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SURFACE HARDENING OF STEEL PARTS

Алаа Фаділ І Ідан, *О.В. Акімов*, *К.О. Костик*. **Поверхневе зміцнення сталевих деталей.** Розробка нових ресурсозберігаючих і економічно доцільних технологій комбінованого зміцнення сталевих деталей із значним скороченням тривалості процесу є важливою і актуальною задачею. ***Мета:*** Метою роботи є розробка технології комбінованого зміцнення сталевих деталей для забезпечення високих експлуатаційних властивостей поверхневого шару сталі шляхом інтенсифікації процесу азотування за рахунок попередньої лазерної обробки поверхні сталевих виробів. ***Матеріали і методи:*** Матеріалом для дослідження є сталі марок 40, 40Х і 38Х2МЮА. Лазерну обробку сталей проводили на установці «ЛАТУС-31». Азотування проводили в середовищі дрібнодисперсної азотовмісної речовини з активаторами при температурі 530…560 ºС протягом 2…3 годин. Процес азотування проводили в закритій атмосфері в камерній печі без застосування захисних атмосфер. Було досліджено вплив попередньої лазерної обробки і кінцевого азотування на структуру, товщину, фазовий склад, мікротвердість поверхневих шарів зразків сталей. ***Результати:*** Показано, що попереднє лазерне зміцнення підвищує поверхневу твердість після азотування в 0,88…1,15 рази в залежності від марки сталі й швидкості переміщення лазерного променя в порівнянні з азотуванням сталей в аналогічних умовах. Комбінована обробка сприяє значному стовщенню зміцненого шару – до 0,49 мм для сталі марки 40, до 0,55 мм для сталі марки 40Х і до 0,65 мм для сталі марки 38Х2МЮА.

Ключові слова: поверхневе зміцнення сталі, комбінована обробка, лазерна обробка, азотування, поверхнева твердість, товщина зміцненого шару.

Alaa Fadhil I Idan, *O.V. Akimov*, *K.O. Kostyk*. **Surface hardening of steel parts.** Development of new resource-saving and cost-effective technologies of combined hardening of steel parts with a significant reduction of the process duration is an important and urgent task. ***Aim:*** The aim of the work is to create a technology for combined toughening of steel parts to provide high operational properties of the steel surface layer by intensifying the nitriding process through the laser pre-treatment of steel products. ***Materials and Methods:*** Materials for study are types of steels 40, 40Cr and 38Cr2MoAl. Laser treatment of steel was performed at the LATUS-31 installation. Nitriding carried out in the environment of fine nitrogen-containing substance with activators at a temperature of 530…560ºC during 2…3 hours. The nitriding process was carried out in the closed atmosphere in the chamber furnace without application of the protective atmospheres. Influence of laser pre-treatment and final nitriding on structure, thickness, phase structure, microhardness of surface layers of steel samples has been investigated. ***Results:*** It is shown that preliminary hardening by laser increases surface hardness in 0.88…1.15 times after nitriding, depending on brand of steel and speed of a laser beam movement, in comparison with steel nitriding in similar conditions. The combined treatment promotes significant increase in the strengthened layer – up to 0.49 mm for 40 steel type, up to 0.55 mm for 40Cr steel type and up to 0.65 mm for 38Cr2MoAl steel type.

Keywords: surface hardening of steel, combined treatment, laser treatment, nitriding, surface hardness, thickness of the hardened layer.

Introduction. One of the perspective directions of operating service life increase of steel parts is creation of parts from an inexpensive matrix with hardening of the surface layer. There are a number of the technologies directed to hardening of a surface of a part, namely: chemical heat treatment; deposition; welding; surface plastic deformation; electroplatings; laser hardening; hardening by currents of high frequency etc. [1].

The combined treatments providing increase in hardness and durability of the surface layer that leads, in turn, to increase in endurance of a part in general are of the greatest interest [2].

All existing technologies can be divided into the following groups: coating; diffusion coating; hardening of the surface layer due to change of structure.

