Inductor Hardening for Magnetic-Pulse Treatment of Tubular Parts

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Abstract. This paper focuses on the issues of modernization of standardized inductor construction for crimping tubular parts by the pulse electromagnetic field with the aim of increasing reliability of technique and its durability. There is given the description of the pilot model of the composite inductor for crimping tubular parts, as well as the results obtained during its test operation.

1. Introduction

High velocity forming methods that exist nowadays allow either to make more irregular parts for the less number of technological process steps or to make such parts that can’t be obtained by any other methods of forming. [1]. Another advantage of forming by the pulse electromagnetic field is the quality of obtained parts that also positively influences the durability of metal treatment [2], as well as the bonding made by the method of crimping. Besides, pressure made by the pulse electromagnetic field has no direct influence on the surface of the objects under manipulation and, as a result, there exist no damages made during that manipulation unlike other kinds of high-speed forming. The disadvantages of this method include a necessity of high electrical conduction for work and inductor materials that restricts materials under manufacture by copper and aluminum alloys.

Techniques for manufacturing by the pulse electromagnetic field, i.e. inductors, experience great mechanic loading. Apart requirements for high electrical conduction, additional severe requirements are imposed to the durability of inductor materials. Reliability of monolithic-type inductors is due to reliability of current-conducting coil material. Beryllium bronze is mostly used as inductor material, as it possesses good electric conductivity and satisfactory mechanic features as compared to copper alloys. For instance, the most suitable coil material for inductors designated for making parts from alloy of Type D16AM with the dynamic yield stress \( Y_0 \approx 200 \text{ MPa} \) is beryllium bronze with yield stress \( \sigma_T = 500 \text{ MPa} \). There should also be considered that by electromagnetic treatment the pressure of the pulse electromagnetic field can outnumber the number of the dynamic yield stress \( Y_0 \) to 1.5...2.0 times. Herewith, bronze should be of primary smelting as the secondary bronze is of less durability because of included gas and porosity that come into the bronze during the smelting. Extra high tensile alloys of Type V95 if and others can’t substitute bronze because of their poor longevity under impulse pressure. The making of current-conducting inductor elements from carbon and high-hardness steels is also
possible; however, such inductors are of extremely low transmission efficiency when translating the greatest part of electrical power into the heat one.

The essence of the electromagnetic treatment is based on the Faraday Law of Electromagnetic induction. Energy during the electromagnetic treatment is stored in the capacitor bank, thus the current electricity flowing in short terms during its discharge. In its turn this current makes magnetic field which is compatible with the current guided in the workpiece. This interaction leads to the generation of Ampere force deforming the workpiece. Figure 1 shows an equivalent electrical circuit of the electromagnetic installment and presents a plain discharge resistor circuit where dying oscillation happens with the frequency of few tens of kilohertz.

![Figure 1. An Equivalent electrical circuit of the electromagnetic installment.](image1)

Time varying magnetic field with value $B(0,t)$ penetrates into the metal of the workpiece, causing the eddy current, which current density $i$ and resultant magnetic field depend on the depth $x$ and time $t$ (Figure 2). To describe the interaction of electromagnet with metal we will consider the current distribution through the skin depth.

![Figure 2. Interaction of nonstationary magnetic field with metal element.](image2)

For a layer with its depth $dx$ Ampere and Faraday Laws can be formulated as follows:

$$i = -\frac{1}{\mu_0} \frac{\partial B}{\partial x}$$  \hspace{1cm} (1)

$$\frac{\partial E}{\partial x} = -\frac{1}{\mu_0 \gamma} \frac{\partial B}{\partial t}$$  \hspace{1cm} (2)

where $\mu_0$ – is a magnetic constant equal to $1.26 \cdot 10^6$ H/m, $\gamma$ – is conductivity, a reciprocal to electrical resistivity, $E$ – is electrical intensity, $B$ – magnetic field strength.
From (2) taking into account the ratio \( i = \gamma E \), where \( \gamma = \text{const} \) differential equations of the interaction of electromagnetic wave with metal are received:

\[
\frac{\partial B}{\partial t} = \frac{1}{\mu_0 \gamma} \frac{\partial^2 B}{\partial x^2} \tag{3}
\]

Time varying magnetic field with value \( B(0,t) \) penetrates into the metal of the workpiece, causing the induced current, which current density \( i \) and resultant magnetic field depend on the depth \( x \) and time \( t \):

\[
B(x,t) = B_m \cdot \exp\left( -\frac{x}{\Delta} \right) \cdot \sin\left( \omega t - \frac{x}{\Delta} \right) \tag{5}
\]

where \( \Delta \) – is the depth of electromagnetic field penetration into the material, equal to the distance \( x \), where magnetic induction amplitude and current density reduce \( e \) times; \( \omega \) – rate of phase change of the electromagnetic field.

