DOI: https://doi.org/10.37434/tpwj2022.12.01

STRENGTHENING OF WELDED STRUCTURES OF 25KhGNMT STEEL BY PULSED BARRIER DISCHARGE TREATMENT

L.M. Lobanov[1], O.M. Berdnikova[1], M.O. Pashchyn[1], O.L. Mikhodui[1], O.S. Kushnaryova[1], T.G. Solomiychuk[1], V.I. Kryvyi[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Scientific and Production Association Praktika
15 Metalistiv Str., 03057, Kyiv, Ukraine

ABSTRACT

The development of high-tech industries stimulates the growth of requirements for the metal of welded structures and the complex of their basic and special properties. The use of pulsed electric currents, plasma currents, pulsed electromagnetic fields and their combined effects to improve the mechanical characteristics of metals and alloys is relevant in connection with the need in replacing traditional energy-intensive technologies for treatment of welded structures with more progressive ones. The use of a pulsed barrier discharge (PBD) in the metal treatment, which generates a low-temperature plasma on the surface of the treated metal is a new approach to optimizing mechanical properties of high-strength steels for welded structures, which is based on electrophysical processes. In the work, strengthening of 25KhGNMT steel as a result of PBD action on its surface was investigated. The PBD treatment of steel took place in a discharge device at an increment rate of voltage $\approx 3\cdot10^{11}$ V/s. The effect of PBD treatment period on Vickers hardness value (*HV*) of test specimens was investigated. Examinations of the structure of 25KhGNMT steel were carried out by the method of transmission electron microscopy to reveal its changes as a result of PBD action. It was found that values of *HV* after PBD treatment increase from 420 to 505 kg/mm^2, which is accompanied by a general increase in the dislocation density and dispersion of the microstructure, which can positively affect the mechanical characteristics of 25KhGNMT steel for welded structures operating under dynamic loads.

KEYWORDS: pulsed barrier discharge, surface treatment, low-temperature plasma, structural steel, Vickers hardness, electron microscopy, microstructure, substructure, dislocation density, strengthening, mechanical characteristics

INTRODUCTION

The development of high-tech industries stimulates an increase in requirements for steel welded structures operating in dynamic loads at high temperatures. The reserve of increasing the life of such products is the development of metal treatment technologies with the use of electrophysical effects. The use of pulsed electric currents (PEC), plasma currents, pulsed electromagnetic fields (PEMF) and their combined effects to improve the mechanical characteristics of metals, alloys and welded joints is relevant in connection with the need in replacement of traditional energy-intensive technologies of treating elements of welded structures with more progressive ones. The results of studies of electrophysical processes occurring in metal materials under the effect of PEC and EMF give reason to consider them challenging for engineering practice from the standpoint of energy efficiency and manufacturability [1–6].

The use of a pulsed barrier discharge (PBD) in the metal treatment, which generates a low-temperature plasma on the surface of the metal being treated, is a new approach to optimizing mechanical properties of metal materials for welded structures based on electric physical processes. The criterion of a rational practical use of technologies for strengthening metals and alloys using PBD is their energy efficiency *Y*, which is determined by much lower energy consumption as compared to heat treatment. The value *Y* is called energy yield and depends on such PBD parameters as voltage, its growth rate and pulse repetition frequency [7].

This is especially true for structural steels used in special purpose products operating at a short-term action of high temperatures in the conditions of dynamic loads. Special requirements are applied to the hardness of such steels, which is one of the characteristics of their protective properties at dynamic contact interactions at rates of about 1000 m/s. An example of such material is 25KhGNMT steel, which is used in critical special purpose structures. The traditional method to increase hardness of such steel is quenching, which is carried out at a temperature $T = 860$ °C in oil with the subsequent tempering at $T = 190$ °C in air [8]. This is a quite energy-consuming technology that requires large-sized metal-consuming equipment. The use of PBD to treat the surface of 25KhGNMT steel in order to improve its mechanical characteristics opens new prospects for the use of electrophysical processes in the metal treatment. Taking into account the abovementioned, it is necessary to consider it ap-

Table 1. Results of analysis of chemical composition of the test specimens of 25KhGNMT steel, wt.%

Metal	C	Si	Mn	S	P	Cr	Ni	Cu	Mo	V	Al	Ti	W
25KhGNMT steel, sheet δ = 4 mm	0.27	0.24	0.84	0.004	0.018	0.50	0.95	0.23	0.40	0.03	0.04	0.007	≤0.02

propriate to study the impact of PBD on the mechanical characteristics of 25KhGNMT steel.

