenomena and lower energy in the impulse. Also greater precision of the ablation in stratums, coatings and material removal is achieved. Thanks to the application of shorter waves of radiation, laser can also interact with polymers and varnish coatings.

During selection of the texturing parameters a proper distribution of the power density has to be applied (e.g. Gauss, top-head, rectangular etc.). It has a major impact on the shape of the obtained pattern and homogeneity of the laser-material interaction. To obtain desired technological effect, for a given wavelength a proper power density has to be chosen.

In the laser texturing technological processes time of the laser impulse interaction with treated material is also very important. During short exposure time (piko-, femtoseconds) one can observe “cold ablation” with simultaneous shallow areas of the laser penetration towards material’s bulk. Thus, only small areas of the structural changes are observed. For such a parameters of the laser texturing one can achieve impressive results of the surface layer modification, but only in the nano- or microscale.

Basing on the literature data and obtained results, one can conclude that laser texturing can be an interesting treatment for industries, especially when machines’ elements are exposed to the abrasive wear and friction. Texture patterns and surface filling (filled textured surface to the total textured surface ratio) what triggers on possibility of tribological properties control and their adjustment to the exploitation conditions of the machine’s element.

Thanks to the fast technological progress in the laser construction and laser optics one can predict increase of the laser application field, especially in the area of surface layer modification of the material and machines’ elements.

5. Conclusions

1. Interactions of laser radiation (λ = 1064 nm) with 41Cr4 steel surface were researched at given focusing with appropriate optics (Galvo head). Power density increase was a result of radiation intensity increase. Laser plasma production was being enhanced then. The area of interaction of laser plasma with alloy was increasing and as a result - area of the treated material increased (heating, melting, ablation with thermal effect).
2. Power density increase, up to $q = 0.53\ MW/cm^2$ strongly increases laser ablation texturing effectiveness. Micro-craters depth and width are increased.
3. Laser ablation increase, above $q > 0.53\ MW/cm^2$ results in laser ablation texturing effectiveness slight increase. A shielding phenomenon caused by plasma cloud is the most probable cause. Further effective interactions of laser beam with Fe - C alloys is difficult.

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