The Eurasia Proceedings of Science, Technology,
Engineering and Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2026

Volume 40, Pages 11-18

ICBAST 2026: International Conference on Basic Sciences and Technology

The Physical Nature and Structural Organization of Steel Surface Layers Formed Under Thermal Deformational Effect Caused by Pulsed Laser Radiation

Elena Shcherbakova
Don State Technical University

Sergey Knyazev
Don State Technical University

Abstract: During pulsed laser processing and modification of the surface of steels and alloys, several still unresolved issues arise related to the structure formation and property development in the irradiated zones. The aim of this article is to study and scientifically analyze the features in phase transformations, structure and properties formation of the steels surface layers under variable modes of high-speed laser heat treatment. Metallophysical studies in the work were carried out on samples of carbon and alloy steels subjected to pulsed laser irradiation using a technological device Kvant-16 with a radiation power density of 50–250 MW/m2. The identification of the phase composition and the materials structure study were carried out by several methods: metallographic, X-ray, scanning probe microscopy, hardness measurement.It is shown that the locality of laser treatment, a high heating rate and high temperature gradients along the layer depth led to the thermoelastic stresses appearance, which play the main role in the steels surface hardening. The physical nature and structural organization of the “white zone” formed around carbide inclusions in steel have been established by metallophysical studies. The main part of the "white zone" is a nanosized austenite-martensite structure with a martensite lath size of ~150nm, which has anomalously high values of microhardness.It has been established that under the conditions of pulsed laser radiation thermal-deformation effect during the treatment of steels and alloys without surface melting, the main role in structure formation and formation of properties is played not by diffusion processes, but by processes of local plastic deformation. It is shown that the presence in laser-hardened steel of a dispersed carbides large amount (more than 40% of the irradiated volume of steel), surrounded by "white zones", contributes to the creation of a structural state on the working surfaces of products with high microhardness values.

Keywords: Laser irradiation, Steels, Carbides, Structure.

Introduction

Pulsed laser treatment has a number of characteristic features that affect the processes of hardening, structure formation, and the formation of the irradiated material operational properties. These include the high concentration of the supplied energy and the treated domain locality; high manufacturability; high processing speed; ease of automation; absence of hazardous waste during irradiation, etc. (Cui et al., 2019; Katancik et al., 2020; Lapouge et al., 2019; Lesyk et al., 2017; Roy et al., 2017; Sagar et al., 2018). The developed surface of such a structure, consisting of low-angle, semi-coherent, low-energy boundaries, determines the low etchiness of the "white zone", which has anomalously high values of microhardness.

An analysis of the prospects and relevance using the laser processing for hardening various materials showed that pulsed laser radiation has unique characteristics that allow heating the materials surface at hyper high speeds (106 deg/s) and with almost complete absence of holding at temperatures above critical points. Subsequent rapid cooling at rates of 104-106 deg/s fixes in the material surface layers some results of phase transformations and structure formation occurring in them at high heating temperatures.

Non-trivial thermal processes lead to the temperature gradients' appearance and the formation of hardened zones with a depth of 0.05-0.18 mm on the steels surface, which have low etching, dispersed crystalline structure, and high hardness. The result of laser treatment depends on the energy characteristics of the heat source, the time of its exposure, and the thermo physical properties of the material being hardened.

To determine the structural and tool steels hyper speed heat treatment technological prospects, the article provides a scientific analysis of the features in phase transformations and structure formation, the formation of properties in the steels surface layers under variable modes of high-speed laser heat treatment.

The created and considered physical models of the phenomena that arise in materials during laser processing will make it possible to purposefully form in the surface layers of steels the necessary, specified structure with the required level of performance properties.

Features of the laser processing process- locality (spot diameter ~1-5 mm), small depth of heat-affected zones (~50-150 microns), high heating and cooling rates - leave an imprint on the structures formed in the surface layers of materials.

