Assembly of metal-composite compounds by magnetic pulse processing

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Abstract. The increasingly widespread use of composite parts in the industry also requires a special approach to the connections between composite and metal parts. One of these methods of forming permanent joints is magnetic pulse processing, which allows forming joints by acting on a metal part and pressing it on another composite one. Calculated the main electrical parameters of the magnetic pulse forming technology has been developed for manufacturing individual elements and assembly of the application structure, following the device structure is assembled.

Keywords: magnetic pulse deforming, high-speed plastic forming, composite items.

1. Introduction
Currently, composite materials are increasingly used in structures, which are used both for manufacturing sheet parts and for axisymmetric elements. At the same time, in many cases, composite materials must be connected to metal structural elements. When designing such joints, it is important for the designer to know the technical capabilities of production and to focus on the most modern technological processes of their manufacture. One of these methods of forming metal-composite compounds is magnetic pulse processing, which is successfully used for manufacturing axisymmetric tubular structures and parts by deformation and joining [1-3]. At the same time, the advantages of magnetic pulse deformation, such as the absence of direct mechanical contact between the tool and the workpiece, high accuracy of dosing the deforming force, high deformation rate, and the ability to distribute forces along the length of the forming workpiece, play an important role in the effectiveness of the method application [4-6]. The technological capabilities of magnetic pulse processing are quite wide, using various schemes of this method, it is possible to perform various sheet stamping operations [7-9]. The most characteristic parts of this symmetrical type are various connections of pipelines, pneumatic pipelines, connections of rods of tubular elements with endings, and similar. These parts are complex, mainly axisymmetric shapes, the production of which is carried out by various methods of plastic deformation, including magnetic pulse processing and welding [7-11].

2. Problem Statement, Work Result
The efficiency of deformation by a pulsed magnetic field depends on many parameters, primarily on the parameters of the magnetic pulse equipment, the electrical and mechanical characteristics of the workpieces, and their geometric dimensions. The scheme of magnetic-pulse action on axisymmetric workpieces and their assemblies is presented in Figure 1. The capacitor bank 2 is charged from the AC network through the step-up transformer 1 and the rectifier device. Then, after reaching the charging level set by the automation, the discharge device 3 is triggered and the accumulated energy is released in the tool – in our case, in a cylindrical inductor for crimping 4, designed to create a magnetic field of a certain spatial configuration. A high pulse current, flowing through the coils of the inductor, by the electromagnetic induction law induces in the deformable axisymmetric workpiece 5, which is a closed electromagnetic circuit, an inductive current directed opposite to the current in the inductor. The interaction between these oppositely directed currents leads to the appearance of electromagnetic forces that deform the workpiece. Under the pressure influence, the workpiece begins to move and acquires a certain speed with which it collides with the matrix, mandrel, or other workpieces, acquiring the appropriate shape. Thus, in this process, the energy of the electric field of the capacitors is converted
into the energy of the magnetic field of the tool-inductor, and then into the work of deformation of the workpiece and partly into heat. Since the actual shaping takes place very quickly, the operation time is mainly determined by the duration of charging the capacitors and the auxiliary time for replacing the workpieces. The pressure of the pulsed magnetic field is variable in time and is a decaying quadratic sinusoid, the pressure time is very short and the process is dynamic. The deformation velocity reaches 10...500 m/s. As a result of the deformation of the outer axisymmetric billet, it decreases in diameter, is compressed, and is connected to the inner axisymmetric billet. In some cases, to eliminate the deformation of the internal workpiece and distortion of its surface in the cavity of the crimped workpiece, stop the mandrel, which is made monolithic for small sizes or thick-walled.

In theoretical calculations of magnetic-pulse deformation, the law of pressure of the pulsed magnetic field is usually accepted in the following form \[5, 9\]:

\[
p = p_0 \frac{\Delta}{u + \Delta} e^{-\beta t} \sin^2 \omega t
\]  

(1)

where \(p_0\) — nominal pressure at \(t = 0\) and \(u = 0\);
\(\Delta\) — equivalent gap between the inductor and the workpiece;
\(\beta\) — damping coefficient;
\(\omega\) — circular current frequency;
\(t\) — time.