The aim of this work is to study the effect of PBD on the hardness of specimens of structural 25KhGNMT steel.

TEST SPECIMENS, EQUIPMENT FOR PBD TREATMENT AND RESEARCH PROCEDURE

As a subject of investigations, plane metal specimens of 40×40×4 mm were used, which were subjected to PBD treatment. Chemical analysis of specimens was carried out in accordance with DSTU ISO 10012:2005 standard, which confirmed the correspondence of the material to be treated to the chemical composition of 25KhGNMT steel according to DSTU 7806:2015 (Table 1).

ELECTRODE SYSTEM FOR STUDYING THE EFFECT OF PBD ACTION ON THE SURFACE OF 25KhGNMT STEEL AND DISCHARGE CHARACTERISTICS

The PBD treatment of the specimen surface was carried out with the use of the electrode system (ES), whose design scheme is shown in Figure 1.

The ES consisted of the test specimen *1* of 25KhGNMT steel, the high-voltage electrode *2* and the glass (quartz glass) dielectric barrier *3* (100×100×1 mm^3). To reduce the marginal effect, the electrode *2* had rounded edges. The diameter of a plane part of this electrode was 36 mm. The treatment was carried out at a gas gap δ of 1 mm thick between the plate *1* and the barrier *3*. A high voltage (*HV*) on the electrode *2* was supplied from the pulse generator (PG), which provided unipolar pulses of voltage with an amplitude of up to 30 kV with a rate of their growth ≈ $3\cdot10^{11}$ W/s and a duration of about 150 ns. PG also included a magnetic key that contributed to discharging the dielectric barrier after passing a direct current pulse through the electrode system. The pulse amplitude was regulated by changing the constant voltage U_0 supplied to the input of PG. The voltage and current oscillograms through the electrode system were registered by means of the TDS1012 oscilloscope and respectively by the sensors P6015 and P6021. All studies were performed at a pulse repetition frequency of 300 Hz. The appearance of a discharge shown in Figure 2 (exposure time is 0.1 s) indicates a homogeneous character in the gap δ rather than a thread-like one.

A typical appearance of oscillograms of current *i*(*t*) and voltage *u*(*t*) in PBD mode, used for treatment of specimens of 25KhGNMT steel, is shown in Figure 3 respectively by the curves *1* and *2*. As is seen from Figure, during the action of the voltage pulse, whose amplitude U_m reaches 26 kV, the PBD current consists of two main parts: direct current with the amplitude I_{m1} = 80 A and reversed one with the amplitude I_{m2} = 65 A, which is predetermined by discharging a dielectric barrier through the magnetic key. The calculations show that during a direct current pulse, the amplitude value of the average current density through the plate is close to 0.9 A/cm^2.

The effect of the treatment time period on the value of hardness of steel was studied. The specimens

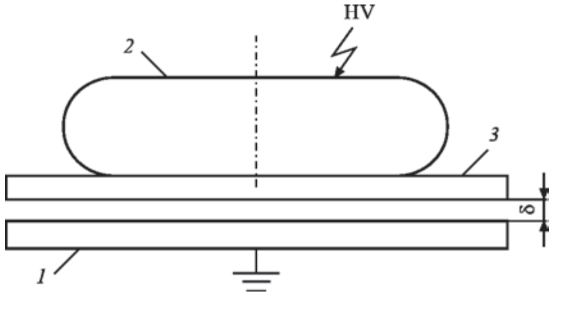

Figure 1. Scheme of electrode system (ES) for PBD treatment of 25KhGNMT steel specimens: *1* — tested specimen of 25KhGNMT steel; *2* — high-voltage electrode; *3* — dielectric barrier; δ — gas gap