Nitrogenation is a fairly common factory technology for hardening the steel surface, but this is a fairly long and expensive process. Currently, the interest is represented by combined treatment with the use of nitriding and additional processing, which reduces the time of saturation of steels with nitrogen.

The development of new resource-saving and economically viable technologies for combined hardening of steel parts with a significant reduction in the duration of the process is an important and urgent task in modern science.

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An analysis of the current state of the question of increasing the service life of machine parts shows that the effective method of surface hardening of steels is chemical-thermal treatment, i.e. such methods as nitriding and laser hardening of the surface.

Laser treatment in comparison with traditional methods of heat treatment of materials has a number of advantages [3]. With traditional heat treatment, the subsequent release of the part is required. It removes internal stresses, but at the same time reduces the hardness of the treated layer. In this case, the hardness is, as a rule, 48...52 HRC. Laser processing does not require additional blazing-off operations. The hardness of the laser-hardened surface zone is more than 58...62 HRC [4]. Such hardness of the hardened layer is achieved due to the martensitic transformation, the optimal combination of solubility of solid solutions with carbon and alloying elements with their heterogeneity, and also due to increasing the density of crystal structure defects [5...8]. The greatest interest in laser processing of steel for further acceleration of the nitriding process is the considerable grain refinement. This leads to an acceleration of the diffusion of nitrogen deep into the metal [9, 10].

There are many technologies of nitriding, but the most interesting are innovative technologies that provide the necessary depth of the diffusion layer in a short time interval of the saturation process [11].

Combined technologies of laser processing and nitriding are known, such as: low-temperature nitriding of steel parts; obtaining of wear-resistant discrete nitrided layers; combined laser-chemical-thermal treatment of materials.

Low-temperature nitriding of steel parts includes preliminary surface local alloyage with nitride-forming elements during laser heating of parts with a coating applied to their surface followed by low-temperature nitriding [12]. Before nitriding, the process of thermal diffusion saturation with doping nitride-forming elements is carried out when heated to a temperature of 690...710 °C with a holding time of 3...4 hours. The nitriding process is carried out in an ammonia medium when heated to a temperature of 570...590 °C with a holding time of 6...8 hours and with subsequent cooling together with the furnace.

The production of wear-resistant discrete nitrided layers includes discrete processing of the surface of steel products by laser irradiation followed by nitriding in an ammonia medium at temperatures of 800...860 K with an exposure time of 15...20 hours where laser processing with power 103...104 W/cm^2 is performed discretely with a processing area of 15...25 % of the total area of the steel product [13]. This improves the wear resistance of nitrided layers of steel products by reducing the friction stress. It is shown that the local stresses in the material, depending on the type of loading of the elementary volume, can be predicted and calculated. In this case, it is necessary to take into account the mechanical properties, type and structure of the transition zone, which arises as a result of laser treatment.

The size of the treatment area is established empirically and is due to the creation of such a stress-strain state, which provides minimum local stresses in friction. These results are confirmed by analytical calculations of the composite material.

A minimally loaded matrix makes it possible to relax the stresses caused by frictional forces. The point reinforcement zones have dimensions of 3...5 mm and are located at a distance of 10 mm between the centers. Steel grades 18CrMnTi, 40Cr, 38CrMoAl were used as strengthened materials. The increase in wear-resisting properties at discrete processing in comparison with continuous processing is conditioned by such stress-strain state at which the stresses are minimal. At this, the preliminary laser treatment intensifies the nitriding process.

The combined laser-chemical-thermal treatment of materials includes the surface treatment of the article in order to increase the defects of the crystal latitude, followed by chemical-thermal treatment of the surface of steel products at a laser radiation speed of 0.5...1.4 m/min and nitriding in an ammonia medium at temperatures of 800...860 K [14].

Known methods have a number of unresolved issues. In particular, *Petrova et al.* [12] presented a method of low-temperature nitriding of steel parts, which disadvantage is that it does not provide sufficient depth of the layer (up to 120...150 μm) and is difficult to use, laborious and energy-intensive.

Additionally, a significant disadvantage of this method is the use of ammonia, which is not only expensive but dangerous in manufacturing and harmful to human health and the environment.

