The influence of electromagnetic component of the process on the structure of dissimilar alloys in high-voltage capacitor welding

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Abstract. The article deals with the difficulties of obtaining welded structures from dissimilar alloys. It is proposed to minimize the time of thermal effect on the zone of connection of the details by using super-rigid modes in high-voltage capacitor welding. The study of the components of the process was carried out: the energy of thermal and mechanical effects on the connection zone, the ratio of these energies is recommended. The microstructure of the obtained compounds is described and the results of energy dispersion analysis are presented.

The complexity of manufacturing structures from dissimilar metals is associated with different thermal properties (melting point, thermal conductivity and electrical conductivity), chemical interaction (formation of intermetallic compounds, carbide and fusible eutectic), as well as different thicknesses of elements that affect the heat conditions and the structure of the welded joint.

To connect parts made of non-ferrous metals, it is recommended to use solid-phase impulsive welding methods characterized by relative local rates of plastic deformation $\dot{\varepsilon} = 10^{-4} - 10^{-5}$ s$^{-1}$ [1–3]. Depending on the temperature and the interaction time, diffusion processes can develop in the connection zone, sometimes reducing the quality of metal compounds with limited mutual solubility [3, 4].

To minimize the development of diffusion processes and to form a joint in the solid phase is possible by reducing the mixing of dissimilar metals in each other; reducing the residence time of metals at temperatures of formation of an unfavorable structure through the use of super-rigid modes of action.

One of the ways of welding, satisfying the above conditions is high-voltage capacitor welding (HVC) developed in DSTU [2, 5].

Features of HVC are the use of electromagnetic energy for the implementation of thermal and mechanical effects in the course of the discharge current through the welded parts and the use of induction-dynamic drive (IDD). The schematic diagram of HVC is shown in figure 1.

IDD is a set of inductor $I$ and pusher 3 of different mass. The pusher 3 is electrically isolated from parts 1 and 2 through the dielectric insert 4.

The accumulated energy in the capacitor banks of the impulse current generator (ICG) when the switching device is triggered causes the flow of current $I_d$ through the IDD, the connection zone and the welded parts 1 and 2, warming up the surface layers of metal, destroying oxide covers and other contaminants. A gap is formed equal to the height of the micro-irregularities, an impulse arc is
aroused, burning in the metal vapor, which initiates the cleaning of the surfaces to be joined. When the magnetic field lines $H$ interact with the induced currents in the pusher 3, there is a magnetic pressure $P_m$ in the working zone of the IDD, which brings the welded parts together. When parts collide, the molten metal with oxide covers and impurities is ejected from the contact zone to the periphery of the rod element under the action of a cumulative jet.

Sequential IDD connection with weldable materials allows to synchronize the process of thermomechanical effects of welded parts.

The aim of the research is to determine the influence of the controlled mass of the pusher on the structure of permanent copper-brass joints.

Experimental studies were carried out on flat samples of brass grade L63 thickness $\delta = 0.8$ mm with core elements of copper grade M01 diameter $D_r = 10$ mm. The capacity of the storage unit of ICG was $1800 \cdot 10^{-6}$ F, the frequency of the discharge current $f = 2600$ Hz. The operating voltage $U$ varied in the range of 2.0–3.3 kV, the mass of the pusher $M$ was 0.5; 1.0; 2.0; 3.0 and 4.0 kg.

For the criterion of the quality of the materials to be joined was chosen – the pull-off force parameter. The structure of permanent joints was investigated by metallographic and optical analysis.

The HVC process was implemented by sinusoidal damped discharge without preliminary formation of welded surfaces with their short circuit [6].

The nature of $I_d, P_m$ changes is shown in figure 2. Discharge current every $\frac{1}{2}$ of period $T$ changes polarity, magnetic pressure decreases over time.
The energy balance at the discharge of capacitor banks at HVC can be determined by the following ratio:

\[ W_{ESC} = W_h + W_m \]  

where \( W_{ESC} \) is the energy stored in an energy storage capacitor (ESC); \( W_h \) is the energy spent on heat generation in the connection zone (Joule heat, impulse arc combustion); \( J \); \( W_m \) is the energy expended on mechanical action parts to be joined, \( J \).

When substituting all components, the energy balance at HVC will take the following form:

\[ \frac{CU^2}{2} = (I_d^2R + Ul_dT_{d.p.}) + \frac{LI_d^2}{2} \]  

where \( C \) is the capacitance ESC, \( F \); \( U \) is the charging voltage, \( V \); \( L \) is the inductive reactance of the discharge circuit, which is determined mainly by the spiral inductor \( N \), \( H \); \( I_d \) is the discharge current, \( A \); \( R \) is the resistance of the discharge setting circuit; \( \Omega \); \( t_{d.p.} \) is the duration of the process of HVC, \( s \); \( t_{d.c.} \) is the duration of an impulse arc combustion under HVC, \( s \).