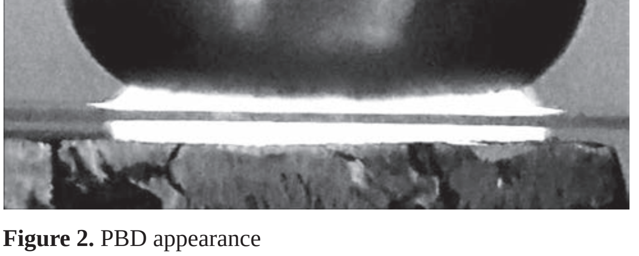

Figure 2. PBD appearance

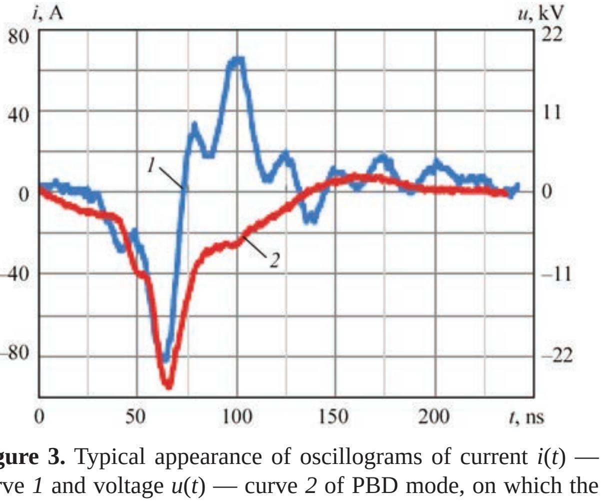

Figure 3. Typical appearance of oscillograms of current *i*(*t*) — curve *1* and voltage *u*(*t*) — curve *2* of PBD mode, on which the specimens of 25KhGNMT steel were treated

were subjected to PBD on the mode in Figure 3 at a variation of time of respectively 5, 10, 15 and 20 min.

Macrosections were prepared from the metal of specimens according to the standard procedure, on which structure examinations and measurements of the Vickers microhardness of treated surfaces (*HV*) according to ISO 6507-1:2005 standard were conducted. The evaluation of the *HV* values was performed with the use of M-400 LECO hardness tester at the specimen loading P = 100 g.

Transmission examinations of the structure were carried out by the method of transmission electron microscopy (TEM) in the JEM-200CX device (JEOL Company) at an accelerating voltage of 200 kV in order to find how the structure and phase composition of the metal of 25KhGNMT steel changes as a result of PBD action on its surface. The examinations by the TEM method allowed obtaining a reliable experimental information at the dislocation level about such structural and phase components as lower or upper bainite, tempered and quenching martensite, parameters of their fine structure and distribution and dislocation density in steel before and after treatment. Namely these structural components have a significant impact on the properties of strength and crack resistance of the metal of high-strength steels used in special purpose products [9, 10].

