Modification of working surfaces details by processing with laser irradiation

Valery Savulyak[a], Olena Shilina[a], Valery Shenfeld[a], Valery Kryvonosov[b], Tetyana Molodetska[a], Andrzej Smolarz[c], Assem Shayakhmetova[d], Mussa Turdalyuly[e]
[a]Vinnytsia National Technical University, Vinnytsia, Ukraine; [b]National Aviation University, Vinnytsia, Ukraine; [c]Lublin University of Technology, Lublin, Poland; [d]Al-Farabi Kazakh National University, Almaty, Kazakhstan; [e]Satbayev University, Almaty, Kazakhstan

ABSTRACT

In order to prevent surface adhesion processes between the two friction surfaces and to reduce static friction coefficients, it is proposed to treat them with laser irradiation and doping with graphene nanoplatelets. The effects of laser irradiation modes on the depth and structure of the modified surface layers were investigated. It was shown that by remelting the surface with laser radiation it is possible to obtain a metal layer with a fine microstructure and sufficiently high hardness. The doping with graphene nanoplatelets made it possible to block the uneven grain growth of the matrix phase of the coating and ensure its homogeneity. An examination of the parameters of the obtained coating after laser remelting shows their sensitivity to changes in the scanning speed of the laser beam on the surface. This makes it possible to control the properties of the surface layers.

Keywords: laser irradiation, graphene nanoplates, alloying components, thermal influence zones, modeling temperature fields.

1. INTRODUCTION

In moving pairs with sliding friction, the most extreme variant of surfaces interaction is the case when they interact at the atomic and molecular level. In this case, there is a high probability by adhesion between the materials of the surfaces, strain hardening of this contact, and, as a result, deep uprooting of the metal from one of the surfaces. This process is also accompanied by anomalous growth of static friction, which negatively affects the kinematics and dynamics of the functioning processes. To avoid adhesion and reduce friction, the crystal lattices of the surfaces should not be coherent, meaning the lattice parameters and cell sizes should not be the same. This is achieved by using of different materials of friction pairs, their thermal treatment using different technologies, coating, in particular, the use of composite materials [1,2,3].

The positive effect in terms of obtaining surfaces that are not prone to adhesion and formation of intense frictional bonds, and wear resistance is achieved through thermal treatment, laser irradiation, plasma, electric spark treatment. Thermochemical treatment methods are also used, such as cementation, nitrocarburizing, boriding and others. The disadvantage of these methods is the significant time, energy consumption and the small depth of the modified layer. In the work[4] it was proposed to combine the treatment of the working surfaces piston rings by laser irradiation with surface boriding. Research have shown that the surfaces treated by this method have high hardness and wear resistance.

Papers[5,6] investigate the treatment of friction surfaces methods surface remelting by laser. The starting material is cast iron, which, after remelting, formed cast iron with nodular graphite. The thickness of the obtained layer varies within the range of up to 200 microns, depending on the specific laser power deposited per unit surface area and the chemical composition of the processed material. The hardness of the resulting surface layers ranges from 500-630 HV. The results of studies on friction surfaces treated using the described technology showed the absence of adhesion and layering of materials on the contacting surfaces. Two different types of coatings, such as Co-Cr-W-C and Ni-Cr-B-Si-C, were considered in works[7,8], which were applied to the surface in the form of a powder mixture and melted using a laser. The coating was analyzed and tested on a tribometer with a steel ball-disc friction pair with a treated surface. The thickness and microhardness of the hardened coatings correlate with the data obtained in works [5,6]. The results of tribotechnical tests showed that the treated surfaces have no burrs, layers, or traces of cohesive interaction.

*e-mail: vsavulyak @vntu.edu.ua

Optical Fibers and Their Applications 2023, edited by Waldemar Wójcik, Zbigniew Omiotek,
Andrzej Smolarz, Proc. of SPIE Vol. 12985, 129850F · © 2023 SPIE
0277-786X · doi: 10.1117/12.3023443

The laser coating based on NiCrMoNb and NiCrBSiC was considered in works[9,10,11]. The analysis of the coating and its testing showed results that correlate with the data of works[7,8,12]. Steel surfaces have been modified and studied using surface laser modification[13,14] and alloying technologies[15,16,17]. As a result of surfaces treatment using such technologies, it is possible to obtain high hardness and wear resistance of surfaces under conditions of dry sliding friction.