Kindrachuk et al. [13], a method for obtaining wear-resistant discrete nitrided layers was proposed, but a significant disadvantage of this method is that it does not allow the formation of coatings with variable density of hardened areas along the friction surfaces of the part.

In turn, *Ischuk et al.* [14] proposed a method for combined laser-chemical-thermal treatment of materials, but this method is characterized by such disadvantages as a considerable duration of the process (up to 20 hours), energy intensity and the fact that the resulting coating has insufficient microhardness (up to 8 GPa), which does not provide high wear resistance of the part.

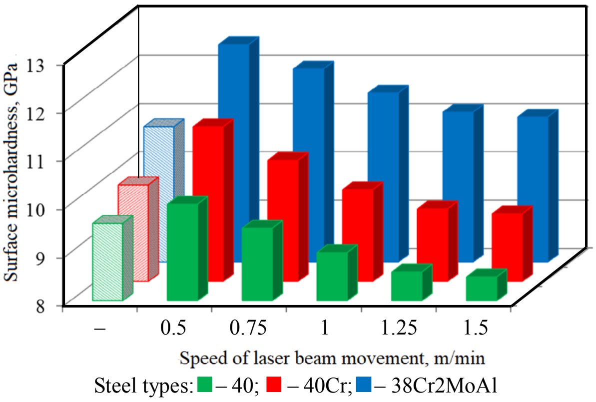

Fig. 1. Change in the surface hardness of steels after combined strengthening treatment, depending on the speed of the laser beam movement in compare to nitriding of steel under similar conditions, but without preliminary laser hardening (shown by hatching)

Overall, the conclusion that can be drawn from the literature analysis is that the existing techniques do not provide sufficient depth of hardened layer and sufficient surface hardness are difficult to use, laborious, energy intensive, long time processes (up to 20 hours).

The aim of this research is to create a technology of combined hardening of steel parts to ensure high performance properties of the surface layer of steel by intensifying the nitriding process through preliminary laser treatment of the surface of steel products.

Materials and Methods. The materials for the study are steels of grades 40, 40Cr и 38Cr2MoAl.

Laser processing of steels was carried out at the LATUS-31 installation in the following mode: the radiation power was 1.0±1.1 kW, the diameter of the beam focusing part was 5 mm, the speed of the laser beam was 0.5...1.5 m/min.

Nitriding was carried out in a medium of finely dispersed nitrogen-containing material with activators at a temperature of 530...560 °C for 2...3 hours. The nitriding process was carried out in a closed atmosphere in the form of a sealed container – in a chamber furnace, without complicated special equipment, without use of protective atmospheres.

The effect of preliminary laser treatment and final nitriding on the structure, thickness, phase composition, microhardness of surface layers of steel samples was investigated. The study was carried out using metallographic analysis using a metallographic microscope MIM-7 with a digital adapter, an automatic X-ray diffractometer DRON-3, a PMT-3 microhardometer, and an analyzer by TM-114.

Results.

Analysis of the influence of the speed of the laser beam on the surface hardness of the strengthened layer. Studies have shown that preliminary laser hardening increases the surface hardness after nitriding by 0.88...1.15 times, depending on the steel grade and the speed of the laser beam moving in compare with the nitriding of steels under similar conditions, but without preliminary laser hardening (Fig. 1).

The presence of alloying elements in the steel increases surface hardness. This phenomenon is associated with the presence in the surface layer of alloyed steel of special nitrides and carbides, which are more solid in compare with nitrides and iron carbides. This conclusion was confirmed by the X-ray structural phase analysis of the steels being studied, as a result of which nitrides ξ-Fe_2N, ε-Fe_3N-Fe_2N, γ'-Fe_4N, Fe_3N and α-Fe were detected in the surface layer of the steel. The nitrides and carbides of the alloying elements were additionally fixed in alloyed steels. The presence of chromium in the steel increases the surface hardness in the surface layer by 1.10...1.12 times (Fig. 2).

The nature of the dependence of the change in the surface hardness of steels after the combined hardening treatment on the speed of laser beam movement is described by the third degree polynomials.