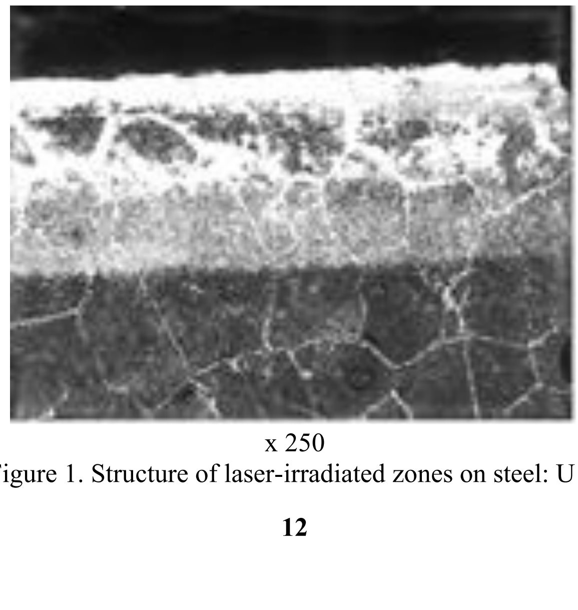
Method

The materials for this study were carbon and alloy steel.

Pulsed laser irradiation was carried out on the technological device: "Kvant-16". Changing the radiation energy, the beam defocusing degree (3-6 mm), the duration of the radiation (1-6) 10^{-3} s made it possible to vary the radiation power density in a wide range (50-250 MW/m^2). The identification of the phase composition and the study of the materials structure after laser processing were carried out by several methods, the combination of which was determined by the research objectives: metallographic, X-ray, study of areas of laser processing using a scanning probe microscope in atomic force microscopy mode, hardness measurement, etc.

Results and Discussion

When carrying out metallophysical studies, it was found that in the irradiated layer of steel, as can be seen in Figure 1, two zones are formed that have a different phase transformations nature. On the surface of the material there is a fusion zone, which is formed during crystallization under laser hardening from a liquid state. It has a dendritic structure, and the dendrites are directed towards the heat sink. In this zone, carbides are almost completely dissolved, and there are no such defects in the liquid metal as craters, slag inclusions, decarburized areas of the slick. The zone of laser hardening from the liquid state is absent in the case of laser processing without melting the metal surface.



x 250

Figure 1. Structure of laser-irradiated zones on steel: U12

Below there is a zone of laser hardening from a solid state, which has a low etching rate and the highest hardness. It was established (Parkin & Zhatkin, 1994) that an important, although not decisive, role in the process of structure formation during high-speed laser processing is played by mass transfer and its special case - diffusion. This is especially true for multiphase steels and alloys, containing a significant carbides amount, the dissolution of which, at least partially, affects the saturation degree of α- and γ- solid solutions with carbon and alloying elements, on the course of phase transformations, on the level of the irradiated materials achieved properties.

It should be noted that, under laser heating conditions, high values of temperature gradients and concentrations, as well as the presence of stress fields, play an important role in the process of structure formation in the irradiated metal. It was found that under pulsed laser irradiation, under time deficit conditions, diffusion processes are observed only in the zones of laser quenching from the liquid state, at the boundary with the quenching zone from the solid state, and in the “carbide - steel matrix” compositions in the material zones irradiated without fusion.

The temperature gradients and thermal stresses that appear in the metal zones irradiated with fusion of the surface contribute to the dynamic convective mixing of the liquid at a speed of 103cm/s, and also, despite the extremely short laser pulse time (10^{-3} s), partial or complete dissolution of carbides.

As a result, the chemical composition of the fused metal changes, the points of martensitic transformation decrease, and a significant amount of textured metastable retained austenite (40-70%) is fixed, which is characterized by a high dispersity of the structure (cross-section of dendrites 5-9 nm) and crystallization texture.