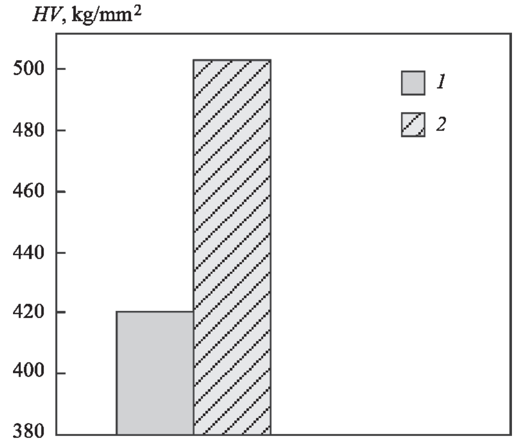

Figure 4. Hardness of 25KhGNMT steel before (*1*) and after (*2*) treatment

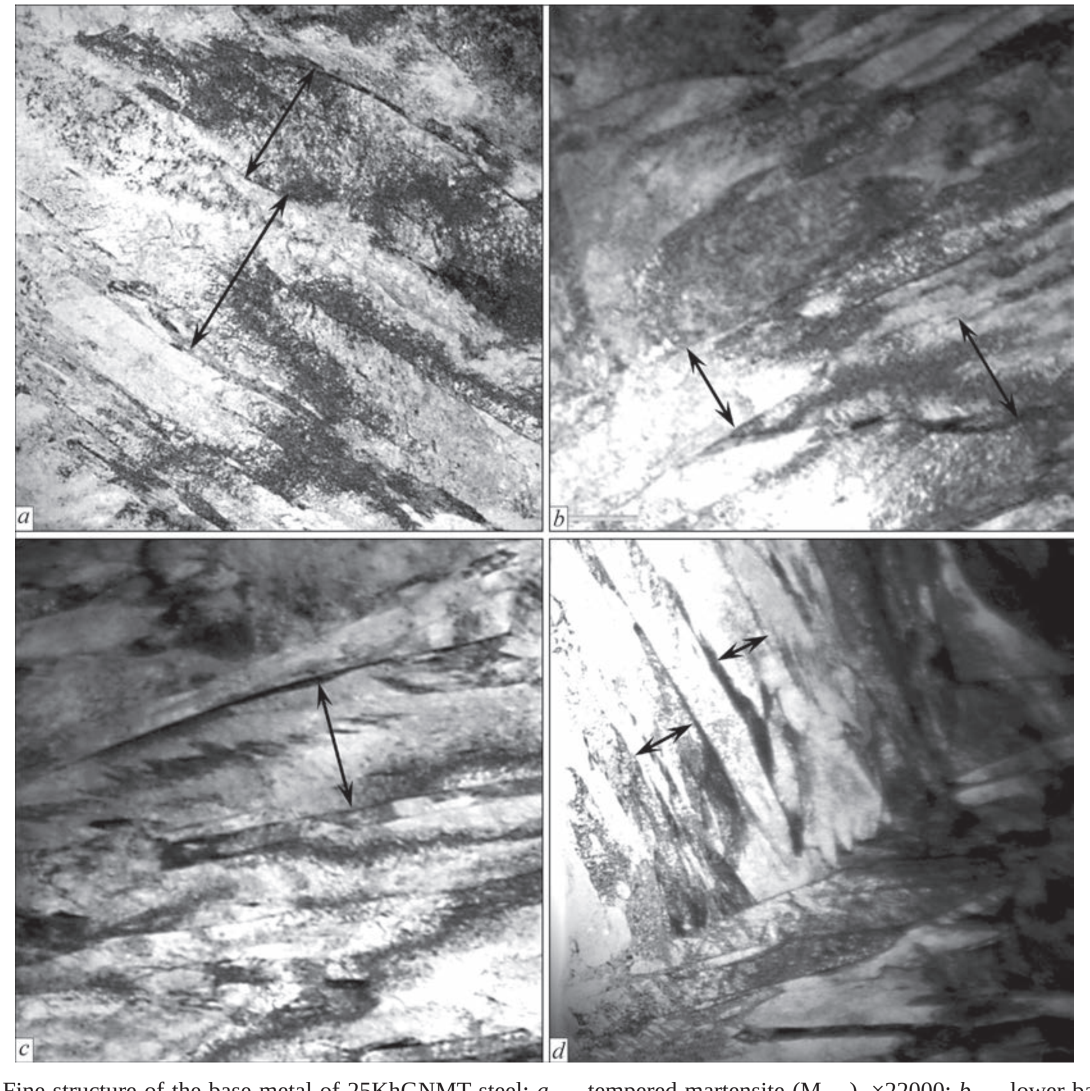

Figure 5. Fine structure of the base metal of 25KhGNMT steel: *a* — tempered martensite (M_{temp}), ×22000; *b* — lower bainite (B_l), ×22000; quenching martensite (M_{quench}), ×18000; upper bainite (B_u), ×22000). Arrows mark the width of the laths

Table 2. Dislocation density ρ in the volume of structural components of lower (B_l) and upper bainite (B_u), tempered martensite (M_{temp}) and quenching martensite (M_{quench}) over the depth from the treated surface and in the base metal (BM)

ρ, cm^{-2}	Distance from the surface, μm					BM
	0–100	150–300	300–1000	1400–1900	2000–2200	
ρ (B_l)	$(2–4)·10^{10}$	$(1–3)·10^{10}$	$(1–3)·10^{10}$	$9·10^9–2·10^{10}$	$8·10^9–2·10^{10}$	$8·10^9–2·10^{10}$
ρ (B_u)	–	–	$(3–5)·10^{10}$	$(2–4)·10^{10}$	$(1–3)·10^{10}$	$(1–3)·10^{10}$
ρ (M_{temp})	$(5–8)·10^{10}$	$(4–6)·10^{10}$	$(4–6)·10^{10}$	$(3–6)·10^{10}$	$(2–6)·10^{10}$	$(2–6)·10^{10}$
ρ (M_{quench})	–	–	–	$(4–7)·10^{10}$	$(4–7)·10^{10}$	$(5–7)·10^{10}$