The problem remains the development of the basics for designing technological processes, surface hardening of friction pairs by using alloying and laser processing. Additional research is needed to study the influence of processing parameters and to establish the relationship between laser heating parameters and the depth of the hardened layer. The high rate of surface heating by a laser beam, the low specific radiation power incident on the surface and quickly absorbed into the metal open up new prospects for material modification[18,19,20].

The use of laser irradiation allows for rapid heating and cooling rates (about 10^6 ° C/s and more). This is what makes it possible to melt cementite and other refractory compounds in such a short time that no decomposition of these chemical compounds occurs before melting[21].

The purpose of the work is to determine the effect of laser irradiation parameters on the depth and features structural formation characteristics of the layer.

2. EXPERIMENT METHODOLOGY

A high-carbon coating with a complex of alloying elements is applied to the surface of a steel sample (quality steel with a carbon content up to 0.45%). The structures of the treated sample surfaces were investigated based on the content of the alloying components applied to the sample surface and the parameters of their laser irradiation.

As powder materials, a powder mixture containing the following elements was used: 1) C – 3,45%, B – 1,2÷1,8%, Si 2,3÷2,8%, and the rest Ni. Graphene nanopowder of about 1% by weight was used in the powder mixture (graphene nanoplates were introduced together with graphite powder). The effect of this additive on the formation of the microstructure and strength of the resulting coating was studied.

The deoxidation of the surface layer was ensured by the introduction of boron and silicon into the charge [7,8].

The hardness of the formed surface layer is ensured by the formation of borides and carboborides in the range of 45…52 HRC. The graphene plates introduced into the powder charge block the growth of matrix grains, which ensures a uniform distribution of structural components.

The surface layers formed by this technology have a permissible operating temperature of up to 700°C with high resistance in both alkaline and oxidizing environments.

A powder mixture of ~1 mm thick was applied to the surface of the samples cleaned of oxides and contaminants using standard technology by gas flame spraying. The bonding strength of the resulting coating to the substrate made of high-quality steel with a carbon content of up to 0,45 % was set at ≈ 30 MPa.

After that, the samples were treated with a laser beam using the surface remelting method on the L-Master DP laser unit. For a pulsed laser source, the power denseness can be calculated [20] using the formula (1)

$$q_n = \frac{kT_E}{2A}\sqrt{\frac{\pi}{\alpha\tau}}, \tag{1}$$

where k is the thermal conductivity coefficient; T_E – evaporation temperature; A – absorption coefficient (A=1–R, R is the reflection coefficient); α – temperature conductivity coefficient; τ – laser pulse duration.

Then, when processing steel ($\alpha = 3{,}45 \cdot 10^{-2}$ cm^2/s) at $\tau = 10^{-4}$ s (the characteristic pulse duration of solid-state lasers operating in the free generation mode) we obtain $\approx 9 \cdot 10^5$ W/cm^2. Based on the research hypotheses and objectives, an experimental plan was devised.

Metallographic studies of the obtained samples were carried out on a raster microscope REM-106I and a horizontal microscope MIM-8M. Durometric tests were carried out on a PMT-3 microhardness tester by indentation a diamond pyramid under a load of 0.5 to 2 N.

3. RESEARCH RESULTS

Surface enhancement was achieved on samples made from steel of the same chemical composition, but with the addition of carbon in the form of graphene. The microstructure and the effect of alloying elements and graphene on wear resistance and microhardness were studied.

The microstructure of steel samples with a graphene-coated mixture after laser irradiation is shown in Fig.1, a.

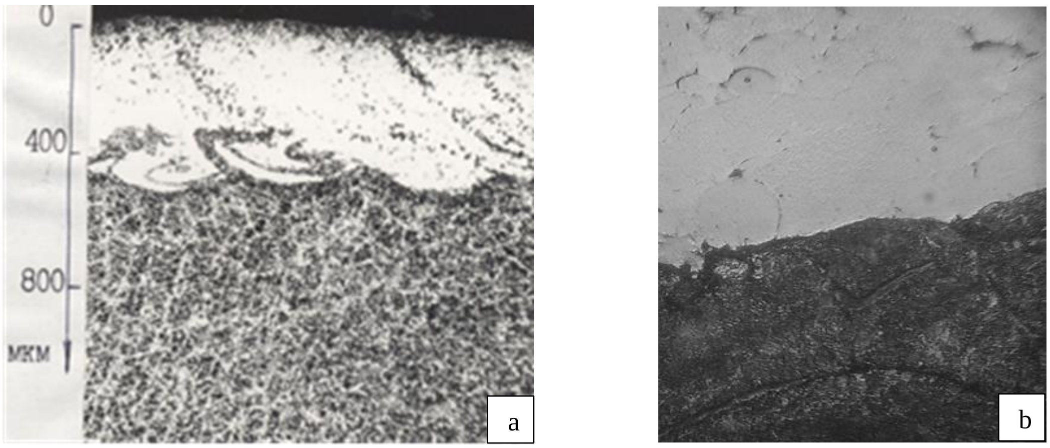

Figure 1. Microstructure of steel samples fused by laser irradiation and deposited with a mixture: a) with graphene; b) without graphene (x300)