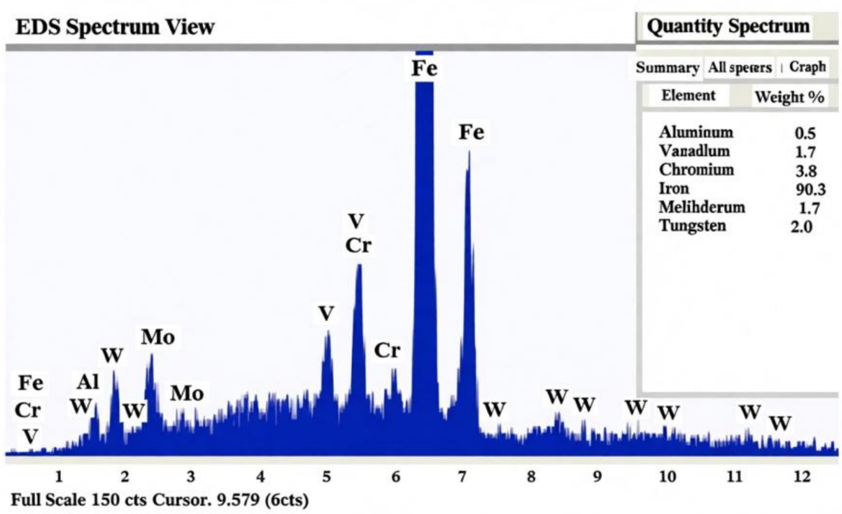
As mentioned above, the irradiated zones have a heterogeneous structure in depth, along with the zone of laser hardening from the liquid state; there is a zone of laser hardening from the solid state. The peculiarities of this zone are its non-etching in conventional reagents, dispersion of the structure and high hardness. The low etching of this zone is apparently associated with the low energy of the interphase boundaries, as well as with the absence of the phase boundaries decoration with dispersed carbide inclusions.

To elucidate the fine structure features of the laser hardening zone from the solid (austenitic) state and the role of mass transfer in its formation, annealed samples of U8 carbon steel after laser hardening were studied using a Hitachi TM-1000 scanning electron microscope, which makes it possible to obtain an undistorted image of the surface metal in reflected and secondary electrons with a high magnification and a depth of field exceeding the optical microscope depth of field, and also allows you to obtain a profile of the investigated surface.

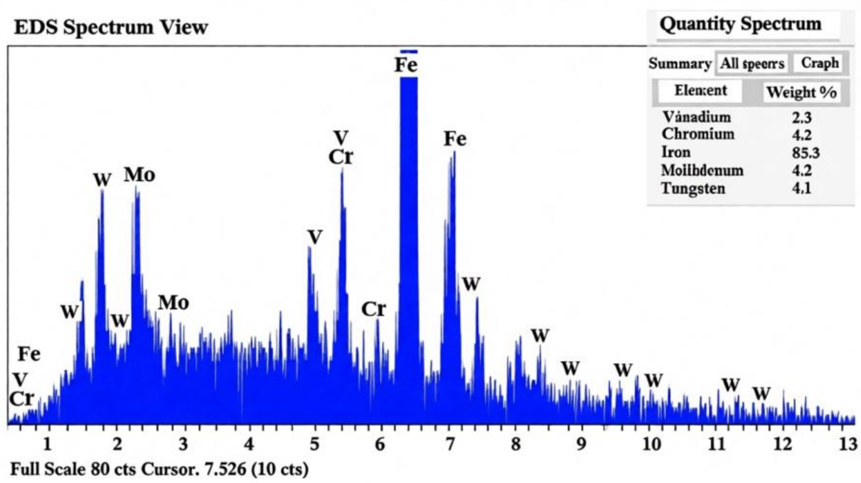
First of all, attention is drawn to the results of the local chemical analysis for the irradiated zones, shown in Figure 2. As can be seen, the chemical composition of the solid state laser hardening zone is similar to the chemical composition of the base metal, that is, there are no explicit macro-diffusion processes in this zone. Despite this, the irradiated steel in this zone has properties that differ from the base metal. For comparison, Figure 2 (b) shows the chemical composition of steel irradiated with melting. As can be seen, with an almost complete dissolution of carbides, the general background and the reflections intensity of alloying elements increase, which indicates the occurrence of diffusion processes in this case. Of interest is the fine structure of the solid-state laser hardening zone (SS zone).

Figure 3 shows the microstructure of the transition zone from the base metal (lamellar pearlite) to the SS zone, as well as the distribution of the surface profile heights in the base metal and in the SS zone. The route of scanning and measuring the height of structural elements is indicated in Figure 3 (a) with a marker line. As can be seen: the SS zone has a dispersed, poorly etched structure; individual elements of the structure cannot be detected at a magnification of 100,000 times.

