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PROSPECTS FOR APPLICATION OF ELECTROMAGNETIC FIELDS IN WELDING AND RELATED PROCESSES

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Development and introduction of new energy-saving technologies meets the modern demands of Ukraine. In the paper background, current state and directions of development of investigations of the influence of electromagnetic fields on mechanical properties and stressed state of metallic materials and welded joints are considered. The possibility of their application for control of the stressed state, evolution of the structure, properties, and extension of the life of welded structures is shown. 49 Ref.

***Keywords*:** *electromagnetic treatment technologies, electromagnetic fields, welded joints, structures, metallic materials, pulsed spark and current discharges, electroplastic effect, stress-strain state, nanodispersed modifiers*

Development of high-tech industries stimulates increase of the requirements to metallic materials, the set of their main and special properties, and methods of their permanent joining.

Considering the current problems of Ukraine, a promising reserve for improving the state of its industry is development and introduction of new energy-saving technologies. Increase of strength, ductility and other mechanical characteristics can be achieved through combined treatment of metallic materials by pulsed electric current (PEC) and electromagnetic field (EMF) of a high intensity during a short period of time. Results of studying the electrophysical processes running in metallic materials under EMF impact give reason to think that the principles of controlling the mechanical properties with EMF application are an alternative to traditional technologies, at the same time having a number of advantages such as energy effectiveness and adaptability to fabrication.

The purpose of the paper is analysis of development, current state and directions of solving the problem of EMF effect on mechanical characteristics and stressed state of metallic materials and welded joints. The question of controlling the structure and mechanical properties of liquid metal with application of EMF in the welding process, that is a separate (and rather urgent) issue of engineering practice [1], is not considered in this work.

Prospects for application of pulsed spark and current discharges for welded joint treatment. Methods of improvement of mechanical characteristics of metals and alloys include different kinds of their PEC and EMF treatment [2]. High-voltage pulsed discharge in liquid is used in industrial technology as a source of dynamic pressure, under the impact of which the treated materials can fail, be formed, and can change their structure and mechanical characteristics. Electrohydropulse treatment (EHPT) consists in the action of mechanical loading on the object, which is initiated by high-voltage pulsed discharge of electric current in the current-conducting medium (water). There are numerous results that confirm the possibility of EHPT application for lowering the residual technological stresses. Investigations of EHPT effect on the stress-strain state of welded joints showed that it reduces tensile stresses in welded structures to 90 % due to activation of dislocation processes. By the effectiveness of lowering the level of residual welding stresses, EHPT is comparable to high-temperature tempering [3].

At the same time, EHPT method has a number of disadvantages, which may include the need to apply technological tanks with water, having a high metal content, which are characterized by a rather complex structure, because of higher rigidity, so as to resist the compression-tension waves, initiated by electrohydraulic effect.

At the same time, EHPT is rational for application in fabrication of large-sized welded products, for instance, cast-welded bed plates. Over the recent years, there was no further development of EHPT in Ukraine that is obvious from absence of publications, and is related to reduction of the volumes of heavy machine-building, but it has good prospects, provided the growth rate of local metal structure fabrication is restored.

Electric spark treatment, widely used in machine-building technology, can be regarded as a technique close to EHPT by the method of its realization (but not by its purpose). At electric spark treatment a PEC discharge is initiated on the surface of the billet that is part of the discharge circuit and is located in the dielectric liquid (kerosene, oil). During this discharge, heat is generated that is consumed for melting, partial evaporation and explosive release of treated metal particles. The similarity between electric spark treatment and EHPT consists in that during their performance the current discharge runs in the liquid medium, and the discharge energy is provided by a capacitive storage. While EHPT realization requires a current-conducting medium, electric spark treatment requires a dielectric one. This method is applied at calibration, piercing holes and dies, cutting and grinding. At the same time, realization of electric erosion processes without application of current-conducting and dielectric environments markedly widens the possibilities of application of electric spark treatment of large-sized metal structures, for instance, for strengthening the cutting surfaces of agricultural machinery parts [4]. The capabilities of this method allow realization of the processes of nanostructuring of the surface layers of structural steels and deposited surfaces, aimed at improvement of their tribological characteristics.

