Influence of laser exposure on the processes occurring in a surface layer of austenitic steel products

S. A. Vologzhanina, *Dr. Eng., Prof., Dept. of Materials Science and Technology of Art Products* [1], *e-mail: vologzhanina_sa@pers.spmi.ru;*
R. M. Khuznakhmetov, *Post-graduate Student, Dept. of Materials Science and Technology of Art Products* [1], *e-mail: ruslan.rh44@gmail.com;*
J. V. Amyaga, *Production Engineer* [2], *e-mail: joooneg@yandex.ru;*
E. Yu. Zhdanova, *Cand. Eng. (Ph. D.), Engineer Technologist* [3], *e-mail: ivan.grey.90@mail.ru;*
A. Ramos-Velazkuez, *Cand. Eng. (Ph. D.), Research Engineer* [4], *e-mail: alejandroramosv@itmo.ru*

[1] *Empress Catherine II Saint Petersburg Mining University (St. Petersburg, Russia)*
[2] *IPG Laser GmbH & Co. KG (Burbach, Germany)*
[3] *LLC «Laser Center» (St. Petersburg, Russia)*
[4] *National Research University «ITMO» (St. Petersburg, Russia)*

The workability of equipment operating in the northern regions can be ensured by using various technologies during its manufacture. Laser exposure is widely used in various industries, including manufacture of welded joints, heat treatment of small areas, application of coatings, preparation of surfaces for further processing, and marking of products both directly on the material surface and on special films. This work examines the processes occurring in the surface layer of AISI 321 austenitic steel products exposed to nanosecond laser radiation. Various methods for controlling the metal melt in the exposed zone are considered. It has previously been established that moving the beam along a trochoidal trajectory allows creation of stable linear relief up to ~700 μm high, while moving along a spiral trajectory produces point elements up to ~500 μm high. In the present study, structures up to ~400 μm high were obtained using a linear trajectory. Laser processing methods that can be implemented using standard low-power laser equipment, were studied, enabling surface processing of austenitic steel without use of protective gas environments. It was shown that laser exposure of surface layers preserves the austenitic structure, stabilizes it, just reduces the oxide phase content, and does not lead to the formation of carbide phases in the area of the formed relief. These results are important for various branches of mechanical engineering, including laser processing during welding, creation of functional surfaces, application of durable markings, production of a preset profile in the manufacture of decorative and applied products, and tactile elements such as Braille script. The study demonstrates the potential of liquid phase control for effective relief formation on the surface of austenitic steels.
Key words: laser processing, austenitic steel, surface relief, microhardness, microstructure, Braille scripts, tactile elements.
DOI: 10.17580/cisisr.2025.02.09

Introduction

Mastering and rapid development of Arctic regions, Siberia and Far East imposes strict requirements to the materials and technologies, which should provide durable and reliable operation of the equipment in the extremal climatic conditions [1–3]. Especially sharply these requirements are manifesting in the petrochemical industry, where equipment is subjected to exposure of aggressive environment, essential mechanical loads and dramatic temperature gradients [4–6]. Supply of machine components, piping, construction components and technological equipment parts with the complex of high operating parameters, which include corrosion resistance, wear resistance and long service life, is critically important in these conditions [7, 8]. Solving this problem needs use of up-to-date methods of surface hardening of the materials.

The technologies of laser processing of metals are considered as prospective direction in this field; they allow modifying of structure and properties of materials surface layers [9, 10]. The laser technologies are widely used in various industries, including welding, local heat treatment, application of coatings and preparation of surfaces [10–12]. These technologies are mostly required when creating decorative and applied products and marking of products both directly on the material surface or on special films [13–15]. Use of laser technologies for processing of austenitic steels attracts especial interest, because they are characterized by optimal combination of corrosion resistance and physical-mechanical properties and are widely used in various industries (from manufacturing medical tools to fabrication of equipment for the power engineering complex, including petrochemical industry) [16–18]. The modern laser technologies achieved the principally new level in the field of metal processing, owing to development of powerful fiber-optic systems with modulated radiation [19–21]. In particular, laser sources of YB-fiber pulsed (YPL) type (IPG Photonics) provide extraordinary accuracy and processing stability, which opens the new prospects for their industrial use [15, 22]. These radiation sources are characterized by high stability of parameters, compact size and possibility of integration in automatized technological complexes [9]. Such equipment can be used in forming of controlled relief and preset phase-structural state on the surface of austenitic steels, what presents essential scientific and practical interest. It allows obtaining the required complex of the properties (including tribologic ones); creating stable marking elements; forming functional surfaces with preset properties; providing tactile identification (e.g. in Braille script) [23–25]. Additionally, the conventional marking methods for steel products (mechanical processing, chemical pickling) often do not ensure the required accuracy and reproducibility [14]. At the same time, laser marking can be used for monitoring of products at all manufacturing stages, for detecting waste metal and for protection against falsification [13].