RESEARCH RESULTS AND DISCUSSION

It was found that the maximum effect of PBD on hardness of 25KhGNMT steel is achieved at the duration of specimen treatment of 15 min (in this mode). At the same time, the values of *HV* after treatment increase by 20 % from 420 to 505 kg/mm^2 (Figure 4). This can contribute to an increase in dynamic strength of welded structures from the mentioned steel during their contact interactions.

As a result of the carried out transmission examinations of the structure by the TEM method, the following was revealed. The structure of the base metal of armoured 25KhGNMT steel is martensitic-bainitic, predominantly (up to 60 %) tempered martensite (M_{temp}) and lower baininite (B_l ~ 30 %) at a uniform distribution of dislocation density in the volume of structural components with a small fraction of quenching martensite (M_{quench}, to 5 %) and upper bain-

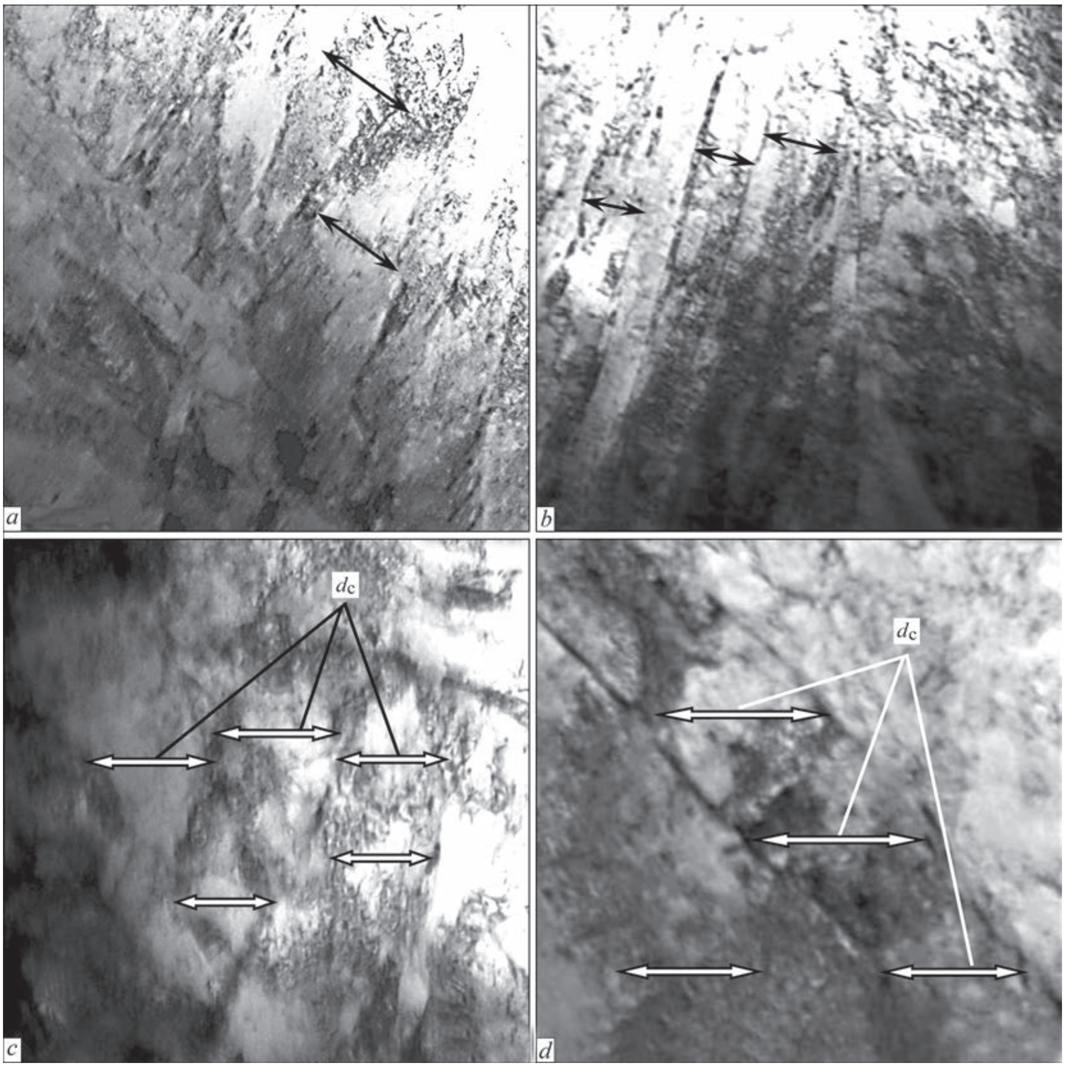

Figure 6. Fine structure of metal of the treated surface of 25KhGNMT steel: *a* — tempered martensite (M_{temp}), ×25000; *b*–*d* — lower bainite (B_l), respectively ×22000, ×25000, ×55000. Arrows indicate the width of the laths h_l (*a*, *b*), cellular (*c*) and fragmented substructure (d_c) (*e*)

ite (B_u ~ 5 %). The total level of dislocation density amounts to $\rho = (1–6)\cdot 10^{10}$ cm^{-2}. When detailing the structural components of the base metal, it was found that the width of the lath structures (h_l) is: 0.3–2.0 μm (M_{temp}, Figure 5, *a*); 0.2–1.0 μm (B_l, Figure 5, *b*); 0.35–1.5 μm (M_{quench}, Figure 5, *c*); 0.3–0.8 μm (B_u, Figure 5, *d*).

Over the depth from the treated surface (from 0 to 2200 μm) in the cross-section of the specimen, a change in structural and phase composition, parameters of the fine structure and dislocation density was revealed (Table 2). Over the depth from the treated surface to 300 μm, exclusively the structure of tempered martensite and lower bainite is formed during its refinement and a uniform distribution of dislocation density ($\rho = (2–8)\cdot 10$ cm^{-2}) (Figure 6). As compared to the base metal, the volume fraction of lower bainite is increasing (up to 50 %). The width of the lath structures (h_l) is: 0.2–1.3 μm (M_{temp}, Figure 6, *a*); 0.15–0.65 μm (B_l, Figure 6, *b*). On the depth of 300 μm from the treated surface, a small amount of upper bainite ($B_u \leq 3$ %) is observed, and at 1400 μm, quenching martensite is fixed ($M_{quench} \leq 5$ %).

