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MAGNETIC-PULSE WELDING OF COPPER RINGS WITH STEEL PARTS USING SINGLE-TURN INDUCTOR

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ABSTRACT

Magnetic-pulse welding is an innovative joining method that allows combining dissimilar metals. The article discusses weldability of copper rings with steel rods in order to study the possibility of using single-turn inductor. All specimens were welded with a discharge energy of 18 kJ. Significant deformations of copper rings were observed. Metallographic examination of welds revealed no defects. High-quality joining of metals in the welding zone with a characteristic wavy boundary interface was noted. However, to obtain more information on the exact mechanisms of weld formation, it is recommended to carry out numerical modeling of the process.

KEY WORDS: magnetic-pulse welding, cold welding, solid state welding, copper, steel, rings, microstructure, microhardness

INTRODUCTION

Magnetic-pulse technologies are increasingly used in modern industry and, in particular, in welding. They are characterized by a more dynamic growth of scientific and technical publications as compared to many conventional methods of welding [1, 2].

Magnetic-pulse welding (MPW) is the solid phase welding, which is performed as a result of the collision of joined surfaces under the action of the pulsed magnetic field of the inductor and the current induced by this field in metal parts. When the inductor current interacts (Figure 1) with the induced current, in a part repulsive forces arise between the inductor and a part. As a result, a part in the area under the inductor, receiving a high speed of movement, moves to a fixed part. The formation of a welded joint is provided by plastic deformations due to the collision of surfaces. The collision rate reaches hundreds of m/s, and the pressure in the contact zone reaches thousands of MPa [3, 4]. The general scheme of the MPW process of cylindrical parts is shown in Figure 1.

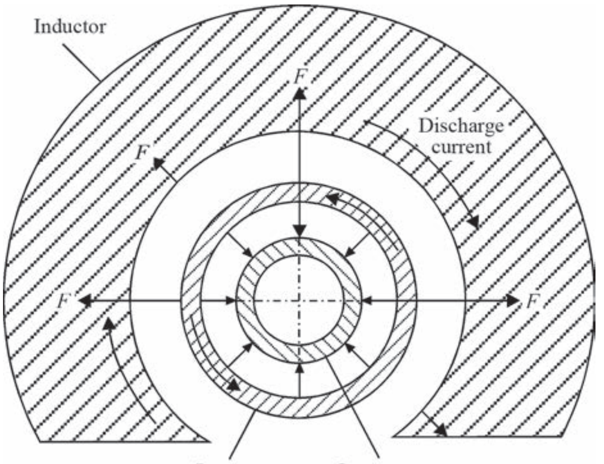

Figure 1. Process diagram for MPW of cylindrical parts

The following advantages of the technology are distinguished: welding of both similar and dissimilar metals; absence of thermal deformations; high speed of welding (pulse duration ~30 μs); high quality of welding and repeatability of results; low energy consumption (approximately 10 times lower than in MIG welding); possibility of process automation; possibility to produce rectilinear welded joints up to 3 m length. The MPW process does not require the operation of cleaning parts, consumables (welding wire, gases) and local exhaust ventilation due to the absence of harmful emissions. It should also be noted that conventional methods of welding rings with cylindrical parts do not meet the needs of modern industry in terms of manufacturability, quality, efficiency, price and environmental impact. From this point of view, MPW technology is the technology of choice for many cases. This is especially true when parts operate in a tribological friction pair “copper ring – steel cylinder” and where high requirements are specified to the absence of solid inclusions in the material of rings and the requirements to process efficiency.

All this initiated a number of activities within the framework of UN and the European Union and led to the foundation of a large-scale international project JOIN’EM, which aims to study some aspects of magnetic-pulse welding [5–7].

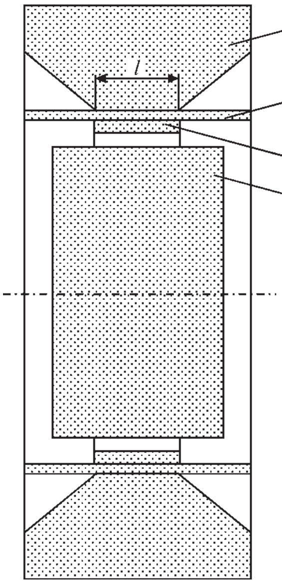

Figure 2. Scheme of single-turn inductor with workpieces before welding: *1* — inductor; *2* — insulator; *3* — copper ring; *4* — steel workpiece — target

Figure 3. Installation H-126A for magnetic-pulse welding

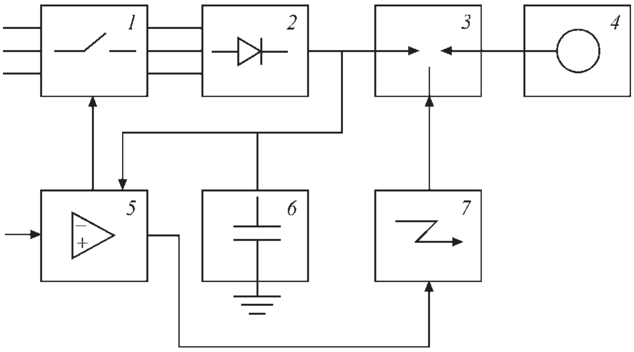

Figure 4. Structural block diagram of design of H126 installation: *1* — controlled network switch; *2* — high-voltage rectifier; *3* — controlled gas-discharge switch (trigatron); *4* — working inductor; *5* — automation unit with manual voltage adjuster; *6* — unit of high-voltage power capacitors; *7* — controlled arc ignition unit (oscillator)

Figure 5. Laboratory inductor

Most scientific and technical publications on this topic are devoted to MPW of cylindrical parts (tube-to-tube, tube-to-rod) [8, 9] using multi-turn inductors and magnetic field concentrators. Taking into account some differences in the processes of deformation of tubes and rings in MPW and increased energy losses when using such inductors with field concentrators, the authors proposed to use single-turn inductors (Figure 2) for welding parts such as “copper ring – steel rod/tube”, which allows producing a quality joint at a discharge energy of less than 35 [9] and 20 kJ |8].