The previous researches [22] displayed possibility of controlled relief forming in steel St3 during one-pass and two-pass laser processing procedures. It was established that the geometry of linear structures depends essentially on trajectory: maximal stability is provided by trochoidal beam motion (up to ~700 μm high), which forms uniform energy distribution and controlled melt flow. For the tasks of tactile marking, forming of dotted structures along a spiral trajectory (up to ~500 μm high), valid for a Braille script, was examined [13, 14, 22]. Layer-by-layer relief growing with alternating of forming and "cleaning" passes was realized in a multipass procedure; it increases the amount of oxide phase [22]. Such results became a methodical base for this research, which was adapted for the stainless steel AISI 321 for evaluation of the effect of procedures on relief forming and phase-structural transformations in the surface layer.

This research presents the results of complex investigation of relief forming processes on the surface of the stainless steel AISI 321 under the effect of nanosecond laser radiation. Special attention was paid to the interaction mechanisms between laser radiation and the material, control possibilities for a liquid phase and analysis of phase-structural transformations in the processing area. It should be noted in this case that the main difficulty during high-temperature processing of austenitic steels is connected with their addiction to oxidation, forming of carbide phases and possible thermal deformations [26, 27]. The conducted research is very important for development of additive technologies, creation of functional surfaces and solving the applied problems in various industries. The obtained results allow optimization of laser processing technologies for austenitic steels and widening of their practical use area.

The aim of this research was to evaluate possibility of controlling melt flow processes during heating with low-power laser in order to form the preset configuration and relief structural state on the surface of products made of the austenitic steel AISI 321.

Materials and methods of the research

Austenitic steel AISI 321 was used as the research material. Selection of this steel was caused by its wide application in the mining and processing industries as well as in the power engineering complex, e.g. in pipelines and vessels at the stages of mining, processing and transportation of raw materials and finished products [28–30]. It is known that high-temperature heating of austenitic steels leads to forming of carbides (mainly $Cr_{23}C_6$) and oxide phases [26]. These oxide phases are characterized by developed porosity and create channels for oxygen diffusion in subsurface layers, what intensifies corrosion processes [27]. It stipulates necessity of optimization of the processing procedures for minimization of oxidation [31, 32].

The experiments were carried out using the automatized laser complex TurboMarker (LLC "Laser Center"), including:

* fiber laser YPL-V2-1-100-100-100 (IPG Photonics) with wavelength 1,064 nm, pulse duration 100 ns, maximal pulse energy 1 mJ and nominal average output capacity 100 W;

* scanning laser system on the base of F-Theta objective, providing focal spot diameter 75 μm, with maximal scanning rate 10,000 mm/s and operating field 180×180 mm.

The main variable operating indicators were selected on the base of data of thermophysical and optical material parameters [33], which are presented in the **Table 1**.

Table 1. The range of variable conditions

Indicator	Range
Scanning rate (V), mm/s	50–275
Frequency of following impulses (f), kHz	50–500
Radiation intensity (P), W	10–100
Beam motion trajectory	Linear
Distance between the lines (R), μm	10–100
Length of vectors (L), mm	0,1–1

The range of indicators covered the area from melting threshold, where forming of concave structures is initiated during directed melt-flow transition; it allowed for assessing the influence of these conditions on melt behaviour. As soon as radiation intensity rises, the height and width of ledges increase to a definite size, following by transition to evaporating procedure with consequent intensity growth, and then geometric dimension of the relief decrease together with elevation of number of defects. Rise of pulse frequency and scanning rate, with other equal parameters, provides decrease of structures height, but forming relief is more smooth and has minimal number of defects. When relief is forming, impulse energy and overlapping degree are especially critical: they should provide melting without transition to ablation and intensive evaporation. Outside the operating area, porosity, unevennesses and oxide inclusions are observed.

The research was based on the previously developed technique for surface processing of the steel St3 and included consequent examination of relief forming processes, using multi-pass treatment along a linear trajectory of beam motion including combination of forming and cleaning passes. This research also was devoted to analysis of influence of number of passes on relief geometrical parameters, its structural and phase state, its properties in the processing zone and adjacent areas [31, 34]. Relief geometrical parameters were assessed via the method of optical microscopy using the inspection microscope ADF C150. Microstructural studies were carried out in accordance with the GOST 5639-1982, using the optical microscope Zeiss Axio Observer 3. Analysis of phase composition was conducted by X-ray diffraction (XRD) Rigaku Ultima IV. Elemental composition was determined via the method of energy-dispersive X-ray spectroscopy (EDS) by scanning electron microscope Tescan Mira 3.