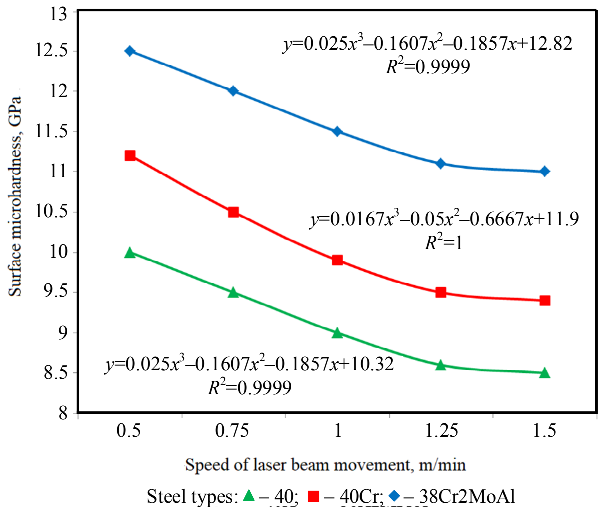

Fig. 2. Dependence of the change in the surface hardness of steels after the combined hardening treatment on the speed of laser beam movement

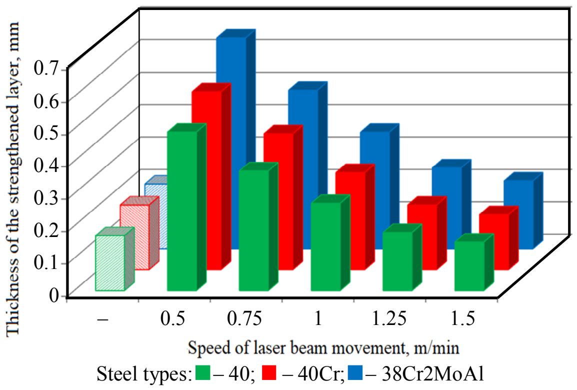

Fig. 3. Dependence of the thickness variation of the hardened steel layer on the speed of the laser beam movement for two processing modes – laser (shown by hatching) and combined

Analysis of the influence of the speed of the laser beam movement on the thickness of the hardened layer. The dependence of the thickness of the hardened steel layer on the speed of laser beam movement is shown in Fig. 3. Comparison was carried out with nitriding of steel under similar conditions, but without preliminary laser hardening.

Nitriding without preliminary laser hardening under similar conditions makes it possible to obtain a hardened layer with a thickness of 0.17 mm (40 steel type) to 0.2 mm (40Cr and 38Cr2MoAl types). Preliminary laser treatment before nitriding promotes a significant increase in the hardened layer: up to 0.49 mm for 40 steel type, up to 0.55 mm – 40Cr and up to 0.65 mm – 38Cr2MoAl. This is explained by the simplification of the diffusion of nitrogen atoms and the increase of its solubility due to the formation of a more defective metal structure after laser irradiation (increase in dislocation density, grain fragmentation and increase in the extent of their boundaries, and the production of ultradispersed disoriented grains).

Fig. 4...6 show the dependence of the change of the hardened layer thickness of the steels being tested on the speed of the laser beam for the two processing modes, laser and combined. With an increase in the speed of laser beam moving to 1.25 m/min, a significant decrease in the thickness of the strengthened layer is characteristic for steels. At further increase in speed, the reduction in the thickness of the strengthened layer is insignificant. As expected, the greater the thickness of the strengthened layer by laser treatment, the greater is the corresponding thickness of the hardened layer after subsequent nitration (combined treatment).