A change in the contrast of the image, which makes it possible to distinguish between the base metal and the SS zone when examined with a scanning electron microscope, may be associated with a local change in the chemical composition at the interface between ferrite and cementite. This is explained by the possible escape of carbon atoms from the boundaries of cementite plates to dislocations of the adjacent ferrite, which leads to a change in the conditions for the interaction of the probe electron beam with these microvolumes of steel. One of the possible reasons for the local change in the chemical composition at the cementite-ferrite boundaries is the difference in the binding energy of carbon atoms with iron atoms in the crystal lattice of cementite in comparison with their binding energy with dislocation cores.

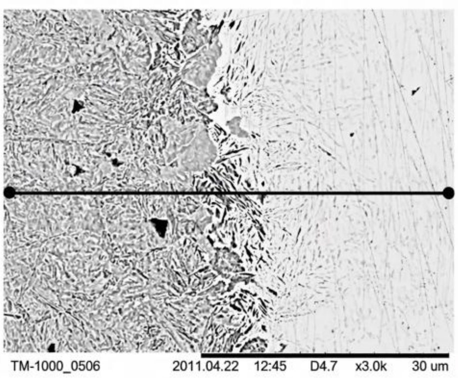


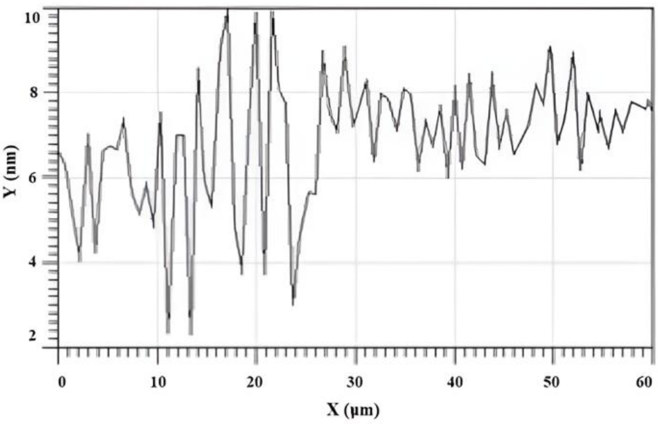
a



b

Figure 2. Local spectral analysis of U8 steel after laser irradiation without (a) melting and (b) surface melting.





a b

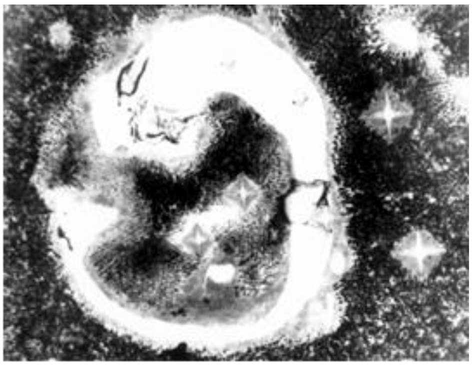
Figure 3. Microstructure of the transition domain from the base metal to the SS zone of the irradiated spot on U8 steel with the lamellar pearlite structure, revealed during the study on SEM (a) and the profilogram indicated by the line of the transition zone (b).

It was found that the metal regions in the SS zone are located above the plane of the thin section, that is, they are harder and more dispersed. The profilogram of this domain does not have sharp fluctuations in height, that is, the transition zones between the matrix and the carbide protruding above the surface of the microsection are smoothed out. As can be seen in Figure 4 (b), in the initial lamellar pearlite, the average height of the sample surface profile is 6.2 nm, and in the SS zone - 7.4 nm. This result, as well as the fact that the chemical composition of the SS zone is practically similar to the chemical composition of the parent metal, may indicate a partial dissolution of carbides, which begins from the interface between them and the ferrite matrix.

In order to expand knowledge about the fine structure and properties of the SS zone, scratch wear tests were carried out using the Nanotest installation. A friction probe equipped with a strain gauge was used, which made it possible to determine the friction force between the indenter and the sample under the action of the gravity of the calibration weights.