Results and discussion

It is shown that density of accumulated energy, which is regulated by laser processing parameters during laser processing of metal surface, determines the phase state of the material. When exceeding a definite energetic threshold, evaporation of substrate occurs, while lower values of energy density are accompanied by material transition in a liquid phase [32, 35–36]. To form the preset surface structure, it is necessary to select such processing procedures, when material in the processing area remains mainly in liquid state without essential evaporation. Melt management is carried out via laser beam motion along the trajectory, which is preset by the system with closely spaced parallel vectors (**Fig. 1**). Concave relief with minimal material loss due to evaporation is formed as a result of directed redistribution of liquid phase. Thus, exact control of energy density and scanning trajectory is a key aspect of the process, providing preferential melt flowithout phase transition in the gas state.

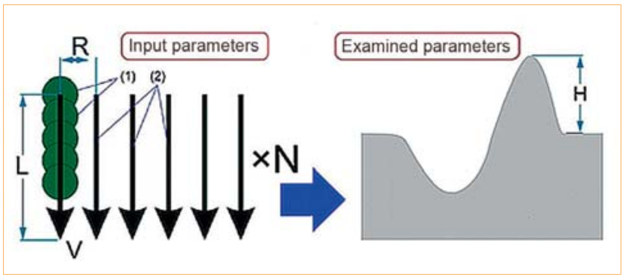
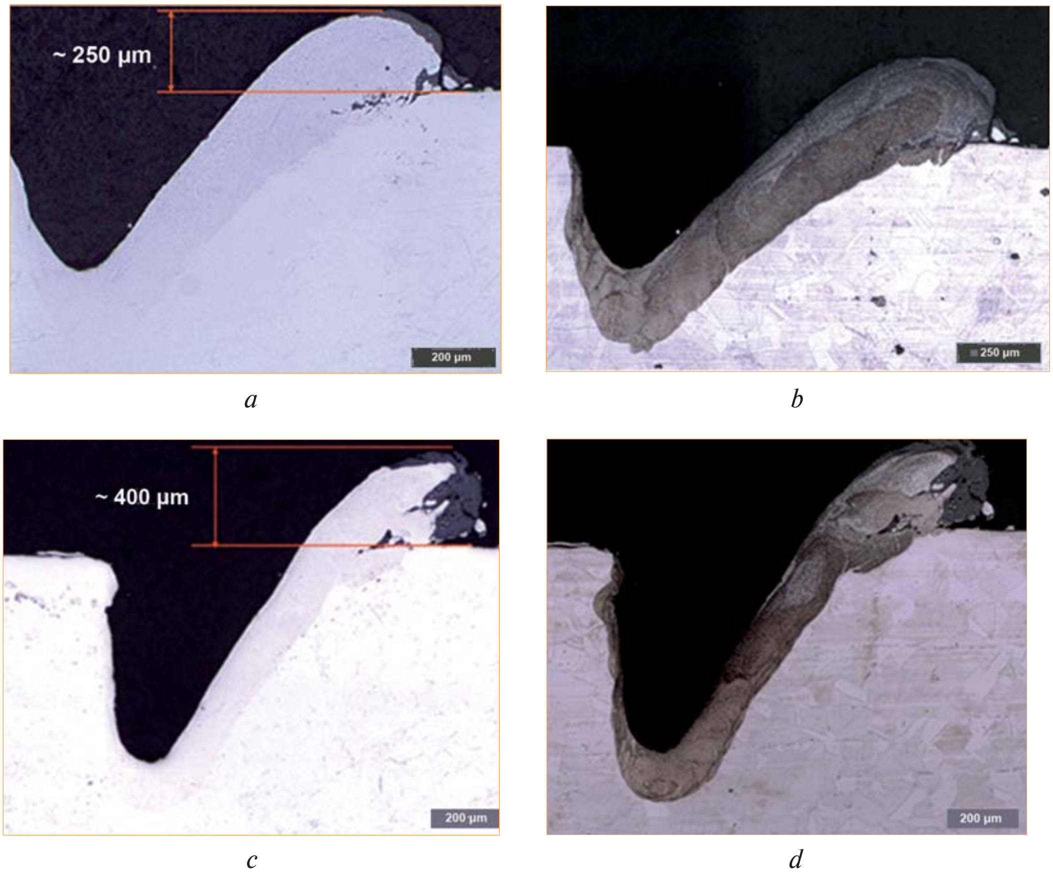


Fig. 1. Scheme of concave relief forming: (1) – laser radiation spots on the surface; (2) – scanning lines L – length of scanning lines; R – distance between scanning lines; V – scanning rate; N – number of cycles; H – roll height

Transversal polished sections of linear relief on the surface of the steel AISI 321 are displayed in the **Fig. 2**. This relief was obtained during multipass treatment, with one processing cycle (Fig. 2 *a, b*) and with two processing cycles (Fig. 2 *c, d*), without use of cleaning passes. Main metal structure consists of austenite with grain size 6–8 grain size number according to the GOST 5639-82. Fine-grain (**Fig. 3** *a*) and ultrafine-grain austenitic (Fig. 3 *b, c, d*) structures with grain size number 16–18 number according to the same standard are formed in different zones in the obtained relief.