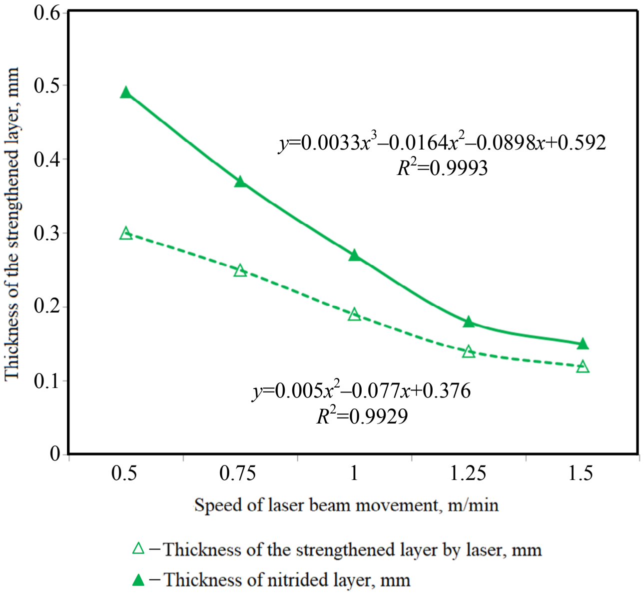

Fig. 4. Change in thickness of the hardened layer of 40 steel type as a function of the speed of the laser beam movement

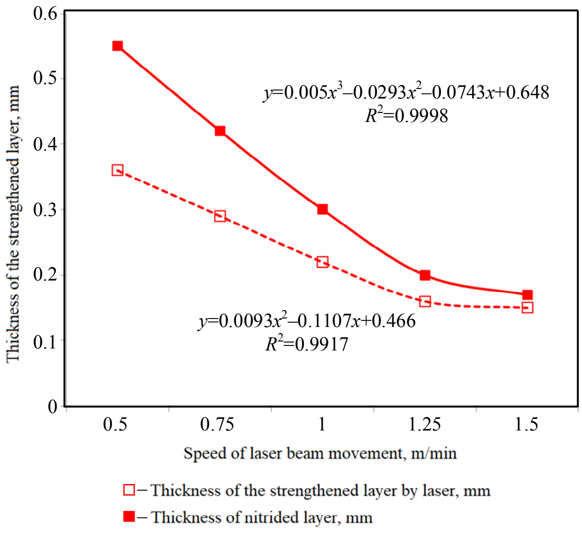

Fig. 5. Change in thickness of the hardened layer of 40Cr steel type, depending on the speed of the laser beam movement

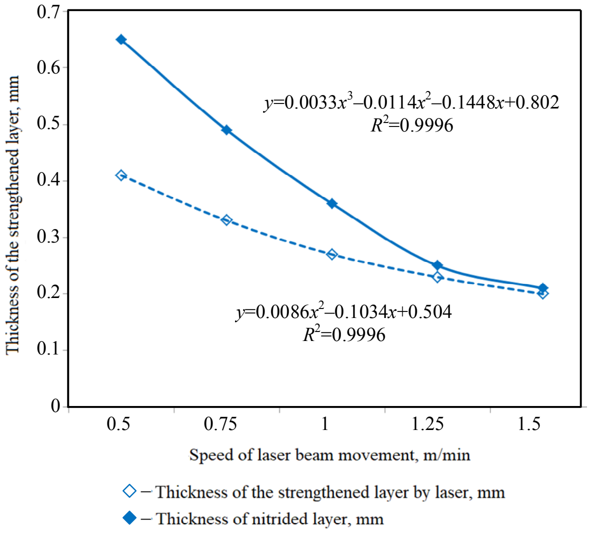

Fig. 6. Change in thickness of the hardened layer of 38Cr2MoAl steel type, depending on the speed of the laser beam movement

Conclusions. As a result of the study, a technology for combined hardening of the surface layer of steel parts was developed, consisting of preliminary laser treatment of the surface layer of steel and its further nitriding.

Studies have shown that preliminary laser hardening in combination with nitriding increases the surface hardness of steel by 0.88...1.15 times, depending on the steel grade and the speed of the laser beam movement. In compare with nitriding, the steel under similar conditions but without preliminary laser hardening, combined treatment promotes a significant increase in the hardened layer: up to 0.49 mm for 40 steel type, up to 0.55 mm – 40Cr and up to 0.65 mm – 38Cr2MoAl.