It has been established that the values of the friction force when the SS zone is scratched by the indenter are 17 MN in comparison with 11 MN for the base metal. It can be concluded that the SS zone is formed at a pulsed thermal-deformation stress of the laser-irradiated metal surface layer. In this case, local plastic deformation occurs, accompanied by dynamic polygonization and quenching of the matrix surrounding the carbides with a possible change in the chemical composition in local domains of the structure at the boundaries of the "carbide - steel matrix" composition. Moreover, different mechanisms are responsible for the degree and result of the changing the chemical compositions processes and mass transfers processes in the SS zone and in the laser-melted metal discussed above.

Let us consider the features of the mass transfer manifestation during laser processing without melting the metal surface. When carrying out metallographic studies, it was noticed that in the laser irradiation zone of alloy steel, despite the short thermal effect duration, the results of the partial carbides dissolution process in the surrounding matrix are clearly visible. As can be seen in Figure 4, this is expressed in the formation of a light non-etched border around the carbide inclusions, the so-called "white zones".



x500

Figure 4. "White zones" around carbides in irradiated steel R6M5.

The micro hardness of these areas is 4-6 GPa. The obtained values of hardness correspond to the hardness of medium-carbon steels martensite. The ensembles formation of such concentration inhomogeneous areas in the irradiated zones additionally strengthens the laser-hardened metal.

It can be concluded that the light non-etched border near the carbide particles indicates the austenite formation during heating and martensite formation during cooling these areas.
The carbon spread from the carbides grain boundaries occurred at a distance of L=2-3 microns. This diffusion path during the action of the laser beam $\tau \approx 10^{-3}$s corresponds to the diffusion coefficient of carbon in austenite $D \approx L^2/\tau \approx 4 \cdot 10^{-5}$cm^2/s, which exceeds the value of the carbon diffusion coefficient in iron (1-5) 10^{-7}cm^2/s at a temperature of 1000ºC and corresponds to the self-diffusion coefficient of iron in the melt.

Such a high diffusion rate of carbon can be explained by the appearance of the liquid phase interlayers at the boundaries of carbides with a matrix (with ferrite) due to contact melting, which occurs at temperatures much lower than the melting temperatures of the components during the thermo-force stresses action at the “carbide-ferrite” boundaries under laser irradiation.

A similar contact melting phenomenon at the boundary of cementite inclusions with a matrix of technical iron was described for the case of laser irradiation in (Dolgachev et al., 2024; Pustovoit et al., 2017) and graphite with a metallic matrix of cast iron in (Li & Guan, 2020). As a result, a complex structural pattern is formed around the carbide inclusions. In the immediate vicinity of the boundary, due to contact melting, a thin shell of liquid metal is formed, which promotes the accelerated mass transfer of carbon atoms and alloying elements from the inclusions to the adjacent matrix layer.

After crystallization around carbides, the formation of a superhard amorphous-like framework is possible. It should be noted that, depending on the heating temperatures reached during the action of the laser pulse, different mass transfer driving forces can prevail in the irradiated metal. At high temperatures, the main mechanism is thermal diffusion caused by high temperature gradients (10^5-10^7 K/cm), which is effective for 7-10 ms. Beginning from 700-800^{0}C, deformation processes, heterogeneous in depth, intensively proceed. During this time period, anomalous accelerated mass transfer occurs, associated with the influence of local microplastic deformation processes occurring in the zones of laser treatment from the solid state (Brover & Shcherbakova, 2023, 2024; Kumar et al., 2023; Lu et al., 2019; Sahoo et al., 2023).

In the main part of the volume of "white zones", the transformation of α→γ under the described extreme temperature-force conditions is carried out according to the shear mechanism, which leads to plastic deformation of the matrix. Under conditions of high-speed laser hardening, the recrystallization processes are suppressed, the dynamic polygonization processes of austenite proceed with the fragmented substructure formation. Austenite crystals are in the form of thin plates separated by semi-coherent boundaries with low energy and high density of epitaxial dislocations (Li et al., 2023; Ma et al., 2022; Tsumura et al., 2025).

In the process of high-speed quenching, an α→γ transformation occurs in the austenite rim. Martensite crystals are shear-formed in austenite lamellae and are also in the form of thin lamellas separated by low-energy semi-coherent boundaries. This leads to a low etching of the "white zone" and a very high microhardness (10-12 GPa) due to the high density of dislocations during shear α→γ→α transformations. Figure 5 shows the results of studying the "white zone" structure using an atomic force microscope.