The layered structure, which was obtained after one forming pass (including the effect according to the preset program – see Fig. 3 *b, d*), is connected with the fact that



a *b* *c* *d*

Fig. 2. Relief (*a*, *c*) and its microstructure (*b*, *d*) obtained via multipass method during one cycle (*a*, *b*) and two cycles (*c*, *d*) of the steel AISI 321 surface processing

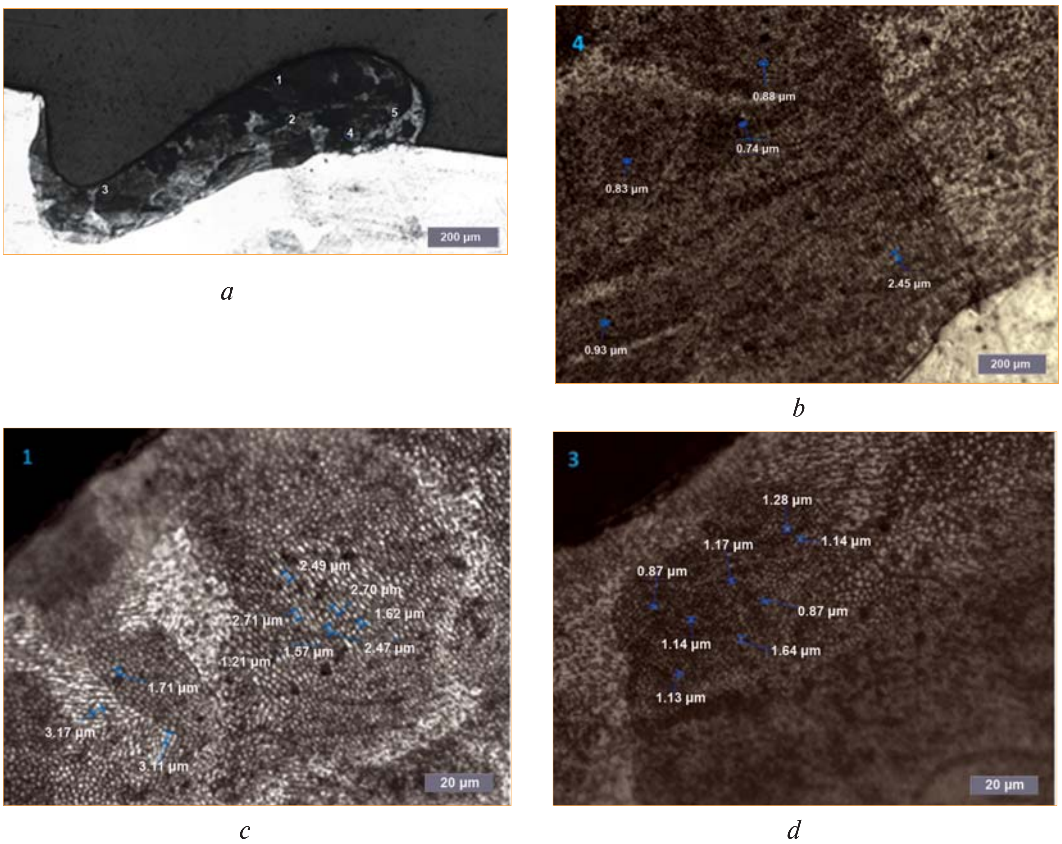


Fig. 3. Relief overview on the surface of the steel AISI 321 and examined area (*a*), microstructure of the examined areas (*b*, *c*, *d*)