Analysis of the formed substructure showed that as a result of a pulsed effect in the area of the treated surface of 25KhGNMT steel, the inner structure of dislocation cellular structures changes with a tendency to smooth disorientations (Figure 6, *c*), which indicates a redistribution of defects in the crystalline lattice. Also, the elements of a fragmented structure of the size d_c($h\times l$, width×length) = 0.2–0.6×0.3–1.4 μm (M_{temp}) and 0.1–0.4×0.25–1.0 μm (B_l) appear (Figure 6, *d*).

The average values of the dislocation density in the volume and the sizes of the laths for each of the structural components in the surface layers and the base metal (BM) are shown in Figure 7.

From Figure 7, it is seen that as compared to the base metal, in the surface layers over the metal depth up to 2200 μm, a general increase (by 1.5 times, Figure 7, *a*) of the dislocation density and refinement (by 1.4 times) of the lath structures as B_l, as well as M_{temp} (Figure 7, *b*) are observed.

As a result of the examinations by the TEM method, it was found that the inner structure of the metal (as compared to BM) is characterized by a general increase in the dislocation density both in the volume as well as on the boundaries of the structural components (up to $\rho = 7\cdot 10^{10}–1.2\cdot 10^{11}$ cm^{-2}), the formation of spectrum of dislocation substructures: cellular; cellular with a smooth disorientation and with a multidimensional discrete disorientation; with signs of fragmentation. Such structural and phase changes contribute to an increase in the overall level of surface strengthening of the metal by increasing the dislocation strengthening caused by an interdislocation interaction (according to the theories of Taylor, Zeger, Motta, etc. [11]) and a substructural strengthening due to dispersion of the structure (in accordance with the Hall–Petch dependence [12]).