PEC treatment is used for strengthening the surfaces of friction contact, which is determined by interaction of wheel-rail pair [5]. The principle of rail strengthening consists in electric spark deposition of coating of a discrete type with regions, having different characteristics of hardness, impact toughness and friction coefficients. Discrete coating of the rail contact surface was formed with application of electric spark treatment. One of the advantages of a discrete coating is its discontinuity that provides a minimum level of residual stresses, compared to a continuous coating. Coating was deposited by moving an electrode from different metallic materials in the form of a disc over the surface being treated. PEC of specified duration and configuration was initiated between the electrode and the rail that provided a discrete metal transfer from the electrode to the rail. Application of the method ensured high tribological characteristics of both the rail contact surface, and wheel-rail pair [6]. Electric spark structure formation is promising from the viewpoint of its realization in the case of welded joints. Development of electric pulse nanostructuring methods, as well as the implantation proper of nanostructures in the specified regions of welded joint cross-section appears to be a promising method of improvement of metal structure service life.

Investigation of electroplastic effect that is the base for promising technologies of welded joint treatment. Investigations in the field of physics of solids that have been conducted since 1960s, allowed establishing the phenomenon of an abrupt increase of ductility and lowering of metal resistance to deformation, due to simultaneous impact of active mechanical loading and high-density PEC. This phenomenon was called the electroplasticity effect (EPE), and the deformation initiated by EPE — the electroplastic deformation (EPD). EPE opened up new possibilities, both for the technologies of mechanical forming of metals and alloys, including refractory materials [7], and for regulation of their stressed state [8]. In 1925 Heckmann, studying the properties of crystals, expressed the idea about the interrelation between their mechanical, electric and thermal characteristics. As electrons are the main «carriers» of electric properties in metals, and the connection between the atoms is carried out by electrostatic forces, then influencing the energy spectrum of free electrons leads to a change of mechanical properties of metals [9]. The question of acceleration of the dislocation movement under the impact of a directed electron flow was studied, and it was shown that such acceleration can take place provided the electron speed is higher than that of the dislocations. It was found that PEC impact causes a jump, lowering the magnitude of the deforming force, and this phenomenon was observed only in the region of elastic-plastic deformations.

The main purpose of the majority of investigations conducted in 1970–1980s consisted in studying EPE mechanism. This became a stimulus for investigation of the influence of side effects: thermal and mechanical (ponderomotive) action of PEC, as well as the impact of nonuniformity of current density distribution over the sample cross-section (skin-effect) on lowering of metal resistance to deformation.

Here, for the considered materials and PEC parameters in the above-mentioned works the skin-layer thickness exceed the sample diameter, i.e. the skin effect was practically absent.

The results of studying the influence of pinch-effect on EPE realization showed that the latter is determined by intensity H of the magnetic field and magnetic permeability of the material, as well as the sample surface area [10]. *H* value directly depends on current value and is inversely dependent on sample cross-section. Pressure *P* develops over the sample surface, as a result of pinch-effect, which is determined by the following expression:

$$P = 0.5\mu_0 H^2, \quad (1)$$

where μ_0 is the absolute magnetic permeability of the material.

Evaluation of the impact of pinch-effect on lowering of sample resistance to deformation showed that its contribution is not more than 0.4–6.0 % of the yield limit of metallic materials. This confirms its small influence on EPD [11].

When PEC flows through the metal, its temperature is increased due to Joule heating. During PEC impact increase of internal energy in the material is determined by pulse duration, current amplitude and magnitude of electric resistance. Thermal energy dissipation in the metal can both lower its resistance to deformation at the moment of PEC impact as a result of thermal strength loss, and cause the change of mechanical characteristics [12].

It should be noted that the main focus of investigations of electric current impact on plastic deformation of metals, was both on establishing the physical essence of the phenomena, and on technological applications of EPE in engineering practice. Investigations of EPE physical model were performed for a large number of metals and alloys of different classes, in different modes of PEC treatment performance, and kinds of loading in a broad temperature range. At present there exist a number of interpretations and descriptions of EPD and EPE mechanisms. The most well-known is the dislocation model of EPE, which is based on electron-dislocation interaction that leads to dislocation disruption from the stoppers and their capture by mobile conduction electrons. However, in [13], another EPE interpretation is proposed. Taken as its base is the gradient-dislocation model, where the chemical potential gradient φ (φ is the minimum energy, required for breaking the electron bonds with crystal lattice atoms) of vacancies in polycrystalline metallic materials is the determinant factor for dislocation movement in pulsed electromagnetic field (PEMF). Dislocation and gradient-dislocation physical models allow clarifying only the increase of ductile properties of metals. A gradient-diffusion physical model was proposed in [14], which provides clarification of the main effects, manifested in metals at PEC treatment. According to this model, at PEC impact due to the concentration of force lines of the electromagnetic field, not only grad φ along the defect boundaries, but also localized fields of thermoelastic stresses form on such structure defects as micropores, cracks and delaminations.