The equivalent gap is found from the expression \(\Delta = \Delta_r + \Delta_e\), where \(\Delta_r\) — the gap between the inductor and the workpiece; \(\Delta_e\) — a term that takes into account the magnetic field penetration into the inductor and the workpiece materials.

When crimping a tubular billet, the pressure \(p_0\) related to the equipment charging energy \(W_c\) by equation:

\[
p_0 = \frac{A}{4\pi\alpha(1 + h)h^2} \frac{W_c}{r^3} \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right] = g \frac{W_c}{r^3},
\]  

(2)

where \(r\) — blank radius;
\(\omega_0\) — equipment natural frequency;
\(p = \frac{\Delta}{r}\) — dimensionless equivalent gap;
\(\alpha = \frac{l}{2r(1 + h)}\) — dimensionless billet length;
\(l\) — billet length;
\(g\) — coefficient that considers energy losses.
\(A = 0.1 + 0.37\alpha \exp[-0.01(0.68Q_1 + 3.10Q_2)]\),
\(k = \left(1 + 0.224\sqrt{Q_2}\right)\exp(-0.175\alpha)\),

where \(Q_1 = \frac{\omega L_1}{R_1}\) and \(Q_2 = \frac{\omega L_2}{R_2}\) — quality factors;
\(R_1\) and \(R_2\) — ohmic resistances;
\(L_1\) and \(L_2\) — the inductance of the single-turn inductor and the workpiece, respectively.

Expressions are used to calculate them:

\[
L_1 = \frac{45.4 \times 10^{-7}(1 + h)r}{2.35\alpha + 1 + h}; \quad L_2 = \frac{45.4 \times 10^{-7}r}{2.35\alpha(1 + h) + 1};
\]

\[
R_1 = \frac{\pi}{\alpha} \sqrt{\frac{2\pi \times 10^{-7} \omega}{\gamma_1}}; \quad R_2 = \frac{\pi}{\alpha(1 + h)} \sqrt{\frac{2\pi \times 10^{-7} \omega}{\gamma_2}},
\]

where \(\gamma_1\) and \(\gamma_2\) — electrical conductivity of the materials of the inductor and the workpiece.
The coefficient $\beta$ is found from the expression:

$$
\beta = \frac{\omega}{L} \left( \frac{L_1}{Q_1} + \frac{L_1 - L}{Q_2} \right),
$$

(3)

where

$$
L = \frac{7.65 \times 10^{-7} \times h^0.6 (2 + h) r \times Q_2^2}{\alpha} + \frac{L_1}{1 + Q_1^2} + \frac{L_1}{1 + Q_2^2}
$$

More complex operations: assembly, forming into a matrix, forming through a transfer medium—are described by the equation:

$$
\frac{d^2 \varepsilon}{d \tau^2} + \arctg \left[ \frac{b \ln(1 + \varepsilon)}{1 + N(1 - \varepsilon) \left( \frac{1 + \varepsilon}{1 + \varepsilon} \right)} \right] + \frac{f(1 - \varepsilon)(\varepsilon - h_1)}{(1 + h_1)^2} \left[ 1 + \frac{N(1 - \varepsilon)}{(\varepsilon + h)(1 + N(1 - \varepsilon))} \right] (1 - \varepsilon) = \frac{mhe^{-\alpha\tau} \sin^2 \Omega \tau}{(e + h)(1 + N(1 - \varepsilon))}
$$

(4)

where $f$ and $N$ — dimensionless stiffness and mass of the substrate, matrix, or medium;

$h_1$ — dimensionless gap between the workpiece and the matrix.

