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Induction Heating during Magnetic Pulse Processing of Metals: Perspective Schemes and their Application

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Abstract
The paper, based on a review of modern literature, highlights the features of the processes of magnetic pulse processing of metals in traditional schemes of technological processes of modern industrial production. New directions of their development are noted, which provide for the transformation of the natural forces of repulsion of the metal of the processed object into the forces of magnetic-pulse attraction while reducing the operating frequencies of the existing fields. The physics of Lenz-Joule heat dissipation is described, the result of which is the induction heating of conductors by Foucault currents in an external electromagnetic field. Examples of the use of induction heating in modern industry are given. Schemes of practical realization of pre-induction heating are offered, which allow to use both autonomous devices for eddy current excitation and stationary connection for the same purpose of additional power source. The possibility of increasing efficiency by increasing the ductility of the metal when heated is noted, as well as its possible limitations associated with increasing the active resistance of metals during the growth of Lenz-Joule heat dissipation. It is offered to use the received results at a choice of design decisions for elements of new schemes of the equipment of magnetic pulse processing of metals.

INTRODUCTION

At the present stage of development of scientific and technological progress, advanced processing technologies based on the use of the energy of electromagnetic fields are increasingly being developed and applied. Devices of this type, without exaggeration, include installations of force action on processed objects (magnetic pressure), technical systems for heating conductive objects by induced currents, devices where various kinds of chemical reactions are initiated by electric fields, etc. [1–6].

From the point of view of practical importance, technologies stand out contactless processing of conductive objects by magnetic pressure forces and the creation of various temperature regimes due to induction effects. Conventionally, the methods of force action of pulsed electromagnetic fields on massive well-conducting objects are referred to as traditional magnetic-pulse processing of metals. Here, some success has been achieved in the implementation of such industrial operations as flat stamping, crimping of conductive pipes, their distribution and, finally, welding of dissimilar metals. The last operation is extremely relevant for modern industrial production. Its implementation required the creation of conditions under which sufficiently high collision velocities of the objects to be welded are achieved. A practically uniform intermediate boundary layer appears, which ensures the strength of the welded joint [7–10].

Recently, there has been a sharp increase in interest in induction heating in various spheres of human activity. Household needs are highlighted, as well as various repair technologies. Here, production operations are successfully developed for cleaning paint and varnish coatings, removing bolted joints, softening body elements of metal coatings to restore damaged surfaces, etc. [11–14]. The idea to use preliminary induction heating in magnetic-pulse processing of metals was proposed by I.V. Bely, L.D. Gorkin, L.T. Khimenko back in 1984. The authors of the proposal have developed and created a system that initiates the flow of current in the winding of the working tool until the moment of force action. Preliminary induction heating made it possible to significantly reduce the amplitudes of the forces of magnetic pressure on the processed objects.

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The purpose of this paper is to propose new directions of preliminary induction heating in modern magnetic-pulse metal processing as a way to increase the efficiency of these production operations, which manifests itself in improving the quality of their performance while reducing the required energy costs.

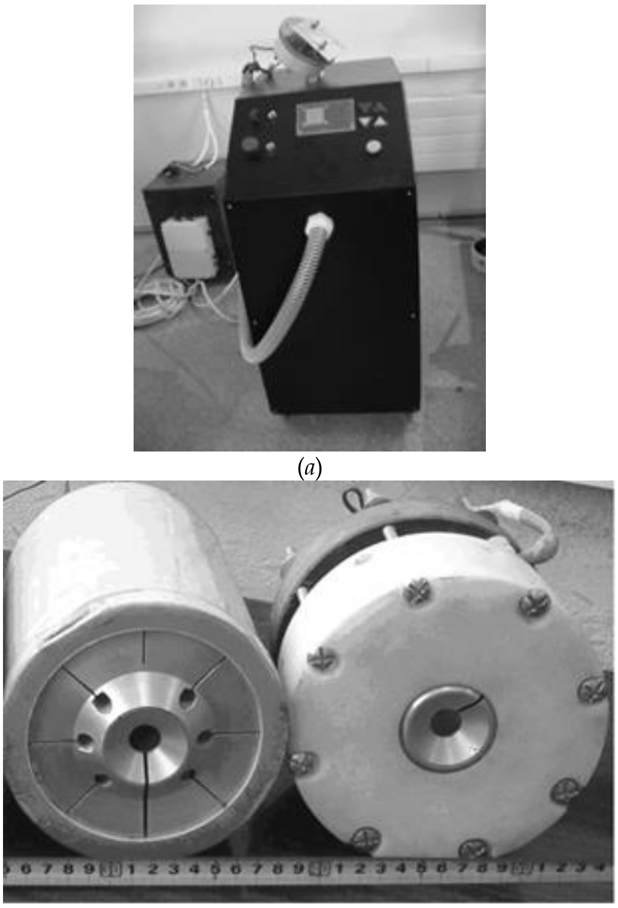
THE PHYSICAL ESSENCE OF THE ONGOING PROCESSES

