DOI: https://doi.org/10.37434/tpwj2025.04.02

MAGNETIC PULSE TREATMENT OF WELDED JOINTS IN FUSION WELDING

L.M. Lobanov[1], M.O. Pashchyn[1], O.L. Mikhodui[1], A.N. Timoshenko[1], K.V. Shyian[1], O.M. Karlov[2], I.P. Kondratenko[2], R.S. Kryshchuk[2], V.V. Chopyk[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: olha.mikhodui@gmail.com
[2]Institute of Electrodynamics of the NASU
56 Beresteiskyi Prosp, 03057, Kyiv, Ukraine. E-mail: ied1@ied.org.ua

ABSTRACT

Treatment with a pulsed electromagnetic field (TPEMF) of welded joints leads to a decrease in the level of residual welding stresses. TPEMF in the welding process contributes to an increase in the efficiency of the welding process (compared to TPEMF after welding) and the simplicity of its technical implementation. On the basis of mathematical modeling and experimental studies of magnetic pulse processes, an automated complex for TIG welding has been developed that is compatible with the TPEMF of the weld metal under the conditions of a thermal deformation welding cycle.

KEYWORDS: pulsed electromagnetic field, welded joints, residual welding stresses, TIG welding, structure dispersion, mathematical modeling, aluminium alloy

INTRODUCTION

Industrial development initiates research into progressive technologies to improve the service properties of welded structures. A promising method in this area is treatment with a pulsed electromagnetic field (TPEMF) of welded joints [1–20]. Based on investigation results [1–5, 11] it should be noted that the impact of a pulsed electromagnetic field (PEMF) is an effective tool of influencing the stressed state of the welded joints. The effectiveness of the impact is enhanced at its application under the conditions of welding [5]. TPEMF can be the base for development of effective technologies of controlling the stress-strain state of the welded joints from non-ferromagnetic metallic materials, which include aluminium alloys, applied in the aerospace and ship-building industry.

THE OBJECTIVE

of this work is development of scientific principles of TPEMF application during welding of non-ferromagnetic materials in the case of aluminium alloy AMg6.

INVESTIGATION PROCEDURE

Increase in TPEMF effectiveness during welding, compared to treatment at room temperature, is based on the following principles: increase in welding process productivity as a result of transition from sequential to simultaneous performance of the main technological operations; possibility of automation; improvement of treatment effectiveness to reduce the residual welding stresses, in keeping with the mechanism, given in [11]; dispersion of the weld metal structure during magnetodynamic impact under the conditions of increased temperatures; use of assembly fixture elements as screens to increase the magnitude of electromagnetic pressure on the treated metal.

It is known that at flowing of an electric current pulse (ECP) in the inductor conductors, eddy currents are excited in the adjacent electrically conductive medium. As was proved in [12, 13], interaction of the induced currents with PEMF which excited these currents, generates electrodynamic force P. Its normal component applies active load to the metallic material section being treated, and, as a result, changes its stressed state. Under the condition that density j of the induced electric current reaches the value of $j \geq 1$ kA/mm^2 in the metal being treated, conditions are in place for realization of the electroplasticity effect (EPE) [11–13]. This promotes intensification of plastic deformation of the material and, as a consequence, relaxation of its residual stressed state. A flat inductor with 95 mm outer diameter and inductance $L = 120$ μH was used for TPEMF realization [12]. A power source based on a capacitor system of the general capacity $C = 5140$ μF, charging voltage U of up to 800 V, and stored energy $E_{st} \sim 1.6$ kJ was used for PEMF generation. To assess TPEMF effectiveness, specimens in the form of a disc of thickness $\delta = 1$ mm and diameter $D_s = 90$ mm from aluminium alloy AMg6 with a TIG weld were used. Welded joints on the disc surface were made in the form of a ring with diameter $D_w = 5$ mm. Thus, there was a distance of 45 mm between the weld and the free edge of the disc.