Література

1. Hahn, D.W. Laser-induced breakdown spectroscopy (LIBS), Part II: Review of instrumental and methodological approaches to material analysis and applications to different fields / D.W. Hahn, N. Omenetto // Applied Spectroscopy. – 2012. – Vol. 66, Issue 4. – PP. 347–419.
2. Mechanism of heat-modification inside a glass after irradiation with high-repetition rate femtosecond laser pulses / M. Shimizu, M. Sakakura, M. Ohnishi, *etc.* // Journal of Applied Physics. – 2010. – Vol. 108, Issue 7. – P. 073533.
3. Influence of laser radiation on structure and properties of steel / O.V. Lobankova, I.Y. Zykov, A.G. Melnikov, S.B. Turanov // Proceedings of the International Conference on Advanced Materials, Structures and Mechanical Engineering, Incheon, South Korea, May 29–31, 2015. – London: CRC Press, 2016. – PP. 75–78.
4. Femtosecond laser treatment of 316L improves its surface nanoroughness and carbon content and promotes osseointegration: An in vitro evaluation / H. Kenar, E. Akman, E. Kacar, *etc.* // Colloids and Surfaces B: Biointerfaces. – 2013. – Vol. 108. – PP. 305–312.
5. Laser fluence dependence of periodic grating structures formed on metal surfaces under femtosecond laser pulse irradiation / K. Okamuro, M. Hashida, Y. Miyasaka, *etc.* // Physical Review B. – 2010. – Vol. 82, Issue 16. – P. 165417.
6. Laser surface hardening of AISI 420 stainless steel treated by pulsed Nd:YAG laser / B. Mahmoudi, M.J. Torkamany, A.R. Sabour Rouh Aghdam, J. Sabbaghzade // Materials & Design. – 2010. – Vol. 31, Issue 5. – PP. 2553–2560.

7. Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy / J. Yang, S. Sun, M. Brandt, W. Yan // Journal of Materials Processing Technology. – 2010. – Vol. 210, Issue 15. – PP. 2215–2222.
8. Исследование влияния режимов лазерной закалки на изменение свойств сталей / А.Ф.И. Идан, О.В. Акимов, Л.Ф. Головко [и др.] // Восточно-Европейского журнала передовых технологий. – 2016. – № 2/5 (80). – С. 69–73.
9. Assunção, E. Comparative study of laser welding in tailor blanks for the automotive industry / E. Assunção, L. Quintino, R. Miranda // The International Journal of Advanced Manufacturing Technology. – 2010. – Vol. 49, Issue 1. – PP. 123–131.
10. Моделирование глубины диффузионного слоя и поверхностной твердости стали при ионном азотировании / М.К. Моханад, В.О. Костик, Д.А. Демин, Е.А. Костик // Восточно-Европейского журнала передовых технологий. – 2016. – № 2/5 (80). – С. 45–49.
11. Kostyk, K. Development of innovative method of steel surface hardening by a combined chemical-thermal treatment / K. Kostyk // Eureka: Physics and Engineering. – 2016. – № 6. – PP. 46–52.
12. Пат. 2415964 Российская Федерация, МПК C23C 8/26. Способ низкотемпературного азотирования стальных деталей / Петрова Л.Г., Чудина О.В., Александров В.А., Брежнев А.А., Барабанов С.И.; патентообладатель Государственное образовательное учреждение высшего профессионального образования Московский автомобильно-дорожный институт (государственный технический университет). – № 2009139309/02; заявл. 26.10.2009; опубл. 10.04.2011; Бюл. № 10.
13. Пат. 25412 Україна, МПК C23C 8/02. Спосіб отримання зносостійких дискретних азотованих шарів / Кіндрачук М.В., Іщук Н.В., Писаренко В.М., Головко Л.Ф., Мутхі Собхі Яхья; заявник та патентовласник НТУУ «КПІ». – № u200703002; заяв. 22.03.2007; надр. 10.08.2007; Бюл. № 12.
14. Пат. 19551 Україна, МПК C23C 8/02. Спосіб комбінованої лазеро-хіміко-термічної обробки матеріалів / Іщук Н.В., Писаренко В.М., Кіндрачук М.В., Головко Л.Ф.; заявник та патентовласник НТУУ «КПІ». – № u200607450; заяв. 04.07.2006; надр. 15.12.2006; Бюл. № 12.