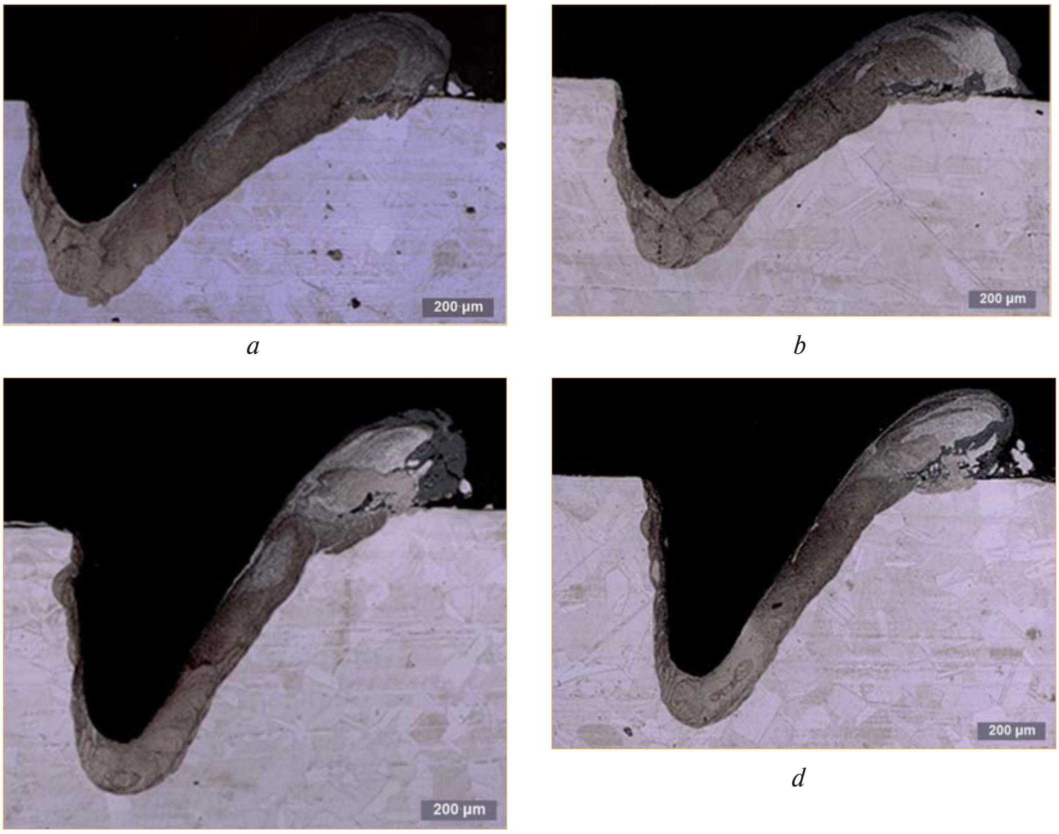
the distance between the vectors (15 µm) is smaller than the laser beam diameter (~ 75 µm); it leads to 5-fold overlapping of the effect zone. Increasing the amount of forming passes led to widening of ultra-dispersed structure in the ridge zone (Fig. 3 *d*) and supposedly of the thin layer of amorphous state due to very high cooling rate. The authors of the work [37] also confirmed possibility of amorphous layer origination during laser surface processing. Presence of oxide film on relief surface is observed in both cases (Fig. 3 *b, d*).

The cleaning passes were additionally conducted at the following stage for decrease of oxides amount. The types of reliefs, which were obtained during multipass treatment with use of additional cleaning pass, are compared in the **Fig. 4**.

The results of examination of the steel AISI 321 have shown that adding the cleaning passes leads to additional grain refining in the roll zone. An appearing temporary delay changes the features of mass transfer: microrelief could have time to transfer the essential portion of thermal energy to the sample. However, the applied laser radiation intensity is chosen in such way, that small decrease of oxide phase amount is provided (**Fig. 5** *a, b*); but carbide phases of various morphology are not forming in this case (Fig. 5, **Table 2**). It is related to the low heat conductivity of austenitic steel, which does not allow to develop carbide forming processes, i.e. forming of the most dangerous carbides of $Me_{23}C_6$ type, which support intercrystalline corrosion [30]. At the same

Table 2. Crystallographic data about the phases, presented in the examined samples

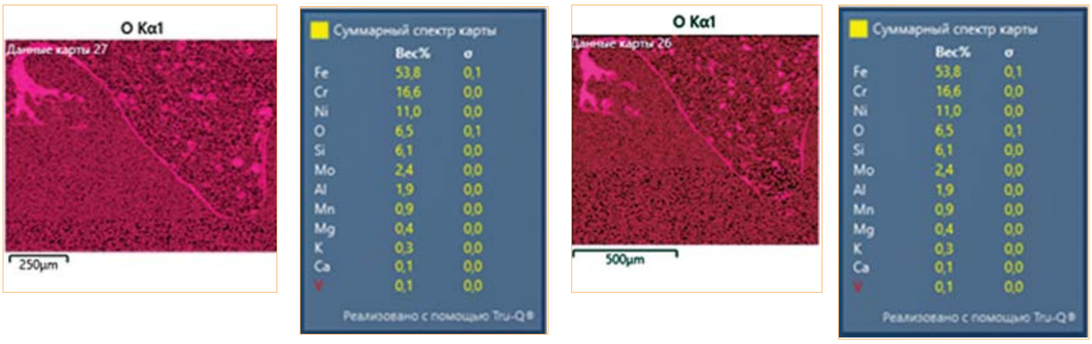
No.	Phase	Formula	Crystalline system	Space group	Cell parameters
1	Iron	(Fe, Ni)	Cubic (FCC)	225: Fm-3m	3.598,3.598,3.598, 90.00,90.00,90.00
2	Iron	Fe	Cubic (BCC)	229: Im-3m	2.866,2.866,2.866, 90.00,90.00,90.00
3	Graphite	C	Hexagonal	194 : P63/mmc	2.465,2.465,6.721, 90.00,90.00,120.00
4	Magnetite	Fe_3O_4	Cubic	227 : Fd-3m	8.396,8.396,8.396, 90.00,90.00,90.00
5	Iron & Chromium oxide	Cr_2FeO_4	Tetragonal	–	8.497,8.497,8.115, 90.00,90.00,90.00
6	Maghemite-C	Fe_2O_3	Cubic	213 : P4132	8.351,8.351,8.351, 90.00,90.00,90.00
7	Maghemite	Fe_2O_3	Tetragonal	96 : P 43 21 2	8.340,8.340,8.322, 90.00,90.00,90.00