The method of electron speckle-interferometry [12, 14] was used for assessment of σ_x of the tangen-

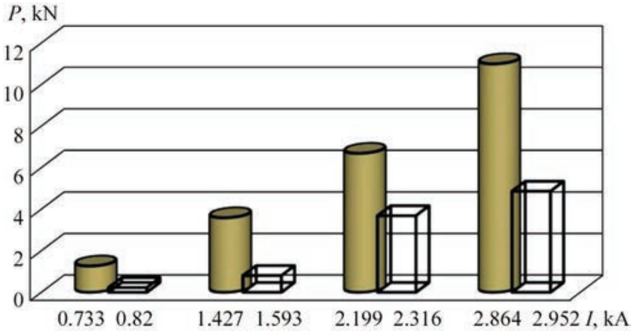

Figure 1. Influence of ECP amplitude values — *I* on pressure *P* during TPEMF of specimens of circumferential welded joints from AMg6 alloy with δ = 10 mm: □ — TPEMF without a screen; ■ — TPEMF with a screen

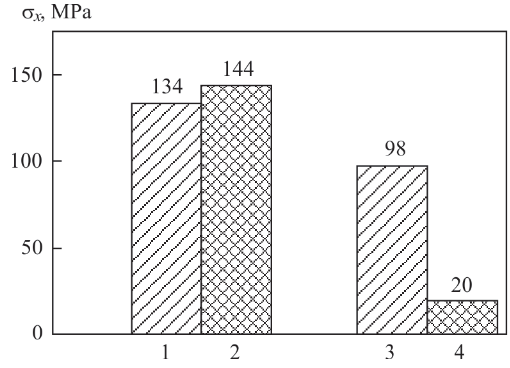

Figure 2. Influence of the weld TPEMF without application (*1*, *3*) and with application (*2*, *4*) of a screen on residual stresses σ_x in the weld metal of AMg6 alloy welded joint: *1*, *2* — before TPEMF; *3*, *4* — after TPEMF

tial component of the welded joint stressed state in points on the line of the circumferential weld.

INVESTIGATION RESULTS

TPEMF of specimens of thickness δ = 1.0 mm and an assembly of a specimen with δ = 1.0 mm and current-conducting screen from AMg6 alloy also in the form of a disc with δ = 5.0 mm (Σδ = 6 mm) and a diameter of 90 mm was performed. TPEMF was conducted as a series of eight ECP in a mode with increase of *U* values in the following sequence: U_1 = 200 V, U_2 = 400 V, U_3 = 600 V; U_4–U_8 = 800 V. ECP at U_1–U_3 facilitated gradual achievement of the nominal mode, and ECP at U_4–U_8 promoted generation of PEMF for specimen treatment. Selection of the quantity of ECP in the nominal treatment mode (at the voltage of 800 V) was based on the results of [15].

In [16] evaluation of intensity *H* of the inductor magnetic field used in this work, was performed with application of a procedure based on Hall sensor. It was found that *H* values of the inductor at capacitor discharge at voltage *U* = 200 and 500 V reached 10 and 30 kA/m, respectively.

With increase in the thickness, electromagnetic force *P* will rise, as it is defined as an integral value in a certain volume, which is confirmed by the data in Figure 1 and the results of [12]. With δ increase to 6.0 mm (due to the screen application), *P* values rise more than two times, compared to TPEMF of specimens with δ= 1.0 mm without a screen. For effective treatment of thin specimens, the current pulse duration should be decreased. Such a method, obviously, requires a change in the discharge circuit parameters, which is not rational. A simpler and more effective approach is proposed in the work in the form of applying additional layers of a similar material, with which the equivalent thickness will be optimal in terms of achieving the largest value of force *P* of electromagnetic pressure. The proposed approach is similar to application of metal “satellites” in the technology of electromagnetic forming, for instance expansion or crimping [10, 11, 17]. Figure 2 gives the distributions of residual stresses σ_x before TPEMF, as well as σ_x after TPEMF of the specimen with and without application of the screen, which confirm the effectiveness of screening during TPEMF. In view of the above, it should be noted that TPEMF can be an effective method of controlling the residual stressed state of welded structures from aluminium alloys. Results of