MAGNETIC PULSED PROCESSING OF METALS (MPPM)

Metal processing technologies using the energy of pulsed electromagnetic fields are based on the phenomenon of their natural force interaction with conducting media. In practice, these technologies are implemented with the help of so-called inductor systems (Fig. 1), which are a combination of the actual inductor-tool (usually a flat or cylindrical solenoid) and an object subject to force. It is necessary to emphasize the peculiarity of the operation of such systems. It consists in the fact that the magnetic pressure is not carried out by any external tool (for example, a cutter in mechanical methods), but is the result of the mutual repulsion of the inductor field and the field of currents induced in the metal of the processed object. In the special literature, physics is also justified.

Omitting the details of the fundamental effectiveness, we can assume that the result of the interaction of the field of the inductor with the conductor is the excitation of the so-called Lorentz forces, the physical essence of which is the interaction of an electromagnetic field with a moving electric charge [15]. Returning to the specifics of field technologies in industry, we can point out that all the practically successful achievements of MPPM were mainly related to its traditional implementations in the period up to 1980. Without repeating the above, it is possible to note modern work on the improvement of traditional methods of excitation of magnetic pressure forces and their implementation in the operation of automated lines of industrial production of automobile and aircraft construction [1, 2].

New possible directions for the development of magnetic-pulse processing of thin-walled metals with a corresponding physical justification for each of them were first presented by the authors of publications [16–21]. The first of them involves the creation of a certain space-time distribution of the intensity of the excited field over the thickness of the object to be processed. In this case, the weakening of the magnetic pressure forces due to the effects of the penetration of the acting fields is leveled [16].



(*a*)

(*b*)

Figure 1. Typical equipment for magnetic pulse metal forming technologies [17, 18]: (*a*) magnetic impulse installation (2.4 kJ) – power source; (*b*) inductors – instruments of force attraction of ferromagnets

The second possible direction consists in the transformation of natural repulsion by Lorentz forces into attraction due to a decrease in the operating frequencies of the acting fields. This solution is sufficient for the treatment of ferromagnets. As for non-ferromagnets, their attraction is carried out due to the introduction into the inductor system an additional conducting a flat plate (screen) [17]. The principle of operation of such instruments is based on the excitation of oppositely directed induced currents in the screen and the object of processing. According to Ampere's law, in such systems their mutual attraction will take place [17]. The third possible direction suggests the transformation of repulsion into attraction using two-frequency (LF and HF) inductor systems. By design, high-frequency fields neutralize repulsion, and low-frequency fields neutralize attraction [16, 18]. Finally, the last possible direction was called the “direct current transmission method”. Its essence is as follows. The main current lead of the inductor is electrically connected to the section of the metal to be deformed, so that the connected conductors are parallel, and the currents flowing through them are unidirectional. According to Ampere's law, these conductors will experience attraction [19–21].

INDUCTION HEATING

A common factor in the causality of the success of the performed production operation, regardless of the method of magnetic-pulse force action, is, first of all, the plasticity of the metal of a given area of the object being processed [15]. From phenomenological considerations, the reliability of which is substantiated by calculations and experiments in the works of various authors, it is obvious that an increase in plasticity is possible with the help of induction heating by Foucault currents [22]. The specificity of the noted physical effect consists in the inhomogeneous distribution of the induced currents over the thickness of the conductor. The penetration of the magnetic field leads to their displacement into the surface layer (skin layer), as a result of which the eddy current density increases sharply, and this metal layer is intensely heated in the first place. The underlying layers are also warming up, but already due to thermal conductivity. Studies have shown that ~ 86.4% of the total amount of Lenz-Joule heat is released in the skin layer. In addition, the size of the skin layer, and accordingly the heating, also depends on the relative magnetic permeability of the metal of the processed object [22, 23].