a *b*

c *d*

Fig. 4. Microstructure of transveral cross section of relief, obtained via multipass treatment during one cycle (*a, b*) and during two cycles (*c, d*) of surface processing of the steel AISI 321: *a*, *c* – without cleaning passes; *b*, *d* – with cleaning passes



a *b*

Fig. 5. Elementary composition of the samples with formed relief , obtained via multipass treatment during two cycles of surface processing of the steel AISI 321: *a* – without cleaning passes; *b* – with cleaning passes

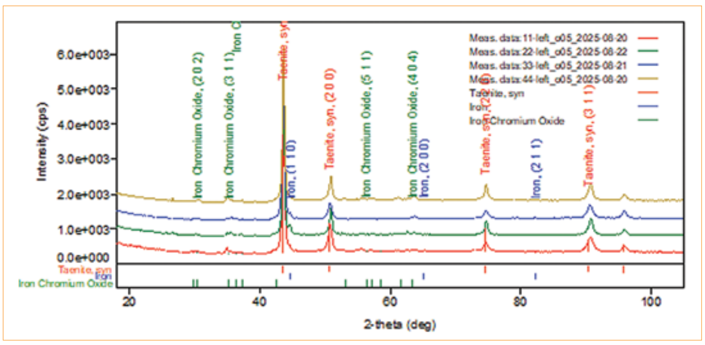


Fig. 6. Combined diffractograms of the examined samples with formed relief obtained via multipass treatment during one or two cycles of surface processing of the steel AISI 321 without and with the cleaning passes

time, carbides, which are existing in steel, can be partly dissolved under laser effect [31].

The phase composition of the samples is presented by the main phase with FCC (face-centered cubic) lattice – γ-Fe. A number of low-intensive diffraction maximal values are presented in all samples as well; they can belong to Fe oxides (Table 2, No. 4–7), such as magnetite Fe_3O_4, maghemite Fe_2O_3, of iron-chromium oxides Cr_2FeO_4 (**Fig. 6**).

The results of investigations have revealed that the lower part of ledge is characterized by more light colour, while when approximating to the initial surface it becomes practically the same as the base metal. It is due to the fact that this area is forming at the initial stages of processing, is covered by melt during the following passes and is not subjected to secondary effect – unlike the zones located above, which are heated and melted many times. Such processes support forming of fine-grain and ultrafine-grain structure.

Conclusion

The conducted investigations demonstrate possibility of controlling ablation processes and liquid phase transition in order to form the preset configuration and phase-structural state during laser processing of surface layers in austenitic steels. The obtained data expand our knowledge about the processes of structure forming under extremal thermal effect, which is important for development of laser technologies for surface treatment of materials. It was revealed that the linear relief with height up to 400 μm can be obtained during processing along the linear trajectory, with power intensity 80 W, frequency 500 kHz and scanning rate 100 mm/s. It was established that use of low-power laser in surface treatment of austenitic steel does not lead to forming of carbide phase.