Concurrent heating at PEC treatment of metal samples in the thermoelastic temperature region leads to reduction of the level of initial tensile stresses [15]. At similar heating without PEC application, the level of stresses in the metal after cooling to room temperature returned to its initial level. Here PEC effect (without taking into account the Joule heating) decreased with increase of the duration of an individual pulse, and at multiple PEC treatment material resistance to deformation increased with increase of the number of current discharges. In terms of electron-dislocation interaction, this is attributed to the fact that at one-time PEC impact a single pulse acts on the material, which has considerable dislocation potential. In multiple impact modes the previous pulses take part of the dislocations out of the relaxation processes, and material reaction to PEC impact is weakened. Change of PEC polarity also affects EPE manifestation. In [16] it is shown that at the same amount of electricity and amplitude of PEC, passing through the loaded sample, bipolar pulses cause smaller relaxation (jump) of stresses that unipolar ones. This is caused by that successive PEC of different polarity, while initiating the movement of dislocations in opposite directions, counteract each other. Hence, their resulting impact is smaller, than that with unipolar PEC. PEC impact on metal ductility is manifested in the region of plastic deformation that is accompanied by relieving of the deformation force, whereas EPE is not observed in the elastic deformation region. In [17] a method for determination of part of the energy of electric current pulse which is directly consumed for plastic deformation work was proposed, based on the mechanism of electroplastic deformation. This allows determination of the stress of the start of plastic flow initiated by PEC, for materials of different classes in the temperature range of 293–4.2 K.

At this moment EPE regularities have been studied in greatest detail, in keeping with the requirements of engineering practice for finding the most effective means to increase the ductility of metallic materials, applied in industry. To reduce the thermal impact of PEC and magnetic field, one of the directions of EPE investigations was their performance at cryogenic temperatures [18] that is important in the scientific and applied aspects. The scientific interest is due to the fact that with temperature lowering from 293 K to values, close to the cryogenic ones, PEC impact becomes stronger, as at such temperatures the electron viscosity (because of absence of Joule heat) becomes the main source of lowering of dislocation mobility that leads to changes in mechanical properties of metallic materials [19]. Applied aspect is associated with development of high-energy products, where the superconductivity effect is used (cryoturbogenerators, thermonuclear reactors). PEC specific impact on EPE realization at cryogenic temperatures is manifested in that the magnitude of stress jump under the action of the current discharge increases with lowering of testing temperature, increase of PEC amplitude and its duration. PEC flowing in the region of elastic stresses gives rise to residual deformation at stresses, which, depending on testing temperature, pulse parameters and material class, are 10–35 % smaller than its yield limit. Here, the above changes become greater with lowering of investigation temperature from 293 to 4.2 K, while PEC amplitude is a more potent factor than its duration [20].

Methods of treatment of metallic materials and welded joints by electromagnetic fields. Proceeding from the results of investigations of electromagnetic impact of PEC on mechanical characteristics of metals and alloys, we developed metal treatment technologies. Changing PEC and PEMF duration and energy, it is possible to manufacture products and parts with specified performance, due to activation of a spectrum of dislocation, phase and other physical processes. Impact of PEC and PEMF of different duration and configuration which is realized in different metal treatment technologies, causes structural changes in metals and alloys [21], that affect their characteristics. An increase of wear resistance of cutting tools [22], corrosion resistance [23], lowering of stress concentration in the treated parts and elements of structures, elimination of fatigue cracks, extension of the life of stamped parts from light and special alloys, are noted. It is established that at optimum parameters of electric pulse impacts material ultimate strength, endurance limit and fatigue strength are increased without detracting from its ductile properties [24]. The mentioned metalworking processes are promising for increase of mechanical characteristics and service properties of welded structures, allowing for structural features and stress-strain state of welded joints. This is confirmed by establishing respective research programs in such European research organizations as University of Birmingham (UK), University of Hertfordshire (UK), Imperial College (UK), Katholieke Universiteit Leuven (Belgium), EBF-Dresden (Germany), Fraunhofer-Institut fur Werkstoff- und Strahltechnik IWS (Germany). A lot of attention to research in this area is given in PRC and Japan, for instance: Sichuan University, China University of Geosciences, Army Academy of Armed Forces, Process Institute of Inner Mongolia First Machinery Group, Wuhan University of Technology, Beijing Institute of Technology, Nagoya University.