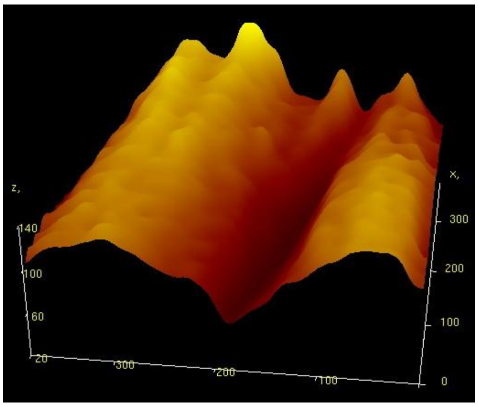


Figure 5. 3D - image of the "white zone" structure (AFM)

As can be seen in the 3D image, martensite crystals have the form of thin laths ~ 150 nm in size and look like protrusions on the surface. The troughs are, apparently, thin wedge-shaped twins, which are formed during diffusionless phase transformations of the martensitic type at the elastic twinning stage (Brover & Shcherbakova, 2023; Kraposhin, 1989; Matyunin et al., 2022). The presence in laser-hardened steel of a dispersed carbides large amount (more than 40% of the irradiated steel volume), surrounded by "white zones", contributes to creation on the working surfaces of products the structural state with high microhardness values, indifferent to external temperature-force loading during operation.

It has been experimentally established that the revealed the structural state features of the steels and alloys irradiated surface layers make it possible, by varying the parameters of the laser radiation mode, to obtain structures in them that have different degrees of adaptation to external loading conditions and have a positive effect on heat and wear resistance.

Conclusion

1. It has been established that under the conditions of pulsed laser radiation thermal-deformation effect during the treatment of steels and alloys without surface melting, the main role in structure formation and formation of properties is played not by diffusion processes, but by processes of local plastic deformation. Which is the

relaxation consequence of thermostrictive stresses and stresses at the phase boundaries in the "carbide-steel matrix" system.

2. It is shown that the presence in laser-hardened steel of a dispersed carbides large amount (more than 40% of the irradiated volume of steel), surrounded by "white zones", contributes to the creation of a structural state on the working surfaces of products with high microhardness values.

3. The possibilities of improving the methods of thermal hardening of materials using pulsed laser heating have been determined. This makes it possible to solve the problem of forming the surface layer structure with varying degrees of adaptability to the temperature-force conditions loading both during irradiation and during operation.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

Funding

* This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements or Notes

* This article was presented as a poster presentation at the International Conference on Basic Sciences and Technology (www.icbast.net) held in Konya/Türkiye on April 02-05, 2026.

References

Brover, G. I., & Shcherbakova, E. E. (2023). The role of carbides in forming the steels structure and properties under pulsed laser irradiation. *Safety of Technogenic and Natural Systems, 4*, 106–118.

Brover, G. I., & Shcherbakova, E. E. (2023). Steel surface layer structure and property evolution during pulsed laser treatment. *Metallurg, 32*, 66–70.

Brover, G. I., & Shcherbakova, E. E. (2024). Influence of the initial structure on the efficiency of the laser processing of steels. *Metallurg, 2*, 36–42.

Cui, J., Li, M., Fu, B., & Hou, Q. (2019). Migration behaviors of helium atoms near tungsten surfaces: A molecular dynamics study. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 455 (15)*, 1-6.

Dolgachev, Yu. V., Pustovoit, V. N., & Vernigorov, Yu. M. (2024). Stress martensite nucleation in a state of premartensitic lattice instability. *Advanced Engineering Research (Rostov-on-Don), 24*(1), 58-65.

Katancik, M., Mirzababaei, S., Ghayoor, M., & Pasebani, S. (2020). Selective laser melting and tempering of H13 tool steel for rapid tooling applications. *Journal of Alloys and Compounds, 849*, Article 156319.

Kraposhin, V. S. (1989). Relationship between microstructure features and heat and mass transfer characteristics in iron of technical purity during laser heating. *Physics and Chemistry of Materials Processing, 1*, 32-37.