Metallographic studies have shown that there is a fairly clear boundary between the applied layer and the basis. The laser-irradiated layer has an amorphous structure that is poorly susceptible to standard etching techniques. Graphite particles stand out in the form of compact inclusions, and graphene plays a positive role in the formation of a nanodispersed matrix structure. The fused zone has high hardness. Beneath the melted layer is a zone in which a cementitious mesh has formed along the boundaries of grain groupings.

The microstructure of the samples without the addition of graphene is shown in Fig.1, b.

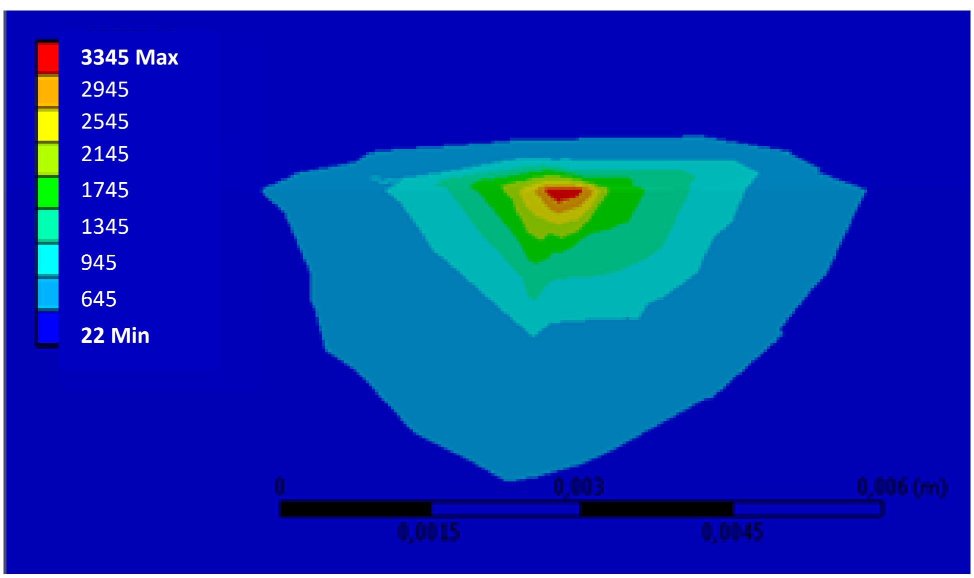

Figure 2. Temperature field from laser beam heating, calculated on a computer model for steel with a carbon content of up to 0.45%

The modeling results showed that the laser irradiation causes the thermal influence depth, which can cause phase transformations, to be greater than the radius of the thermal impact spot on the sample surface. This is due to a large thermal investment on a very small section of the sample surface. The diameter of the plot thermal impact with temperatures above 700 °C is 3 mm, while the depth is 4,5 mm.

By changing the beam relocation speed, we obtain a different configuration of the thermal impact field, penetration depth, and microhardness depending on the hardening depth. Based on the results of the study, obtained the results and plotted the dependencies are presented in Figs. 3 i 4.

Figure 3 shows the dependence of the hardening depth of a sample of quality steel with a carbon content of up to 0,45% and applied a graphene-coated mixture, as well as samples without the addition of graphene after laser irradiation on the speed relocation of the beam along the surface of the samples (Fig. 3a). The hardening depth decreases monotonically with the speed of scanning the surface with a laser beam. This is due to a decrease in the energy input per unit area of the sample, which allows steer by the volume of heated metal and the hardening depth.

Figure 3b shows the dependence of the hardening width of a sample made of quality steel with a carbon content of up to 0,45 % on the beam scanning speed over the sample surface, which also decreases monotonically. It should be noted that the surface spot of the thermal affected zone on the samples with the applied graphene-containing mixture is significantly larger.

Figure 4 shows the change in microhardness at different depths from the surface of the fused sample.