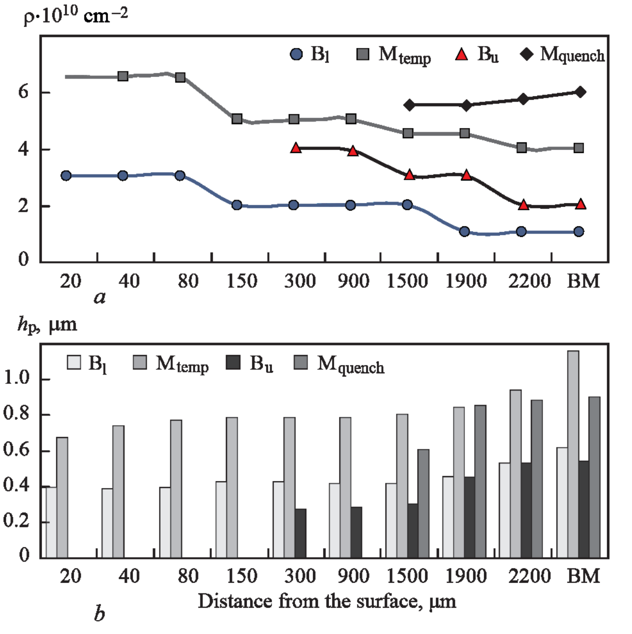

Figure 7. Changing the average parameters of the fine structure of lower bainite (B_l), tempered martensite (M_{temp}), upper bainite (B_u), quenching martensite (M_{quench}) over the depth of the treated surface and in BM: *a* — dislocation density (ρ) in the volume of structural components; *b* — width of the laths (h_l)

Thus, in the metal of the treated surface (as compared to the base metal), an overall increase in the dislocation density, as well as the structure dispersion will foster an increase in the overall level of metal strengthening. At the same time, the absence of quenching martensite and upper bainite in the surface layers of armoured steel indicates an increase in the crack resistance of metal in this area [11].

Based on the abovementioned data, the specimen of 25KhGNMT steel, whose surface was treated during 15 min, an overall strengthening of the metal due to an increase in the dislocation density and dispersion of the structure was observed as compared to the metal without treatment. As a result of PBD treatment under the action of a pulsed current in non-equilibrium conditions, it is possible to obtain a metastable state in the surface layers of the metal [13]. The action of a direct current pulse probably initiates periodic fluctuations of atoms, which results in a redistribution of defects in the crystalline lattice. The result is a deformation strengthening of the metal with a general increase in the dislocation density, refinement of the structure and the substructure formation. This will help to strengthen 25KhGNMT steel as well as to increase its crack resistance [9, 10].

Analyzing the abovementioned results, it should be noted that a local PBD treatment of 25KhGNMT steel in the future can become the basis for developing a number of surface engineering technologies that will be aimed at extending the life of metal materials for welded structures, operating in special conditions.

CONCLUSIONS

1. It is shown that the use of a pulsed barrier discharge (PBD) for treatment of 25KhGNMT steel is the basis for developing surface engineering technologies aimed at extension of life of metal materials for welded structures operating in special conditions.

2. It was found that as a result of 15 min PBD treatment of 25KhGNMT steel, an increase in its Vickers hardness (*HV*) by 20 % to a depth of 2 mm occurs, which is predetermined by the refinement of a martensite-bainite structure at an increase in the fraction of lower bainite and the formation of dislocation substructures with the features of fragmentation that promotes an increase in the overall level of surface strengthening of the metal by increasing dislocation and substructure strengthening.

3. The mechanism of strengthening steel as a result of PBD treatment, which is based on obtaining the metastable state in the surface layers of the metal in the non-equilibrium conditions is proposed. The action of a direct current pulse initiates periodic fluctuations of atoms, which results in a redistribution of defects in the crystalline lattice. The result is deformation strengthening of the metal and refinement of the lath structure of martensite.