A fairly large number of scientific publications are devoted to the development of the theory of induction heating. Without dwelling on their detailed listing and comments on the results obtained, as an example of research directions, we will give typical works where it is about the influence of current distribution on the integral efficiency of heat release not only in the metal of the processed object, but also in the winding of the exciting solenoid [24]. Thus, the authors of [24] calculated the induction heating of a conductor in the inner cavity of a cylindrical solenoid. The features that distinguish the processes under study in cases of flat and curvilinear geometry are shown. It is noted that they are conditioned by the penetration of excited magnetic fields.

From a practical point of view, the latest proposals of the scientists of the Kharkov National Automobile and Highway University (KhNAHU) to increase the intensity of the Lenz-Joule heat release in the metal of the object of processing are of interest [25, 26]. The authors of [25] theoretically and experimentally substantiated the advisability of introducing ferromagnets into the design of inductor systems. It is shown that, in the presence of ferrite filling, there is a significant increase in the amplitudes of the excited currents and it is possible to increase the intensity of the induction process by more than ~ 1.5 times. A Ukrainian patent was obtained for a method of processing sheet metals with concentrated sources of energy of magnetic fields with preliminary induction heating [26]. It should be noted that recently there has been a sharp increase in interest in induction heating in vehicle repair technologies. Here, production operations are successfully developed for removing glass, cleaning paint and varnish coatings, removing bolted joints, softening metal coatings of bodies before straightening dents, etc. [27–29]. Illustrations of the corresponding typical equipment developed at KhNAHU and engineers of the BETAG concern (Switzerland) are shown below in Fig. 2 [17].

(*a*)

(*b*)

Figure 2. Typical equipment for local induction heating in vehicle repair technology development of KhNAHU (Ukraine) [17, 28] (*a*): *1* – power source; *2* – connecting cables with heating tools; development of BETAG (Switzerland) [29] (*b*): *1* – power source; *2* – connecting cable; *3* – inductor-heating tool

PRELIMINARY INDUCTION HEATING IN MPPM

Schematic diagrams of the application of induction heating of sheet metals in magnetic-pulse technologies are shown below in Fig. 3. In Fig. 3, *a* shown the use of an autonomous induction heating system (for example, in Fig. 2). The algorithm for the implementation of the production operation involves the initial placement of the inductor-tool of induction heating on the processing area and the actual heating to the so-called tarnishing colors. After that, the power supply to the system is turned off, and the inductor-tool for induction heating is removed. In its place is placed an external inductor-tool of magnetic-pulse force action [30]. The inclusion of a current from the MPPM excites a strong magnetic field in the working area of the tool. Its effect deforms a given area of the processed sheet object, the plasticity of which is increased by preheating.