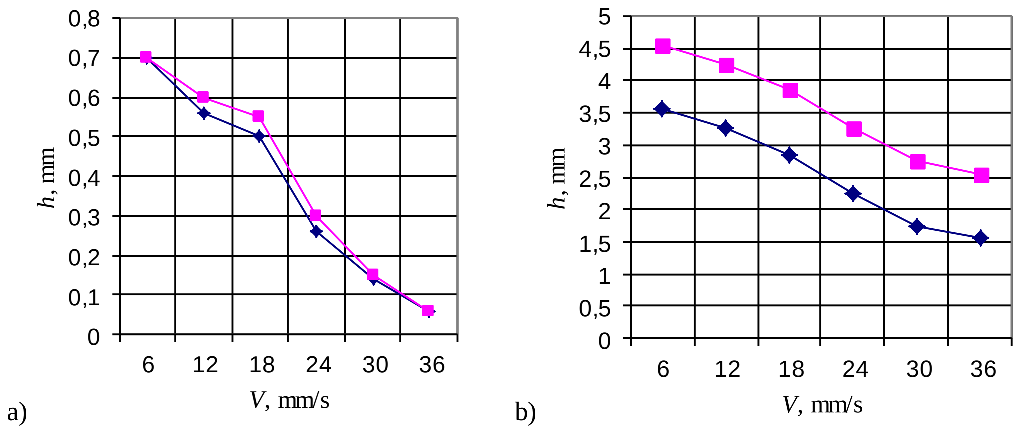

Figure 3. Dependence of a) hardening depth on the surface of the fused sample, b) hardening width on the beam scanning speed (□ – mixture with graphene, ◊ – mixture without graphene)

Attention should be paid to the positive impact of adding graphene nanopowder to the mixture applied to the surface before fused. The microhardness of the treated surface and its value at different depths from the surface of the fused sample is about 10% higher than the surface obtained by a similar technology but without the use of graphene.

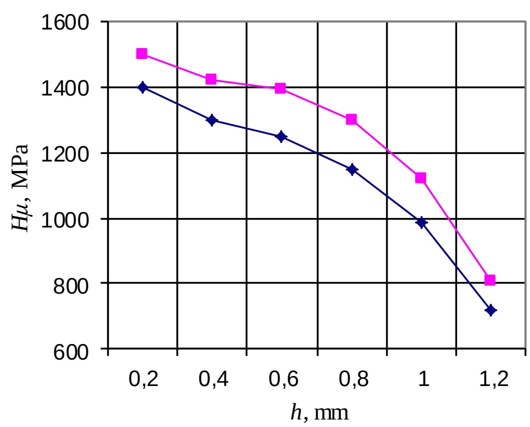

Figure 4. Dependence of microhardness of hardening in depth on the surface of the fused sample (□ – mixture with graphene, ◊ – mixture without graphene)

4. CONCLUSIONS

1. The drawback of the formed coating on samples of quality steel with a carbon content of up to 0,45% by applying PG-10N-04 type powders by gas flame spraying is the presence of pores, insufficient adhesion strength to the substrate, and heterogeneity, which does not allow recommending them for use in friction pairs operating in a shock and abrasive environment.
2. Positive results in terms of hardness and homogeneity were shown by applying a powder mixture of carbon – 3,45%, boron – 1,2÷1,8%, silicon 2,3÷2,8%, the rest nickel and it fused with a laser beam at different scanning speeds.
3. The addition of graphene nanopowder to the sputtered mixture can significantly improve the uniformity of the formed surface layer, increasing its microhardness, and its wear resistance.

REFERENCES

[1] Teng J.G., Dilum F., Tao Yu, Xiao-Ling Zhao., "Treatment of Steel Surfaces for Effective Adhesive Bonding. Advances in FRP Composites in Civil Engineering," Proceedings of the 5th International Conference on FRP Composites in Civil Engineering (CICE 2010), Sep 27–29, 2010, Beijing, China, 865-868 (2010).

[2] Farshidianfar M. H., Khajepouhor A., and Gerlich A., "Real-time monitoring and prediction of martensite formation and hardening depth during laser heat treatment," Surface and Coatings Technology, Vol. 315, 326–334 (2017).

[3] Carrera-Espinoza, R., Rojo Valerio, A., del Prado Villasana, J., Yescas Hernández, J.A., etc., "Surface Laser Quenching as an Alternative Method for Conventional Quenching and Tempering Treatment of 1538 MV Steel," Advances in Materials Science and Engineering, (2020).