Preliminary calculations showed that to obtain permanent connections of dissimilar metals with the strength of not lower than \( (0.6\ldots0.8)\sigma_s \), the ratio of the energies must be \( W_s/W_m = (60\ldots70)\%/(40\ldots30)\% \).

One of the indicators of the magnetic field energy is the magnetic pressure generated by the inductor on the pusher, which can be determined experimentally by calculation [2]:

\[ P_m = \frac{B}{2\mu_0} \cdot \sin^2 \omega t \left( \frac{N}{m^2} \right) \]  

where \( B \) is the magnetic induction generated by the inductor, \( T \); \( \mu_0 \) is the magnetic constant, \( H/m \).

Registration of magnetic induction \( B \) in the working area of the IDD is produced by milliteslometer TPU-02 with a contactless measuring probe.

The magnitude of the specific magnetic pressure impulse \( J_{m.p.} \) (mechanical component of the HVC process) was determined experimentally by calculation:

\[ J_{m.p.} = \frac{P_m \cdot t_i \left( \frac{N \cdot S}{m^2} \right)}{N} \]  

where \( t_i \) is the time of interaction between welded surfaces, \( s \left( t_i \leq \frac{T}{4} \right) \).

The specific magnetic pressure impulse determines the relative degree of plastic deformation in the connection zone \( \epsilon_s \), which was calculated experimentally-by calculation on the macro-glyphs of welded joints. The cross-sectional structure of the welded joints and the phase composition of the joint zone were studied by micrographs using a scanning electron microscope (SEM) Carl Zeiss EVO 50.

Metallographic studies were conducted on experimental samples obtained by high-voltage capacitor welding. The microstructure of welded joints is shown in figure 3. Metallographic studies of samples at HVC showed the following. M01 grains have a polyhedral structure typical of the microstructure of annealed copper in the form of polyhedra of different geometry. In the vicinity of the connection zone (figure 3a), the zone of small grains of copper in the form of flat narrow crushed formations obtained in the solid phase under the influence of a short hard mechanical impulse is distinguished, as well as deformation doubles (crossing all fields of copper grain) characterized by intensive mechanical action at HVC. With an increase in the mass of the pusher, due to the inertia of the system, the thermal effect begins to prevail over the deformation (figures 3b, 3c). There are no oxide inclusions in the near-seam zone of copper, which does not prevent the growth of grains. The near-seam zone of brass is characterized by disoriented grains of \( \alpha \) phase of polyhedral shape and smaller grains of \( \beta \) phase (dark inclusions) penetrated by small-angle boundaries of narrow doubles. With a decrease in the interaction time of the contacting surfaces of \( t_i \) (figure 3a) by reducing the mass of the pusher, the grains of \( \alpha \) and \( \beta \) phases and doubles are oriented to the connection zone at angles not exceeding 90°. With increasing mass of the pusher (figure 3c) in the near-seam zone, there is a turn of grains in the flatness (parallel crystals of dark and light tones), the process of collective recrystallization develops due to crystallographic adjustment of individual verges of contacting grains and their increasing in size. Increased grain sizes indicate the intensity of the activation process of the contacting grain surfaces due to thermal deformation.
Figure 3. Microstructure of compounds of dissimilar alloys, brass at the top, copper at the bottom, with different weight of the pusher: (a) $M = 0.5$ kg; (b) $M = 2.0$ kg; (c) $M = 4.0$ kg.

Energy dispersion analysis of the distribution of chemical elements across the welded joint zone under low-intensity thermal effects on the transition zone metal revealed no diffusion of zinc into copper from brass, which indicates the formation of a welded joint in the solid phase (figure 4) [6]. As a result of the analysis of experimental samples, the degree of relative local plastic deformation $\varepsilon_l$ and the width of the zone of compounds $y$ depending on the specific magnetic pressure impulse $J_{m.p.}$ (figure 5).

Figure 4. Elemental composition of the compound of dissimilar materials (1-1-analysis zone).

Figure 5. The dependence of the relative local plastic deformation $\varepsilon_l$ and the width of the weld zone $y$ on the specific magnetic pressure pulse $J_{m.p.}$ at $W = 6.5$ kJ.
With an increase in the mass of the pusher, the impulse of the specific magnetic pressure increases, but at the same time, due to the high cooling rates of the connection zone, the relative plastic deformation decreases.

By increasing the inertia of the system with an increase in the mass of the pusher, the width of the thermal impact zone increases.

Summary. One of the technological methods that affect the structure of the weld zone in high-voltage capacitor welding of dissimilar nonferrous materials is the specific magnetic pressure impulse, characterized by the mass of the pusher of the induction-dynamic drive. Varying of the mass of the pusher allows to adjust the ratio of thermal and mechanical components of the HVC process. Recommended range \( W_h/W_m = (60-70)%(40-30)\%\). With the increase of the thermal component, in the structure of the compound grains take the form of broad formations. The prevalence of the mechanical component contributes to the formation of the structure in the form of narrow deformation doubles.

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