High frequency current through the inductor section at MIOM is distributed unequally [1]. When the frequency of changes in external field \( \omega \) and metal conductivity \( \gamma \) increases electromagnetic field and current are concentrated in a thinner surface layer. The value of penetrating the electromagnetic field into the metal \( \Delta \) is called a “skin-layer”, and thus, it can be approximately considered that all currents coming through the inductor coil and workpiece material are concentrated in this layer of metal. Skin depth can be found with the help of expression (6).

\[
\Delta = \sqrt{\frac{2}{\mu_0 \gamma \omega}} \tag{6}
\]

According to the Ampere Law, force appearing in the unit volume of conductor is

\[
\vec{f} = \vec{j} \times \vec{B} \tag{7}
\]

The greatest intensity of the electromagnetic field can be defined when electromagnetic field pressure on the material is equal to the yield stress of inductor material.

\[
B_T = \sqrt{2\mu_0 p_m} \tag{8}
\]

when \( p_m \) – is material yield stress.

So, if the material of the inductor is copper M3, magnetic field strength is limited with volume 13.2 T. If it is an alloy of D16AT and beryllium bronze, then the created intensity of the electromagnetic field is limited with volumes 31.7 T and 22.4 T correspondently.

Operating frequency of current discharge of industrial installations for electromagnetic treatment is usually within the limits of 10 and 40 kHz, skin depth for copper and aluminum alloys under pulse electromagnetic field being less than 1 mm. Therefore, the weight of the inductor coil, that is mainly intended to guarantee the inductor and heat dissipation stiffness, has practically no influence on inductor electrical data of.

This paper focuses on one of the methods for increasing inductor durability at the expense of the composite construction which allows increasing operating pressure on the part under manipulation.
2. Results and Discussion

The construction of inductors for electromagnetic treatment is most commonly presented in the form of single- or multi-turn coils, made by mechanic work and either copper winding or copper alloys (brass) one [4,5]. Besides, inductors are additionally covered with the special bondage that prevents from fragment dispersion in case of inductor emergency destruction. Figure 3 presents a typical construction of flat multi-turn bronze. The given inductor is a multi-turn bronze coil of square section, embedded by polyurethane compound.

![Figure 3. Overall view of a multi-turn inductor with a square-angled coil.](image)

The division of the inductor coil into electric and power components allows increasing inductor stiffness and durability. In this case the electrical current flows through copper conducting loop, and the power impact of the electromagnetic field is accepted by the sound steel foundation. The main condition for effective work of such an inductor is a depth of copper layer, which must be at least 2 times thicker than a skin-layer at the operating frequencies of the electromagnetic installation.

The suggested conception can be realized with the help of a detachable single-turn coil inductor for crimping tubular parts (pencils of electric wiring harnesses) made according to OST 1 03967-81. The typical construction of a detachable single-turn coil inductor made from high-tensile-strength beryllium bronze OST 18175-78 became a basis for modernization. The inductor resistance of this construction is no more than 200 cycles, and then the destruction of the inductor happens. The main drawback of inductors of the suggested construction is rather high cost of beryllium bronze, as well as unrepairability of this construction – there appear thermal damages on the contacted surfaces while in service, that finally lead to the failure of the whole inductor. Inductor recycling or the recycled bronze usage reduces its resistance to 50-60 cycles.

Fig. 4 shows a modernized construction of a composite copper - steel inductor. Removable tapes from beryllium bronze play the role of the conductive part (3 and 4) 1.5 mm deep. The massive frame takes the power and thermal loading (1 and 2), which is made from steel alloy. The depth of conductive tapes is much higher than the skin depth at the operating frequencies of electromagnetic installment. Thus, the electrical current flows mainly through conductive tapes. The construction of the inductor allows changing malfunctioned copper tapes, whereas the amount of bronze used in the
The trial run of the given inductor has revealed no substantial differences as compared to the regimes (power stored in the capacitor battery), got for the inductor totally made from bronze [1]. The construction of the inductor withstand more than 250 technological cycles without the breakage of the inductor steel frame.

To identify the durability of the composite inductors it is necessary to carry out some trials on inductor, however, the received results proved the workability and importance of the suggested conception. Besides, on the basis of this conception it is possible to improve even more the construction of inductors for electromagnetic treatment, as well as to create a composite multi-turn coil inductor for sheet treatment by the pulse electromagnetic field.

3. Conclusion

References The following conclusions were made on the basis of the trial run of the suggested composite inductor construction:

1. The construction of the composite inductor proved its workability.
2. While using the inductor of the suggested construction there is no necessity in changing the regimes of electromagnetic treatment – trials have not revealed any changes as compounds made according to the OST 103967-81.
3. Durability of composite inductor is 25% higher than durability of the inductor, made from beryllium bronze.
4. The suggested construction allows an easy change of damaged busbars that reduces the operation costs.
5. The content of the high-priced bronze in the construction is 15 times reduced as compared to the typical inductor construction for analogous purpose.
References

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