[4] Hlushkova D., Volchuk V., "Determination of the optimal parameters of laser boriding to improve the wear resistance of piston rings," New materials and technologies in metallurgy and mechanical engineering, 2 (2022).

[5] Pascu, A., Hulka, I., Tierean, M.H., Croitoru, C., Stanciu, E.M. and Roată, I.C., "A comparison of flame coating and laser cladding using Ni based powders," In Solid State Phenomena, Trans Tech Publications Ltd., Vol. 254, 77-82 (2016).

[6] Wang, B., Pan, Y., Liu, Y., Lyu, N., Barber, G.C., Wang, R., Cui, W., Qiu, F. and Hu, M. "Effects of quench-tempering and laser hardening treatment on wear resistance of gray cast iron," Journal of Materials Research and Technology, Vol. 9, 8163-8171 (2020).

[7] Jeyaprakash, N., Yang, C.H., Duraiselvam, M. and Sivasankaran, S., "Comparative study of laser melting and pre-placed Ni–20% Cr alloying over nodular iron surface," Archives of Civil and Mechanical Engineering, 20(1), 1-12 (2020).

[8] Jeyaprakash N., Yang Che-Hua & Sivasankaran S. "Laser cladding process of Cobalt and Nickel based hard-micron-layers on 316L-stainless-steel-substrate," Materials and Manufacturing Processes, (2019).

[9] Jeyaprakash N., Yang Che-Hua, Tseng Sheng-Po. "Characterization and tribological evaluation of NiCrMoNb and NiCrBSiC laser cladding on near-α titanium alloy," The International Journal of Advanced Manufacturing Technology, Springer London, 2347-2361 (2020).

[10] Mthisi A., Popoola A.P.I., Popoola O.M., "Tribological behaviour of laser synthesized Ti-Al2O3 coatings on Ti-6Al-4V alloy," Int J Adv Manuf Technol, 103, 655–664 (2019).

[11] Jeyaprakash N., Duraiselvam M., Raju R., "Modelling of Cr3C2-25% NiCr laser alloyed cast iron in high temperature sliding wear condition using response surface methodology," Arch Metall Mater, 63, 1303–1315 (2018)

[12] Xi W., Song B., Yu Z., Yu T, Wang J., "Geometry and dilution rate analysis and prediction of laser cladding," Int. J. Adv. Manuf. Technol., 103, 4695–4702 (2019).

[13] Xu X., Mi G., Xiong L., Jiang P., Shao X., Wang C., "Morphologies, microstructures and properties of TiC particle reinforced Inconel 625 coatings obtained by laser cladding with wire,". J. Alloys Compd. 740, 16–27 (2018).

[14] Sassatelli P., Bolelli G., Gualtieri M.L., Heinonen E., Honkanen M., Lusvarghi L., Manfredini T., Rigon R., Vippola M., "Properties of HVOF-sprayed Stellite-6 coatings,". Surf. Coat. Technol., 338, 45–62 (2018).

[15] Barka, N., Sattarpanah Karganroudi, S., Fakir, R., Thibeault, P. and Feujofack Kemda, V.B., "Effects of Laser Hardening Process Parameters on Hardness Profile of 4340 Steel Spline—An Experimental Approach," Coatings, 10 (4), 342 (2020).
[16] Zhou, W., Zhou, Y., Wu, N. and Maharjan, N. "Laser surface hardening of AISI 1055 steel in water submerged condition," (2019).
[17] Zhang, L., Yu, G., Li, S., He, X., Xie, X., Xia, C., Ning, W. and Zheng, C., "The effect of laser surface melting on grain refinement of phase separated Cu-Cr alloy," Optics & Laser Technology, 119, 105577 (2019).
[18] Cui, Y., "Influence of laser surface melting on tribological behaviour of AZ31B," Surface Engineering, 34 (4), 296-300 (2018).
[19] Newishy, M., Abdel-Aleem, H., Elkousy, M.R., El-Mahallawi, I. and El-Batahgy, A., "Surface Treatment of AISI M2 Tool Steel by Laser Melting. In Key Engineering Materials," Trans Tech Publications Ltd., Vol. 786, 128-133 (2018).
[20] Afanasieva O.V., Lalazarova N.O., Fedorenko Ye.P., "Lazerna poverkhneva obrobka materialiv," Kharkiv, FOP Panov A.M., 100 (2020).
[21] Gotra Z., Grigorchak I., Pavlov S., etc., "Submicron and nanoscale structures of electronics," Chernivtsi, Technological Center, 839 (2014).