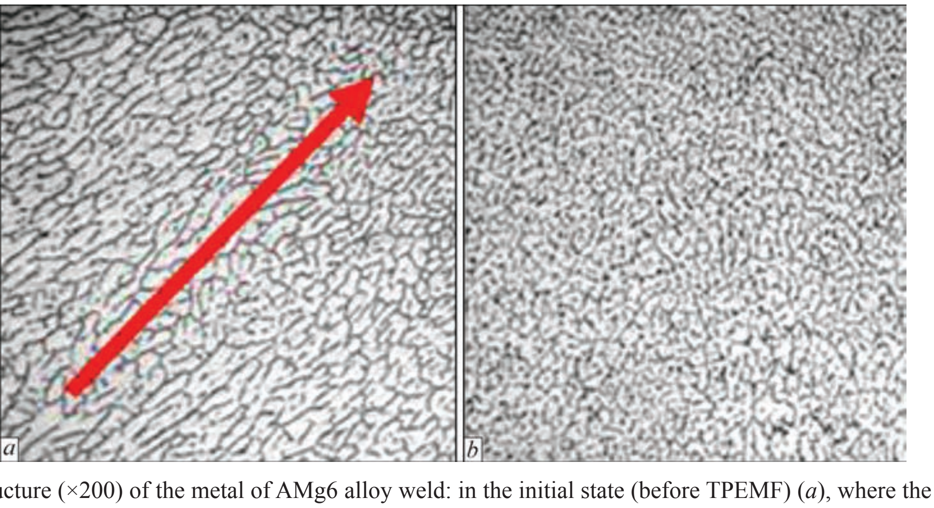

Figure 3. Microstructure (×200) of the metal of AMg6 alloy weld: in the initial state (before TPEMF) (*a*), where the arrow shows the direction of crystal growth; after TPEMF (*b*)

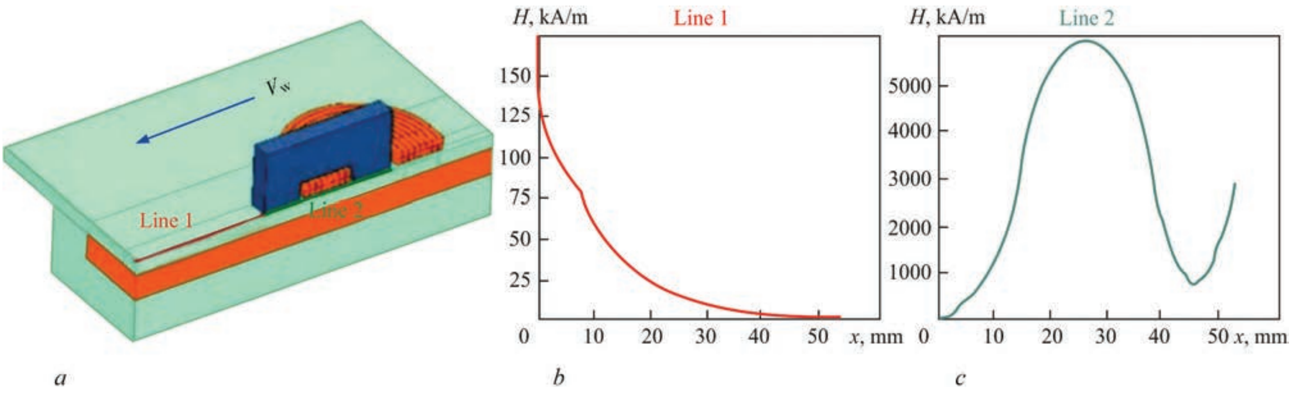

Figure 4. Mathematical modeling of electrophysical parameters of TPEMF (weld) during welding; *a* — schematic of a U-shaped TPEMF inductor along the welding direction V_w; *b* — distribution of TPEMF intensity *H* along line 1; *c* — distribution of TPEMF intensity *H* along line *2*