REFERENCES

1. Dubodelov, V.I., Goryuk, M.S. (2018) *Application of electromagnetic fields and magnetohydrodynamic phenomena for intensification of effect on metallic systems: World and Ukrainian experience*. In: Science of Materials. Achivements and Prospects. In: 2 Vol., Vol. 2, 24–50, Kyiv, Akademperiodyka [in Ukrainian].
2. Sydorenko, Y.M., Pashchin M.O., Mykhodui, O.L. et al. (2020) Effect of pulse current on residual stresses in AMg6 aluminum alloy in electrodynamic treatment. *Strength of Materials*, 52(**5**), 731–737. DOI: https://doi.org/10.1007/s11223–020–00226–2
3. Lobanov, L.M., Pashchyn, M.O., Mikhodui, O.L. et al. (2021) Modeling of stress–strain states of AMg6 alloy due to impact action of electrode-indenter in electrodynamic treatment. *The Paton Welding J.*, **6**, 2–11. DOI: https://doi.org/10.37434/tpwj2021.06.01
4. Zhang, Jun, Liu, Ji-De, Zhang, Xin-Fang et al. (2021) Effect of high density current pulses on microstructure and mechanical properties of dual-phase wrought superalloy. *Acta Metallurgica Sinica*, 34(**12**), 1635–1644. DOI: https://doi.org/10.1007/s40195–021–01211–7
5. Diao, Aimin, Wang, Jingpen, Yang, Yuqiu et al. (2022) Fatigue damage recovery of 20 carbon steel under pulsed current. *Tezhong Zhuzao Ji Youse Hejin/Special Casting and Nonferrous Alloys*, 42(**3**), 318–322. DOI: https://doi.org/10.15980/j.tzzz.2022.03.009
6. Guo, J.D., Wang, X.L., Dai, W.B. (2015) Microstructure evolution in metals induced by high density electric current pulses. *Materials Sci. and Technology (United Kingdom)*, 31(**13a**), 1545–1554. http://www.maneyonline.com/doi/pdfplus/10.1179/1743284715Y.0000000001doi: 10.1179/1743284715Y.0000000001
7. *Fangmin* Huang, Li Chen, HonglinWang, Zongcheng Yan. (2010) Analysis of the degradation mechanism of methylene blue by atmospheric pressure dielectric barrier discharge plasma. *Chemical Eng. J.*, **162**, 250–256.
8. https://s-metall.com.ua
9. Kostin, V.A., Poznyakov, V.D., Berdnikova, O.M. et al. (2021) Influence of structural transformations on the mechanical properties of welded joints of armor steels. *Materials Sci.*, 56(**4**), 472–480. https://doi.org/10.1007/s11003–021–00453–1
10. Berdnikova, O.M., Kostin, V.A., Poznyakov, V.D. et al. (2020) Structure and crack resistance of special steels with 0.25–0.31 % carbon under the conditions of simulation of thermal cycles of welding. *The Paton Welding J.*, **5**, 2–8. DOI: https://doi.org/10.37434/tpwj2020.05.01
11. Goldshtejn, M.I., Litvinov, V.S., Bronfin, B. M. (1986) *Physics of metals of high-strength alloys*. Moscow, Metallurgiya [in Russian].
12. Farber, V.M., Belenkij, B.Z., Goldshtejn, M.I. (1975) Evaluation of strength of low-carbon low-alloy steels by structural data. *Fizika Metallov i Metallovedenie*, 3(**2**), 403–409 [in Russian].
13. Gridnev, V.N., Trefilov, V.I. (1988) *Phase and structural transformations and metastable states in metals*. Kyiv, Naukova Dumka [in Russian].

ORCID

L.M. Lobanov: 0000-0001-9296-2335,
O.M. Berdnikova: 0000-0001-9754-9478,
M.O. Pashchyn: 0000-0002-2201-5137,
O.L. Mikhodui: 0000-0001-6660-7540,
O.S. Kushnaryova: 0000-0002-2125-1795,
V.I. Kryvyi: 0000-0003-2611-528X

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

M.O. Pashchyn
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: svarka2000@ukr.net

SUGGESTED CITATION

L.M. Lobanov, O.M. Berdnikova, M.O. Pashchyn, O.L. Mikhodui, O.S. Kushnaryova, T.G. Solomiychuk, V.I. Kryvyi (2022) Strengthening of welded structures of 25KhGNMT steel by pulsed barrier discharge treatment. *The Paton Welding J.*, **12**, 3–8.

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 02.08.2022
Accepted: 30.01.2023