REFERENCES

1. Romasheva N., Dmitrieva D. Energy resources exploitation in the Russian Arctic: challenges and prospects for the sustainable development of the ecosystem. *Energies*. 2021. Vol. 14. Art. 8300. DOI: 10.3390/en14248300.
2. Buslaev G., Tsvetkov P., Lavrik A., Kunshin A., Loseva E., Sidorov D. Ensuring the sustainability of Arctic industrial facilities under conditions of global climate change. *Resources*. 2021. Vol. 10. Art. 128. DOI: 10.3390/resources10120128.
3. Litvinenko V. S., Petrov E. I., Vasilevskaya D. V., Yakovenki A. V., Naumov I. A., Ratnikov M. A. Assessment of the role of the state in the management of mineral resources. *Journal of Mining Institute*. 2023. Vol. 259. pp. 95–111. DOI: 10.31897/PMI.2022.100.
4. Bolobov V. I., Tsvetkov A. S., Popov G. G., Dagaev S. E., Salnikov D. R., Tigranyan G. A. Comparison of existing methods for studying compatibility of pipeline steels with compressed hydrogen. *International Journal of Engineering, Transactions A: Basics*. 2026. Vol. 39. No. 04. pp. 917–924. DOI: 10.5829/IJE.2026.39.04A.10.
5. Solovyeva V. A., Almuhammadi K. H., Badeghaish W. O. Current downhole corrosion control solutions and trends in the oil and gas industry: a review. *Materials*. 2023. Vol. 16. No. 5. Art. 1795. DOI: 10.3390/ma16051795.
6. Shakhnazarov K. Y., Rafikov A. R. The influence of hardening heat treatment modes on the crack propagation resistance of 5H2SMF die steel. *Frontier Materials & Technologies*. 2025. No. 2. pp. 95–101. DOI: 10.18323/2782-4039-2025-2-72-8.
7. Cherepovitsyn A. E., Tcvetkov P. S., Evseeva O. O. Critical analysis of methodological approaches to assessing sustainability of Arctic oil and gas projects. *Journal of Mining Institute*. 2021. Vol. 249. pp. 463–479. DOI: 10.31897/PMI.2021.3.15.
8. Pashkevich N. V., Khloponina V. S., Pozdnyakov N. A., Avericheva A. A. Analysing the problems of reproducing the mineral resource base of scarce strategic minerals. *Journal of Mining Institute*. 2024. Vol. 270. pp. 1004–1023.
9. Chichenev N. A., Gorbatyuk S. M., Karfidov A. O., Chicheneva O. N. Experimental study of the process of laser treatment of steel Kh12M. *CIS Iron and Steel Review*. 2024. Vol. 27. pp. 193–107.
10. Rezayat M., Rovira J. J. R., García A. M. Phase transformation and residual stresses after laser surface modification of metastable austenitic stainless steel. *Advances in fracture and damage mechanics XX*. 2023. Vol. 2848. No. 1. pp. 020005.
11. Zhang Z., Ma G., Azarmi F., Cui Y. Suppression of shrinkage porosity in laser-joining of CFRP and steel using a laser surface modification process Sur-Sculpt®. *International Journal of Adhesion and Adhesives*. 2018. Vol. 85. pp. 184–192. DOI: 10.1016/j.ijadhadh.2018.06.013.
12. Pryakhin E. I., Pribytkova D. A. The influence of the quality of surface preparation of pipes for heating networks on their corrosion resistance during operation in underground conditions. *Chernye Metally*. 2023. No. 11. pp. 97–102.
13. Chen C., Wang J., Zhang Z., Dai Y., Zhang J., Dong B. et al. Boosting NIR laser marking efficiency of a transparent epoxy using a layered double hydroxide. *ACS Applied Polymer Materials*. 2024. Vol. 6. No. 14. pp. 8679–8686. DOI: 10.1021/acsapm.4c00648.
14. Lu Y., Shi X., Huang Z., Li T., Zhang M. et al. Nanosecond laser coloration on stainless steel surface. *Scientific Reports*. 2017. Vol. 7. Art. 7092. DOI: 10.1038/s41598-017-07373-8.
15. Lazov L., Dinev D., Stoyanov V. et al. Influence of power density and frequency on the process of laser marking of steel products. *Infrared Physics & Technology*. 2021. Vol. 116. Art. 103783. DOI: 10.1016/j.infrared.2021.103783.
16. Dong J., Liu Y., Pacella M. Surface texturing and wettability modification by nanosecond pulse laser ablation of stainless steels. *Coatings*. 2024. Vol. 14. No. 4. Art. 467. DOI: 10.3390/coatings14040467.
17. Li X., Li G., Lei Y., Gao L., Zhang L., Yang K. Influence of laser surface texture on the anti-friction properties of 304 stainless steel. *Machines*. 2023. Vol. 11. No. 4. Art. 473. DOI: 10.3390/machines11040473.
18. Zawadzki P., Dobrotvorskiy S., Aleksenko B., Talar R. Effect of nanosecond laser texturization on tribological behavior of AISI 321 stainless steel. *Materials*. 2024. Vol. 17. No. 23. Art. 5870. DOI: 10.3390/ma17235870.
19. Gazott I., et al. Influence of surface treatment by laser irradiation on bacterial adhesion on titanium implants and their alloys: systematic review. 2024. DOI: 10.17605/OSF.IO/FTA3W.
20. Gornyi S. G., Grigor'ev A. M., Patrov M. I., Solov'ev V. D., Turichin G. Specific features of metal surface processing by nanosecond laser pulse trains. *Quantum Electronics*. 2002. Vol. 32. pp. 929–932. DOI: 10.1070/QE2002v032n10ABEH002320.
21. Blackburn J., Hilton P. Producing surface features with a 200 W Yb-fibre laser and the Surfi-Sculpt® process. *Physics Procedia*. 2011. Vol. 12. No. 1. pp. 529–536. DOI: 10.1016/j.phpro.2011.03.065.
22. Amiaga J. V., Gorny S. G., Vologzhanina S. A. Development of a fast method for forming Braille on the surface of steels with IR nanosecond pulsed 50 W fiber laser. *AIP Conference Proceedings*. 2020. No. 2285.
23. Kolobov Yu. R., Manokhin S. S. Kolpakov A. Ya., Poplavskii A. I., Yapryntsev M. N., Odintsova G. V., Betekhtin V. I., Kadomtsev A. G., Narykova M. V. A study of the influence of irradiation of carbon diamond-like coatings with nanosecond laser pulses on their structural-phase composition and tribological properties. *Russian Physics Journal*. 2021. Vol. 64. No. 6. pp. 1055–1059. DOI: 10.1007/s11182-021-02465-5.
24. Samanta A. et al. Nanosecond pulsed laser processing turns engineering metal alloys antireflective and superwicking. *Journal of Manufacturing Processes*. 2020. Article ID 102929. DOI: 10.1016/j.jmapro.2020.02.029.
25. Pryakhin E. I., Azarov V. A. Study of protective properties of fluoroplastic polymer compositions on steel samples with the aim