However, the calculation method is mainly successfully used for the assembly of tubular metal structures, as for metal-composite compounds, in this case, more precise effects on the deformable workpiece are required. In turn, to perform metal-composite joints, it is necessary to apply an additional material-an adhesive layer and theoretical calculations require complex expressions, so it is much easier to perform process modeling, for this purpose, the characteristics of not only the material of the deformable outer billet but also the adhesive layer, as an incompressible liquid, as well as the data of the composite material itself and the support (mandrel) are introduced.
A model of a typical metal-composite joint is shown in Figure 2, where the inner axisymmetric billet made of composite material is highlighted in yellow, and the outer one is made of aluminum alloy. In more detail, the formation of a metal-composite compound under the influence of magnetic-pulse deformation is shown in Figure 3. The outer axisymmetric workpiece 1 is made of aluminum material, as the material most well deformed by the influence of a pulsed magnetic field, an annular protrusion 2 is made on one of the ends of workpiece 1. The internal axisymmetric blank 3 is made of a composite material (for example, by winding fiberglass), and the connection zone with the outer part is made thickened 4 with smooth transitions of the grooves 5, which prevent the destruction of the composite material in the process of contact with the outer deformable part and the conical part at the end of the thickening, performed, depending on the properties of the composite material with taper angles of 60, 75, 90 degrees. Inside the composite part, we insert a monolithic mandrel 6, which prevents distortion of the inner surface of the composite part in the joint area. An adhesive layer 7 is applied to the composite part in the joint area. And the effect on the outer axisymmetric workpiece is carried out in stages [10]. First of all, the outer axisymmetric blank is compressed in the zone I, which allows first to fix the outer blank 1 on the inner composite component (on its conical section), and then the impact of a pulsed magnetic field is produced in section II. As a result of deformation in this joint area, the outer workpiece is deformed, moves axially, and comes into contact with the inner part. Where there are protrusions on the inner part, the movement of the outer billet stops, and further movement occurs in the zones of smooth annular grooves and smooth transitions 8 are formed, providing high strength and tightness of the connection, and the outer billet is crimped at the first stage I along the mandrel and takes the form 9. After curing the adhesive mass, mandrel 6 is removed and the formed joint is checked for strength and tightness.

Figure 3. Scheme of a metal-composite compound formation

In turn, one of the main elements that experience significant dynamic loads are inductors, which must be made not only strong but also have the ability to transfer energy to a deformable axisymmetric workpiece with high efficiency. Multiple-acting inductors must have increased mechanical resistance to shock loads. This requirement comes into conflict with the desire to use materials with high electrical conductivity for their manufacture, and as is known, good conductors usually have low mechanical strength. The heat release that occurs when the current is discharged causes the inductor to heat up. Therefore, intensively working inductors are supplied with forced air or water cooling.

The key element of the inductor is a conductive spiral, the shape of which determines the configuration of the magnetic field. The spiral is made by winding or turning from a solid billet. For mechanical reinforcement of the inductor spiral, special bandages, ties, housings, etc. are used. To increase the efficiency of the inductor, its shape should be close to the shape of the workpiece to be
processed. For this purpose, special screens, inserts, and magnetic field concentrators are used, which increase the local magnetic field strength many times compared to the strength in other parts of the spiral.

The following design of such an inductor is proposed: inside the inductor case 1 there is a current-conducting spiral (not shown), which is compressed axially by the flange 2, current-carrying plates 3 and 4 are installed at the ends, which are attached to the flanges of the inductor spiral with the help of fasteners 5 and are fixed in the current outlets of the magnetic pulse installation.

**Figure 4.** Inductor for crimping.

**Figure 5.** The units shape after deformation.

Figure 5 shows samples of axisymmetric parts of different diameters obtained by crimping into annular grooves. The section shows that the deformable part has acquired the form of smooth annular grooves (transitions) of the internal composite part.

**Conclusion**

1. The calculations on the magnetic-pulse deformation of the external axisymmetric workpiece were carried out following the methodology. They allowed preliminary estimation of the required parameters of the annular grooves of the composite part and the required deforming force of the pulsed magnetic field.

2. A scheme for the formation of metal-composite joints of axisymmetric structures by deforming the outer billet along the inner one is developed. The deformation of the outer workpiece is carried out by the influence of a pulsed magnetic field, and to increase the strength and tightness of the joints, several annular grooves of a smooth shape are made on the composite part.

3. To improve the required characteristics of the joints, the impact of a pulsed magnetic field is proposed to be carried out in stages, with the initial fixation of the outer axisymmetric part on the inner part and subsequent deformation into the annular grooves of the composite part. The adhesive layer between the parts to be connected also helps to increase the strength and tightness of the joints, which also reduces the dynamic impact of the deformable zone on the inner surface.

4. The inductor design makes it possible to successfully implement a magnetic pulse effect with a minimum geometric gap between the tool and the deformable outer workpiece.

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