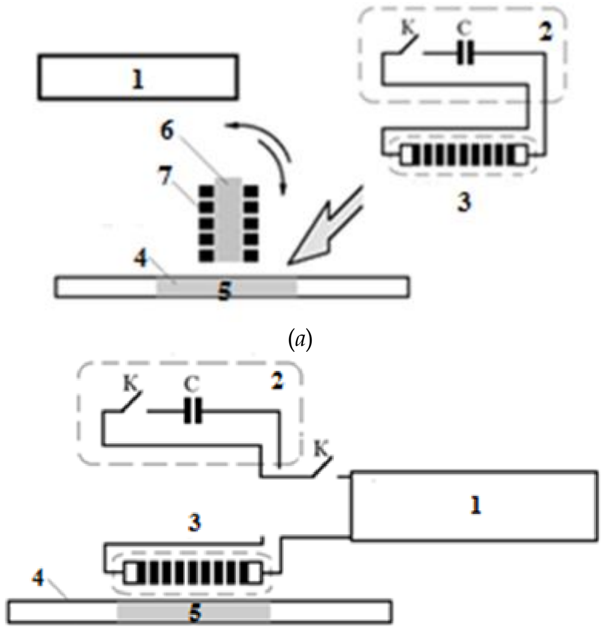


Figure 3. MPPM circuits with preliminary induction heating [17, 28], a separate autonomous induction heating system (*a*): *1* – power source; *2* – magnetic impulse installation; *3* – inductor – MPPM tool; *4* – sheet heating object; *5* – area of localization of heating and force action; *6* – ferrite; *7* – inductor-heating tool; induction heating system with connection to the winding inductor-tool MPPM (*b*): *1* – power source for induction heating; *2* – magnetic impulse installation; *3* – inductor-heating and MPPM tool; *4* – sheet object of processing; *5* – area of localization of heating and force action

An essential advantage of this circuit is the possibility of using inductors with ferrite inserts, which significantly increase the intensity of Lenz-Joule heat release.

In Fig. 3, *b* shown a diagram where the signal source for induction heating is connected directly to the winding of the MPPM inductor-tool. The algorithm for the implementation of the production operation assumes the initial switching on of the power source for preliminary induction heating of the given area of the force action. Then this power source is turned off. The current is connected from the magnetic-pulse installation. Excited pondermotor forces deform a given area of the treatment object.

It should be noted that in this scheme, it is impossible to include ferrite inserts in the design of MPPM inductor-tools. In addition, problems arise in matching the active-inductive load (the inductor itself) and the circuit of the power source for induction heating.

In conclusion, a phenomenological remark should be made about the effect of induction heating on the efficiency of MPPM. As is known, the excitation of eddy currents and an increase in temperature leads not only to an increase in the plasticity of metals, but also to an increase in their active resistance, which is the reason for a decrease in the actually induced currents and, accordingly, a decrease in the intensity of Lenz-Joule heat release. From physical considerations, it is obvious that in this regard, the highest efficiency of induction preliminary heating should take place only for metals in which the rate of increase in plasticity will exceed the rate of growth of their active resistance [17, 18].

CONCLUSIONS

The state and application of induction heating in modern magnetic-pulse processing of metals, as a way to improve the quality of its implementation, are briefly highlighted.

The schemes of practical implementation of preliminary induction heating are proposed, allowing the use of both autonomous devices for excitation of eddy currents, and a stationary connection for the same purpose of an additional source of electrical power.

The possibility of increasing the efficiency by increasing the plasticity of the metal upon heating is noted, as well as its possible limitations associated with an increase in the active resistance of metals with an increase in the Lenz-Joule heat release.

DISCLOSURE STATEMENT

No potential conflict of interests was reported by the author(s).

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Індукційний нагрів при магнітно-імпульсній обробці металів: перспективні схеми та їх застосування

Юрій Батигін, Євген Чаплигін, Світлана Шиндерук, Марина Волосюк

Анотація. У статті на основі огляду сучасної літератури висвітлено особливості процесів магнітно-імпульсної обробки металів у традиційних схемах технологічних процесів сучасного промислового виробництва. Відзначено нові напрями їх розвитку, які передбачають трансформацію природних сил відштовхування металу об'єкта обробки в сили магнітно-імпульсного тяжіння при зниженні робочих частот існуючих полів. Описано фізику розсіювання тепла Джоуля-Ленца, результатом якого є індукційний нагрів провідників струмами Фуко в зовнішньому електромагнітному полі. Наведено приклади використання індукційного нагріву в сучасній промисловості. Запропоновано схеми практичної реалізації передіндукційного нагріву, які дозволяють використовувати як автономні пристрої для збудження вихрових струмів, так і стаціонарне підключення з цією ж метою додаткового джерела живлення. Відзначено можливість підвищення ККД за рахунок підвищення пластичності металу при нагріванні, а також його можливі обмеження, пов'язані зі збільшенням активного опору металів при зростанні тепловиділення Джоуля- Ленца. Отримані результати запропоновано використовувати при виборі конструктивних рішень для елементів нових схем обладнання магнітно-імпульсної обробки металів.

Ключові слова: магнітно-імпульсна обробка металів, індукційний нагрів, схеми попереднього індукційного нагріву.

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