of their potential use for internal coatings of main gas pipelines. *Chernye Metally*. 2025. No. 4. pp. 62–66.
26. Xu J., Zou P., Wang W., Kang D. Study on the mechanism of surface topography evolution in melting and transition regimes of laser polishing. *Optics & Laser Technology*. 2021. Vol. 139. Art. 106947. DOI: 10.1016/j.optlastec.2021.106947.
27. Fayazfar H., Salarian M., Rogalsky A., Sarker D., Russo P., Paserin V., Toyserkani E. A critical review of powder-based additive manufacturing of ferrous alloys: process parameters, microstructure and mechanical properties. *Materials & Design*. 2018. Vol. 144. pp. 98–128. DOI: 10.1016/j.matdes.2018.02.018.
28. Petkova A. P., Zlotin V. A. Analysis of the efficiency of reducing hydrogen losses in a pipeline made of various austenitic stainless steels. *Chernye Metally*. 2024. No. 9. pp. 50–54.
29. Yuan B. S., Wu X., Chen L., Tong Z., Gong H. The effect of spot size combination mode on ablation morphology of aluminum alloy by millisecond–nanosecond combined-pulse laser. *Materials*. 2018. Vol. 11. No. 8. Art. 1419. DOI: 10.3390/ma11081419.
30. Kuznetsov P. A., Krasikov A. V., Staritsyn M. V., Mushnikova S. Y., Parmenova O. N. Features of local corrosion of AISI 316l steel manufactured by selective laser melting. *Protection of Metals and Physical Chemistry of Surfaces*. 2018. Vol. 54. No. 3. pp. 484–489. DOI: 10.7868/S0044185618030142.
31. Brover G.I., Shcherbakova E.E. Role of carbides in the formation of structure and properties of steels under pulsed laser irradiation. *Safety of Technogenic and Natural Systems*. 2023. Vol. 7. No. 4. pp. 106–118. DOI: 10.23947/2541-9129-2023-7-4-106-118.
32. Alkhawaldeh O., Coupland J., Jones L.C. Increasing the efficiency of material removal using dual laser micromachining. *The International Journal of Advanced Manufacturing Technology*. 2020. Vol. 107. pp. 3995–4007. DOI: 10.1007/s00170-020-05250-9.
33. Certificate of State Registration of the Database No. 2024624959 (Russian Federation). *Database of Thermophysical and Optical Parameters of Metals for Selecting Laser Processing Modes:* No. 2024624795: filed Oct 29, 2024; published Nov 6, 2024. Vologzhanina S. A., Khuznakhmetov R. M., Aleksandruk B. S.; applicant: Federal State Budgetary Educational Institution of Higher Education “Saint Petersburg Mining University named after Empress Catherine II.”
34. Rezayat M., Moradi M., Mateo A. Nanosecond multi-passes laser surface texturing on AISI 301LN TRIP steel // *The International Journal of Advanced Manufacturing Technology*. 2024. Vol. 132. P. 4753–4764. — DOI: 10.1007/s00170-024-13638-0.
35. Mazhukin V. I., Samokhin A. A., Demin M. M., Shapranov A. V. Explosive boiling of metals upon irradiation by a nanosecond laser pulse. *Quantum Electronics*. 2014. Vol. 44. No. 4. pp. 283–285. DOI: 10.1070/QE2014v044n04ABEH015388.
36. Bauer F., Michalowski A., Kiedrowski T., Nolte S. Heat accumulation in ultra-short pulsed scanning laser ablation of metals. *Optics Express*. 2015. Vol. 23. No. 2. pp. 1035–1043. DOI: 10.1364/OE.23.001035.
37. Atroshenko S. A., Gerashchenkov D. A., Kuznetsov A. V., Savenkov G. G., Smakovsky M. S. Influence of combined treatment of the surface layer on the impact resistance of steel. *Physics of the Solid State*. 2024. Vol. 66. No. 2. pp. 245–258. DOI: 10.61011/FTT.2024.02.57248.269.