metallographic investigations of specimens before and after TPEMF confirmed the positive influence of treatment on evolution of the weld metal structure (Figure 3). In the general case the microstructure is a light matrix — an α-solid solution with precipitation of the excess phase in the form of a network along the crystal boundaries. However, while without TPEMF the crystals are of a predominantly elongated shape, oriented along the direction of their growth (arrow in Figure 3, *a*), after TPEMF with screening an equiaxed orientation of the grains is observed (Figure 3, *b*), which is accompanied by their refinement. Obtained results are attributable to dynamic impact of force *P* and eddy currents on intergranular boundaries during TPEMF, accompanied by local Joule heating of the grains [18–20].

Based on the results of [20], mathematical modeling of electrophysical parameters of TPEMF of the weld during welding was performed. Modeling results (Figure 4) should promote optimization of TPEMF parameters for relaxation of residual stresses in sheet welded joints. Figure 4, *a* shows the scheme of positioning a U-shaped inductor along the welding direction V_w (arrow) for TPEMF, where line 1 is the weld surface in front of the inductor, line 2 is in the zone of direct TPEMF impact on the weld metal. Figure 4, *b* shows the distribution of intensity *H* of PEMF, which allows determination of the optimal position of the inductor relative to the welding torch, which is determined by maximum value *H* along line 1 (beginning of the line on the side surface of a U-shaped inductor). From the results in Figure 4, *b* we can come to the