References

1. Hahn, D.W., & Omenetto, N. (2012). Laser-induced breakdown spectroscopy (LIBS), Part II: Review of instrumental and methodological approaches to material analysis and applications to different fields. *Applied Spectroscopy*, 66(4), 347–419. DOI:10.1366/11-06574
2. Shimizu, M., Sakakura, M., Ohnishi, M., Shimotsuma, Y., Nakaya, T., Miura, K., & Hirao, K. (2010). Mechanism of heat-modification inside a glass after irradiation with high-repetition rate femtosecond laser pulses. *Journal of Applied Physics*, 108(7), 073533. DOI:10.1063/1.3483238
3. Lobankova, O.V., Zykov, I.Y., Melnikov, A.G., & Turanov, S.B. (2016). Influence of laser radiation on structure and properties of steel. In M. Kaloop (Ed.), *Proceedings of the International Conference on Advanced Materials, Structures and Mechanical Engineering* (pp. 75–78). London: CRC Press.
4. Kenara, H., Akman, E., Kacar, E., Demir, A., Park, H., Abdul-Khaliq, H., ..., Karaoz, E. (2013). Femtosecond laser treatment of 316L improves its surface nanoroughness and carbon content and promotes osseointegration: An in vitro evaluation. *Colloids and Surfaces B: Biointerfaces*, 108, 305–312. DOI:10.1016/j.colsurfb.2013.02.039
5. Okamuro, K., Hashida, M., Miyasaka, Y., Ikuta, Y., Tokita, S., & Sakabe, S. (2010). Laser fluence dependence of periodic grating structures formed on metal surfaces under femtosecond laser pulse irradiation. *Physical Review B*, 82(16), 165417. DOI:10.1103/PhysRevB.82.165417
6. Mahmoudi, B., Torkamany, M.J., Sabour Rouh Aghdam, A.R., & Sabbaghzade, J. (2010). Laser surface hardening of AISI 420 stainless steel treated by pulsed Nd:YAG laser. *Materials & Design*, 31(5), 2553–2560. DOI:10.1016/j.matdes.2009.11.034
7. Yang, J., Sun, S., Brandt, M., & Yan, W. (2010). Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy. *Journal of Materials Processing Technology*, 210(15), 2215–2222. DOI:10.1016/j.jmatprotec.2010.08.007
8. Idan, A.F.I., Akimov, O., Golovko, L., Goncharuk, O., & Kostyk, K. (2016). The study of the influence of laser hardening conditions on the change in properties of steels. *Eastern-European Journal of Enterprise Technologies*, 2(5), 69-73. DOI:10.15587/1729–4061.2016.65455
9. Assunção, E., Quintino, L., & Miranda, R. (2010). Comparative study of laser welding in tailor blanks for the automotive industry. *The International Journal of Advanced Manufacturing Technology*, 49(1), 123-131. DOI: 10.1007/s00170-009-2385-0

10. Mohanad, M.K., Kostyk, V., Domin, D., & Kostyk, K. (2016). Modeling of the case depth and surface hardness of steel during ion nitriding. *Eastern-European Journal of Enterprise Technologies*, 2(5), 45–49. DOI:10.15587/1729-4061.2016.65454
11. Kostyk, K. (2016). Development of innovative method of steel surface hardening by a combined chemical-thermal treatment. *Eureka: Physics and Engineering*, 6, 46–52. DOI:10.21303/2461-4262.2016.00220
12. Moscow Automobile and Road Construction State Technical University. (2009). *Procedure for steel part low temperature nitriding.* Russian Patent: RU 2415964.
13. "Kyiv Polytechnical Institute" National Technical University of Ukraine. (2007). *Method for obtaining of wearproof discrete nitrided layers*. Ukraine Patent: UA 25412.
14. "Kyiv Polytechnical Institute" National Technical University of Ukraine. (2006). *Method for combined laser-chemico-thermal treatment of materials*. Ukraine Patent: UA 19551.

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