At operation of metal structures, including welded structures, microcracks initiate and propagate in the metal under the impact of loads. They cause a lowering of metal mechanical properties that leads to product failure. The problem of «healing» such defects is urgent, and now several methods of its realization are known: restoration heat treatment (RHT); mechanothermal treatment (MTT); and diffusion metallization (DM) [7]. These methods have their disadvantages, which include high power consumption, limited application for large-sized metal structures, and long duration of the process. Energy impact on a propagating crack can be realized at its treatment by PEC and PEMF, which can not only slow down crack propagation, but also increase the metal strength in the zone of the defect tip [25]. PEC passage through a part with a marginal crack is accompanied by a microexplosion in its tip, leading to formation of a crater, at 5 to 10 mm distance from which the metal is heated by several tens of degrees. This phenomenon can be used for blunting the crack tip. A method of healing microcracks in 65G steel and armco-iron, using crossed fields of PEC and PEMF, was proposed. Structure refinement at concurrent increase of microhardness relative to the initial material is observed in the zone of restored continuity [26].

At cyclic testing, the impact of PEC and PEMF leads to increase of fatigue resistance of metallic materials, which is related to microcrack healing, evolution of defective structure and phase composition, as well as elimination of the stress raisers. Positive impact of PEC on technological tensile stresses in spray-deposited surfaces of tool steels was established [27]. However, the given results did not have any further development.

Analyzing on the whole the results of EPE investigations at regulation of the stress-strain state of metallic materials, it should be noted that application of electromagnetic impacts was performed, mainly, in the plastic region of loading, in connection with the focus on EPE practical application in forming technologies. Here, the region of elastic deformation of metallic materials at electromagnetic impact remains little studied [28]. At the same time, investigation of the features of elastic stress relaxation in metals and alloys at their electromagnetic treatment is urgent for regulation of stressed state of welded structures. Results of studying the PEC and PEMF impact on controlling the residual welding stresses showed that EPE realization at welded joint treatment is limited by the features of discharge circuit formation, which includes the structure being treated. So, in the majority of cases, the welded structure dimensions do not allow providing the required current density j in the zone of PEC impact. PEC treatment of small-sized welded products is an exception, for instance hardfaced surfaces of cutting tools parts, where the cross-sections allow providing current density values, necessary for EPE realization. Studies were performed of PEMF impact on lowering residual stresses in butt welded joints of an aluminium alloy with application of a system of flat inductors rigidly fixed on the surface of plates, which were treated, and were part of the discharge circuit [29]. Conducted studies showed the possibility in principle of lowering the welding stresses at PEMF impact, although their initial level after treatment was reduced by not more than 30 %. PEMF impact on lowering the residual stresses in welded and surfaced samples of low-carbon steels, which is based on intensification of dynamic effect of magnetostriction [30], ensured lowering of the initial level of stresses to 40 %. Here, the features of fastening the welded joints influence the effectiveness of PEMF impact. Thus, at sample treatment under the conditions of rigid fastening, relaxation of residual welding stresses proceeds more intensively, than under the conditions of free support.

In work [31] investigation of electromagnetic impact on the change of mechanical properties of welded joints of carbon and low-alloyed steels was performed, which demonstrated an essential increase of impact toughness values after treatment of samples of steels of grades 20 and 09G2S at preservation of their ultimate tensile strength characteristics. Explanation of the obtained results is based on the theory of electron-dislocation interaction, as well as magnetoelastic interaction of interdomain boundaries (Bloch walls) with dislocations, that stimulate their movement at magnetization [32]. The ambiguous results of studying PEMF impact on the change of residual welding stresses are shown in [33]. So, residual stresses in samples of steels St2ps(semi-killed) and 20KhMFL in the active zone decrease by 3–25 %, while increasing up to 15 % in the reactive zone. At the same time, PEMF lowers stresses of the second kind to the level that is provided by annealing at the temperature of 1060 °C, and also leads to a more uniform distribution of α-phase through the treated metal volume.