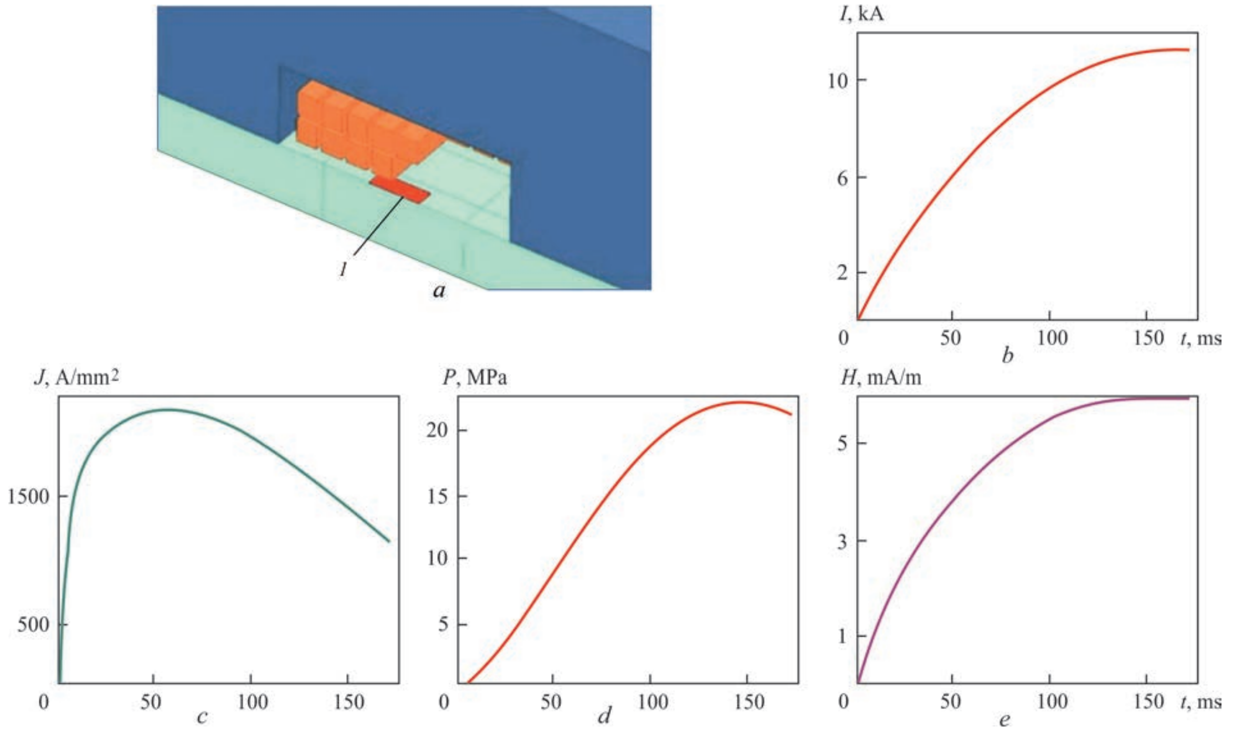

Figure 5. Results of modeling the time distributions of electrophysical parameters of the weld TPEMF (for explanations of Figure 5, *a*–*d* see the text)

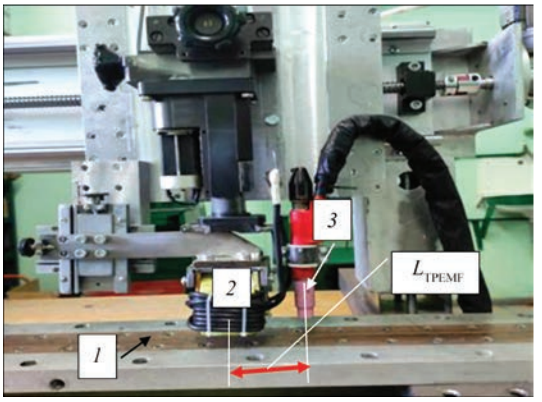

Figure 6. Automated complex for TIG welding under the conditions of accompanying TPEMF of the weld: *1* — forming backing acting as a screen; *2* — inductor; *3* — torch; L_{TPEMF} is the distance between the torch and line 1 of the indoor (Figure 4)

conclusion that at 40 mm distance from the edge of the magnetic core ($x = 0$), H value is close to zero. The diagram in Figure 4, *b* allows determination of the distance between the inductor and the welding torch, on which PEMF influence on the welding process is minimal. Figure 4, *c* shows H distribution of TPEMF along line 2 (Figure 4, *a*).

Figure 5 gives the results of modeling the time distributions of electrophysical parameters of the weld TPEMF. In Figure 5, *a* area *I* of 3.5×5.0 mm size is highlighted (which corresponds to the weld pool rear edge), for which we determined average current density J (Figure 5, *c*) and average value of pressure P (Figure 5, *d*) during the impact of ECP — I (Figure 5, *b*) on the solidifying weld, which promotes relaxation of welding stresses. At moment of time of about 50 μs the average current density J on the metal surface is close to 2200 A/mm^2 (Figure 5, *c*), while pressure P reaches the maximal value of 23 MPa at 150 μs (Figure 5, *d*). This should provide relaxation of welding stresses at the stage of their formation during the weld solidification due to realization of electroplasticity effect [7]. Figure 5, *e* gives the distribution of PEMF intensity H in the inductor cross-section for the moment of highest I and H values of PEMF, providing stress relaxation.

Based on the results of investigations [1–8, 11–12, 20], an automated complex was developed for TIG welding under the conditions of TPEMF of the solidifying metal of the weld (Figure 6), where forming backing *1* from a non-ferromagnetic material is used as the screen (enhancing the action of force P), and distance L_{TPEMF} between line 1 (Figure 4) of inductor *2* and TIG torch *3* ensures the maximal efficiency of TPEMF during welding.

CONCLUSIONS

1. It is shown that TPEMF has a positive effect on the residual stressed state and structure of the welded joints, and the effectiveness of the impact is enhanced under the TIG welding conditions.