Kumar, H., Bhaduri, G. A., Manikandan, S. G. K., Kamaraj, M., & Shiva, S. (2023). Effect of laser surface processing on the microstructure evolution and multiscale properties of atmospheric plasma sprayed high-entropy alloys coating. *Journal of Thermal Spray Technology, 32*, 831-850.

Lapouge, J. P., Dirrenberger, J., Coste, F., & Schneider, M. (2019). Laser heat treatment of martensitic steel and dual-phase steel with high martensite content. *Materials Science and Engineering: A,752*, 128-135.

Lesyk, D. A., Martinez, S., Mordyuk, B. N., Dzhemelinskyi, V. V., Lamikiz, A., Prokopenko, G. I., Milman, Yu. V., & Grinkevych, K. E. (2017). Microstructure related enhancement in wear resistance of tool steel AISI D2 by applying laser heat treatment followed by ultrasonic impact treatment. *Surface and Coatings Technology, 328*, 344-354.

Li, X., & Guan, Y. (2020). Theoretical fundamentals of short pulse laser-metal interaction: A review. *Nanotechnology and Precision Engineering, 3*, 105–125.

Li, X., Wang, Q., & Zhou, W. (2023). Interface analyses and mechanical properties of stainless steel/nickel alloy induced by multi-metal laser additive manufacturing. *Journal of Manufacturing Processes, 91*, 53–60.

Lu, G., Sokol, D. W., Zhang, Y., & Dulaney, J. L. (2019). Nanosecond pulsed laser-generated stress effect inducing macro-micro-nano structures and surface topography evolution. *Applied Materials Today, 15*, 171–184.

Ma, C., Xia, Z., & Zhong, Y. (2022). Carbides refinement and mechanical properties improvement of H13 die steel by magnetic-controlled electroslag remelting. *Journal of Materials Research and Technology, 19*, 3272–3286.

Matyunin, V. M., Kudryakov, O. V., Varavka, V. N., & Marchenkov, A. Yu. (2022). Micromechanics of small deformations in metal alloys under laser irradiation. *Industrial Laboratory. Diagnostics of Materials, 88*(10), 66–72.

Parkin, A. A., & Zhatkin, S. S. (1994). Features of heating and mass transfer processes in a material under pulsed laser action. *Physics and Chemistry of Materials Processing, 8*, 27-35.

Pustovoit, V. N., Dombrovsky, Yu. M., & Dolgachev, Yu. V. (2017). Structural identification of the phenomenon "white zone". *Metal Science and Heat Treatment, 59*(1), 1-5.

Roy, S., Zhao, J., Shrotriya, P., & Sundararajan, S. (2017). Effect of laser treatment parameters on surface modification and tribological behavior of AISI 8620 steel. *Tribology International, 112 (11)*, 94-102.

Sagar, V. R., Warmefjord, K., & Soderberg, R. (2018). Geometrical variation from selective laser heat treatment of boron steels. *Procedia CIRP, 75*, 409-414.

Sahoo, S., Mishra, R., Srivastava, N., & Arora, A. (2023). FEM simulation of pulsed laser welding of high-carbon alloy steel: Using different heat source models. *Transactions of the Indian Institute of Metals, 66*, 1005–1013.

Tsumura, Y., Paradowska, A., Rode, A. V., Mohan, M., & Proust, G. (2025). Simplified method for predicting melting and ablation process parameters during laser surface treatment of metals and alloys. *Journal of Applied Physics, 137*, 235102.

Author(s) Information

Elena Shcherbakova
Don State Technical University
Gagarina Sq.,1, Rostov-on-Don, Russian Federation, 344003
ORCID iD: https://orcid.org/0000-0002-9239-1955
*Contact e-mail: *etsherbakova@donstu.ru*

Sergey Knyazev
Don State Technical University
Gagarina Sq.,1, Rostov-on-Don, Russian Federation, 344003
ORCID iD: https://orcid.org/0000-0002-8607-3416

*Corresponding author(s) contact email

To cite this article:

Shcherbakova, E. & Knyazev, S. (2026). The physical nature and structural organization of steel surface layers formed under thermal deformation effect caused by pulsed laser radiation. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 40,* 11-18.