Proceeding from the presented results, evaluation of PEC and PEMF impact on regulation of stress-strain state of welded joints of steels and aluminium alloys, leads to the conclusion that, despite the obvious effect, maximum lowering of the initial level of stresses is not more than 40 %. Development and improvement of energy-effective technologies of electromagnetic impact on welded joints, clad and spray-deposited surfaces, with which stress lowering would be close to 100 %, seems to be promising.

Realization of EPE at direct passage of PEC through metal structure elements is a rather complex task, because of the need to ensure the current density $j \geq 10^3$ A/mm^2 in the cross-sections, the area of which is much greater than 100 mm^2. The difficulty is associated with scattering of current force lines that occurs already at a small distance from the points of connection of the discharge circuit to the part. The scattering factor can be minimized through localizing of the region of current flowing in the treatment zone, and its density j that is required for EPE realization, is achieved through movement of dynamic contact of the current-conducting electrode with the treated surface. This scheme of PEC impact was studied for the novel method of nondestructive testing of stress-strain state of welded joints [34], where it is shown that adding dynamic loading to the electrode during PEC impact improves the reliability of electrode contact with welded joint surface. Here, dynamic loading intensifies dislocation movement and multiplication that determines the degree of plastic deformation of polycrystalline structures under the conditions of PEC impact. The controlling mechanism of the impact of dynamic loading, considered in the physical model of discontinuous metal flow at cryogenic temperatures [7], was extended to the region of temperatures in the range from 273 to 293 K, for the case of magnetic-pulse forming of ferromagnetic materials [35]. It is found that the small jump of stress that is caused by dynamic or thermal loading [36], acts as an initiator or synchronizer of plastic deformation, which is determined by mass breaking of dislocations through barriers over the entire volume of polycrystalline structure, to which active mechanical loading is applied. Here, directed movement of conduction electrons at the moment of PEC impact promotes dislocation advance, increasing the degree of plastic deformation of material, compared to the case of application of purely mechanical loading. Work [37] presents the results of studying the influence of mechanical and electromagnetic effects at summary and divided impact of PEMF and mechanical pressure pulses on mobility of edge dislocations in NaCl and LiF crystals. The dislocation free path l was taken as the characteristic of pulsed impact on their mobility. It is found that the mean free path length $<l>$ increases considerably at simultaneous impact of PEMF and mechanical loading pulses, compared to $<l>$ values, that are recorded under the action of each of the factors taken separately. Increase of $<l>$ under the impact of current is related to increase of the intensity of electromagnetic pumping of the crystal, and superposition of pulsed impacts of different origin initiates rather extended in time relaxation processes in the crystals that affect their stressed state. This physical model is valid also for metal polycrystalline structures that was confirmed in [38], which shows the results of evaluation of the influence of current pulses and mechanical loading σ on plastic deformation rate $\dot{\varepsilon}$ in Zn samples. It is shown that PEC impact at the value of current density j above the threshold one, increases velocity v of dislocations moving in the direction of current action. Increase of $j > 1.0$ kA/mm^2 initiates the above-mentioned process, PEC impact accelerating the dislocation movement due to their interaction with charge carriers (electrons).

The possibility of simultaneous application of electric pulse and mechanical impact for welded structure treatment with the purpose of their service life extension was substantiated proceeding from analysis of previous research [39]. This was the base for development of a new kind of welded joint treatment — electrodynamic treatment (EDT) [40]. At EDT the metal is subjected to bulk electrodynamic impact, which is characterized by simultaneous running of electric pulse and dynamic processes, the first of which causes EPE in the treatment zone, and the second results in formation of waves of stresses with the specified amplitude, plastic deformation and refinement of metal structure. Interaction of stress waves with the static field of residual stresses can initiate relaxation of the latter that may lead to decrease of their values. PEC localization in the deformation zone reduces the factor of scattering of current force lines, thus ensuring achievement of threshold density that is a mandatory condition of EPE realization. Interaction of the components of electrodynamic effect during PEC passage through the metal determines the effectiveness of EDT impact on the residual stresses, structure evolution, accuracy and fatigue life of welded structures from light alloys [41].

Proceeding from the mechanism of electron-dislocation interaction for creation of the conditions for crystallization, which ensures formation of a fine-grained structure, development of the technology of welded joint modifying by nanostructured highly dispersed materials is believed to be promising. This will be the subject of further investigations of advanced methods of structural material treatment.