2. It was established that improvement of TPEMF effectiveness during welding, compared to treatment at room temperature, is based on increase of the welding process productivity, as a result of transition from successive to simultaneous performance of the main technological operations, possibility of treatment automation, and positive influence of the thermal cycle of welding.

3. It is shown that TPEMF application promotes lowering of residual stresses and refinement of the weld metal structure in welded joints of AMg6 alloy.

4. A mathematical model of the TPEMF process was developed, on the base of which it was proved that the value of electrophysical parameters of treatment ensure relaxation of the residual stresses through realization of the electroplasticity effect.

5. An automated complex for TIG welding under the conditions of accompanying TPEMF was developed and produced, proceeding from the results of mathematical modeling and experimental studies of the magnetic-pulse processes.

REFERENCES

1. Lobanov, L.M., Pashchin, N.A., Cherkashin, A.V. et al. (2012) Efficiency of electrodynamic treatment of aluminium alloy AMg6 and its welded joints. *The Paton Welding J.*, **1**, 2–6.
2. Lobanov, L.M., Pashchin, N.A., Mihodui, O.L. (2014) Repair of the AMg6 aluminum alloy welded structure by the electric processing method. *Weld. Res. Appl.*, **1**, 55–62.
3. Lobanov, L.M., Pashchin, N.A., Yashchuk, V.A., Mikhodui, O.L. (2015) Effect of electrodynamic treatment on the fracture resistance of the AMg6 aluminum alloy under cyclic loading. *Strength of Materials*, **47**, 447–453. DOI: https://doi.org/10.1007/s11223-015-9676-5
4. Lobanov, L.M., Pashchin, N.A., Timoshenko, A.N. et al. (2017) Effect of the electrodynamic treatment on the life of AMg6 aluminum alloy weld joints. *Strength of Materials*, **49**, 234–238. DOI: http://dx.doi.org/10.1007/s11223-017-9862-8
5. Korzhik, V.N., Pashchin, N.A., Mikhodui, O.L. et al. (2017) Comparative evaluation of methods of arc and hybrid plasma-arc welding of aluminum alloy 1561 using consumable electrode. *The Paton Welding J.*, **4**, 30–34. DOI: https://doi.org/10.15407/tpwj2017.04.06
6. Batygin, Y.V., Lavinsky, V.I., Khimenko, L.T. (2003) *Pulsed magnetic fields for advanced technologies*. Ed. by Yu.V. Batygin. Kharkov, MOST-Tornado [in Russian].
7. Andrea, D., Burleta, T., Körkemeyerb, F. et al. (2019) Investigation of the electroplastic effect using nanoindentation. *Materials & Design*, **183**, 108153. DOI: https://doi.org/10.1016/j.matdes.2019.108153
8. Nayanathara Hendeniya, Gayan Aravinda Abeygunawardena, Indika De. Silva, Shiranga Wickramasinghe (2020) The tensile electroplasticity of low carbon steel with low amplitude pulse current. In: *2020 Moratuwa Engineering Research Conf. (MERCon)*, 165–169. DOI: https://doi.org/10.1109/MERCon50084.2020.9185238
9. Turenko, A.N., Batygin, Y.V., Gnatov, A.V. (2009) Pulsed magnetic fields for advanced technologies. Monography. In: Vol.3. *Theory and experiment of attraction of thin-walled*

metals by pulsed magnetic fields. Kharkiv, KhNADU [in Russian].
10. Batygin, Y.V., Lavinskyi, V.I., Khavin, V.L. (2009) *Method of magnetic pulsed processing of thin-walled metal billets*. Pat. UA 74909, 15.02.2006 [in Ukrainian].
11. Lobanov, L.M., Pashchyn, M.O., Mikhodui, O.L. et al. (2022) Stress-strain state of welded joints of AMg6 alloy after electrodynamic treatment during welding. *Strength of Materials*, 54(**6**), 983–996. DOI: https://doi.org/10.1007/s11223-023-00474-y
12. Lobanov, L.M., Pashchyn, M.O., Mikhodui, O.L. (2021) Pulsed electromagnetic field effect on residual stresses and strains of welded joints of AMg6 aluminum alloy. *Strength of Materials*, 53(**6**), 834–841. DOI: https://doi.org/10.1007/s11223-022-00350-1
13. Vasetsky, Y.M., Dzyuba K.K. (2017) Analytical method of calculation of quasi-stationary three-dimensional electromagnetic current field flowing along a contour of arbitrary configuration near an electrically conductive body. *Tekhnichna Elektrodynamika,* **5**, 7–17 [in Russian]. DOI: https://doi.org/10.15407/techned2017.05.007
14. Lobanov, L.M., Pivtorak, V.A., Savitsky, V.V., Tkachuk, G.I. (2006) Procedure for determination of residual stresses in welded joints and structural elements using electron speckle-interferometry. *The Paton Welding J.,* **1**, 24–29.
15. Lobanov, L.M., Pashchin, N.A., Mikhodui, O.L. (2012) Influence of the loading conditions on the deformation resistance of AMg6 alloy during electrodynamic treatment. *Strength of Materials*, 44(**5**), 472–479. DOI: https://doi.org/10.1007/s11223-012-9401-6
16. Lobanov, L.M., Pashchin, N.A., Cherkashin, A.V. et al. (2012) Repair welding of intermediate cases of aircraft engines from high-temperature magnesium alloy ML10 with application of electrodynamic treatment. *The Paton Welding J.*, **11**, 28–33.
17. Belyi, I.V., Fertik, S.M., Khimenko, L.T. (1977) *Handbook on magnetic pulse treatment of metals*. Kharkiv, Vyshcha Shkola [in Russian].
18. Batygin, Yu.V., Chaplygin, E.A. (2006) Eddy currents in flat sheet metal blanks. *Elektrotekhnika i Elektromekhanika*, **5**, 54–59 [in Russian].
19. Strizhalo, V.A., Novogrudsky, L.S., Vorobiev, E.V. (2008) *Strength of materials at cryogenic temperatures with regard to the influence of electromagnetic fields*. Kyiv, IPP [in Russian].
20. Rashchepkin, A.P., Kondratenko, I.P., Karlov, O.M., Kryshchuk, R.S. (2019) Electromagnetic field of an inductor with a W-shaped core for magnetic pulse treatment of materials. *Tekhnichna Elektrodynamika*, **6**, 5–12 [in Ukrainian]. DOI: https://doi.org/10.15407/techned2019.06.005

ORCID

L.M. Lobanov: 0000-0001-9296-2335,
M.O. Pashchyn: 0000-0002-2201-5137,
O.L. Mikhodui: 0000-0001-6660-7540,
K.V. Shyian: 0000-0001-9198-6554,
O.M. Karlov: 0000-0002-1350-1870,
I.P. Kondratenko: 0000-0003-1914-1383,
R.S. Kryshchuk: 0000-0002-1933-0144,
V.V. Chopyk: 0000-0002-5046-5223

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

O.L. Mikhodui
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: olha.mikhodui@gmail.com

SUGGESTED CITATION

L.M. Lobanov, M.O. Pashchyn, O.L. Mikhodui, A.N. Timoshenko, K.V. Shyian, O.M. Karlov, I.P. Kondratenko, R.S. Kryshchuk, V.V. Chopyk (2025) Magnetic pulse treatment of welded joints in fusion welding. *The Paton Welding J.*, **4**, 7–11. DOI: https://doi.org/10.37434/tpwj2025.04.02

JOURNAL HOME PAGE

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

Received: 08.01.2025
Received in revised form: 28.02.2025
Accepted: 08.05.2025