A mathematical model of EDT process was developed in order to assess the influence of electrophysical and dynamic components of electrodynamic impacts that determine the change of characteristics of residual welding stresses. This allowed optimizing the treatment modes, in order to control the stress-strain state of welded joints of aluminium alloy AMg6 [42–44]. Improvement of the current model will allow calculation of stress-strain state of welded structures under the conditions of concurrent heating of the weld, with different schemes of fastening the structure being treated, and at magnetic field impact.

Considering the results of [8], where it is shown that concurrent heating stimulates stress relaxation at electric pulse treatment of thin steel rods, it is promising to study the effectiveness of EDT of a cooling weld, which is performed during the thermodeformational cycle of welding. Development of hybrid technologies (automatic welding + EDT) will allow lowering the energy intensity of the treatment process, shortening the working time of metal structure fabrication at its improved quality [45].

Among the novel techniques of external impact on the quality of metal products, studies are actively performed of the action of constant magnetic fields (CMF) that are applied to the melt during its solidification, when producing cast billets and parts from nonferromagnetic materials, for instance, aluminium alloys. It is established that CMF action promotes the evolution of material structure, and increase of corrosion resistance. The structure forming mechanism is based on CMF action manifestations, namely refinement of structural components, change of intermetallic phase morphology, increase of their microhardness, change of their dimensions and configuration that corresponds to the processes of solidification at high cooling rates [46]. It should be noted that the liquid metal of the pool in fusion welding under certain conditions, is similar by its properties (at much smaller volume) to cast metal, i.e. is suitable for CMF treatment. Considering the conditions of formation of the pool rear edge, CMF treatment of cooling weld metal is promising, as a method to control the stressed state and structure of the joint metal. This can stimulate development of a promising method of CMF treatment of welded joints during the thermodeformational cycle of welding and can prompt development of hybrid technologies (automatic welding + CMF treatment) for nonferromagnetic metallic materials based on Al, Mg, Fe.

Modification of metals and alloys by doping the melt with nanomodifiers has a marked effect on crystallization, for instance, causes dispersion of the structural components and change of their distribution. Modifying improves the alloy mechanical properties. Quality characteristics of modifiers are the size of individual refractory particles, its chemical purity and price. A certain quantity of modifiers is manufactured by powder metallurgy methods, or with application of ball mills. It is known that the high-voltage electric discharge (HVED) in the dispersed system of metal powder + kerosene allows not only refining the metal particles, but also initiating chemical reactions. At HVED application the possibility of manufacturing highly dispersed nanostructured modifiers and their prices are attractive for their commercial application in metalworking. The technology of dispersion with HVED application is similar, by its acting mechanism, to EHPT method, shown above. It should be noted that scientific principles were developed for HVED treatment in kerosene of mixtures of Al, Ti powders, where dispersion and synthesis of refractory components, in particular TiC, $AlTi_3$, AlTi, Al_2Ti, Al_3Ti, Ti_3AlC, $TiAlC_2$, Ti_3AlC_2, Ti_2AlC and longsdaleite, take place [47, 48]. Alongside foundry, nanomodifying can be applied in the technologies of welding and surfacing by adding nanoparticles of refractory chemical compounds to the weld pool during laser and electroslag welding, and electron beam deposition. At surfacing with high-temperature resistant alloys based on iron, nickel and chromium and carbon steels, which are modified by nanoparticles, resistance of the surfaced tool exposed to cyclic temperature-force impact, is increased. At modifying by nanoparticles, transcrystallization zones in the deposited or welded metal are removed, dendrite dimensions are refined, morphology and topography of the strengthening phases are improved that promotes higher high-temperature strength and fatigue resistance of the alloys [49]. There are certain limitations for nanomodifying of metal at automatic and manual arc welding. The main problem for application of nanocomposites in fusion welding is adding the latter to the weld pool. One of the ways to solve this problem is development of advanced technologies of producing welding and surfacing consumables (electrodes, fluxes, flux-cored wires) with addition of highly-dispersed nanostructured modifiers, produced on the base of energy effective HVED method. This is a new approach to improvement of service characteristics of welded structures that is based on electric pulse processes.

Thus, the experience of many years of investigations of the impact of electromagnetic technologies on metals and alloys proves their applicability for controlling the stressed state, structure evolution, tribological and mechanical characteristics, extension of the service life of welded structures in different sectors of machine-building, metallurgical complex, aerospace and defense industry.

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