It is also relevant to realize the MPW process on metals and alloys of domestic production, the composition and properties of which often differ from those analogues produced abroad.

MATERIALS, EQUIPMENT AND RESEARCH METHODS

The study was performed using a modified installation H-126A (Figure 3). This installation was designed by the E.O. Paton Electric Welding Institute and was the first MPW installation certified at the EU, manufactured by a commercial batch.

When conducting metallographic examinations, a procedure was used that includes metallography — optical microscope Neophot-32, durometric analysis — hardness tester M-400 of LECO Company at a load of 0.098 and 0.249 N.

The structural scheme of the design of H-126A is shown in Figure 4.

Table 1. Chemical composition (wt.%) of the material 3sp steel, DSTU 4484:2005/GOST

C	Si	Mn	Ni	S	P	Cr	N	Cu	As
0.14–0.22	0.15–0.3	0.4–0.65	≤0.3	≤0.05	≤0.04	≤0.3	≤0.008	≤0.3	≤0.08

Table 2. Chemical composition (wt.%) of the material M1 copper. DSTU EN 1057: 2016

Fe	Ni	S	As	Pb	Zn	O	Sb	Bi	Sn	–
≤0.005	≤0.002	≤0.004	≤0.002	≤0.005	≤0.004	≤0.05	≤0.002	≤0.001	≤0.002	Cu+Ag min 99.9

Figure 6. Specimens joined by MPW

The process of measuring current was performed according to a new method proposed at the PWI, which is supposed to be an alternative to the conventional method, using the so-called Rogowski coil. The measurements used a high-speed USB oscilloscope DATAMAN 570 and the corresponding software for processing and post-processing of the obtained data.

For the study of joints of dissimilar metals produced by the MPW method, cylindrical specimens with an outer diameter D_{out} — 26.3 mm of 3sp steel (Table 1) and rings of copper of grade M1 (Table 2) with an outer diameter D_{out} — 30.6 mm, inner diameter D_{in} — 28.6 and width of 7 mm were prepared.

A laboratory single-turn inductor (Figure 5), insulators and specimen aligning fixtures were also manufactured.

RESULTS OF RESEARCH AND DISCUSSION

The process of welding-on rings of M1 copper to steel specimens of 3sp steel (Figure 6) was carried out at a charge voltage on the battery of 18 kV capacitors. The total capacitance of the capacitors was 115 μF. Current switching was performed using a controlled arc discharger of “trigatron” type. The width of the working turn of the inductor was 6 mm. From the experience of previous experiments it was found that for a given geometric configuration of parts, the optimal gap between them is 1.15 mm. Before the process of welding the specimens, the pulse current was registered on the inductor without a workpiece and with a workpiece (Figure 7).

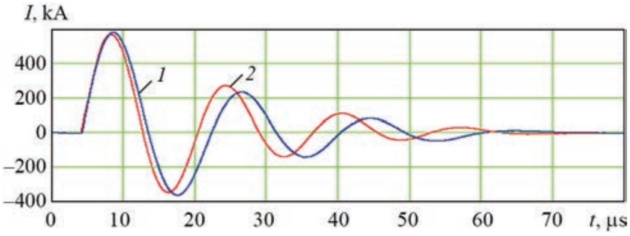

Figure 7. Oscillograms of currents in MPW at a charge energy of the capacitor battery of 18 kJ: *1* — inductor without a workpiece; *2* — inductor with a workpiece

The appearance of the specimens after welding indicates the presence of significant plastic deformation of copper rings (see Figure 6).

Metallographic examinations showed that when joining copper rings with a wall thickness of 1 mm and a width of 7 mm with cylindrical steel surfaces, the areas of linear joining of 2.3–5.0 mm size with a wavy-tooth line of the zone of this joint are observed. The relief and

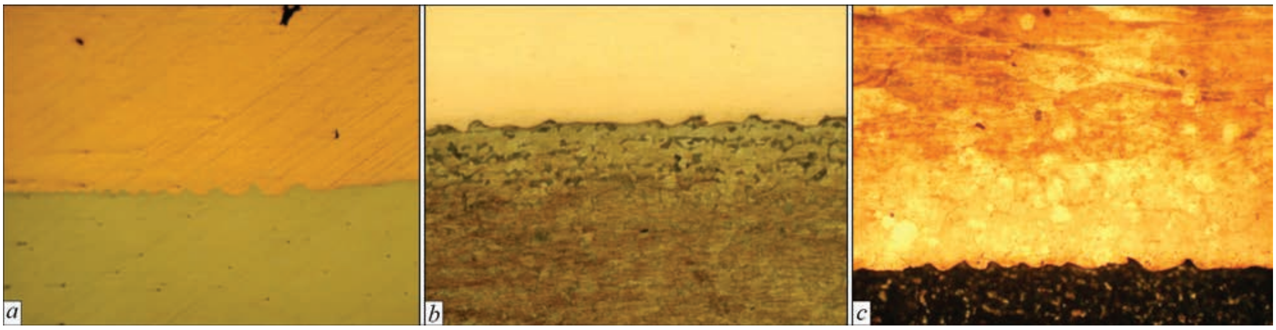

Figure 8. Macro- (*a*) and microstructure (*b*, *c*) of copper-steel joints produced by MPW method

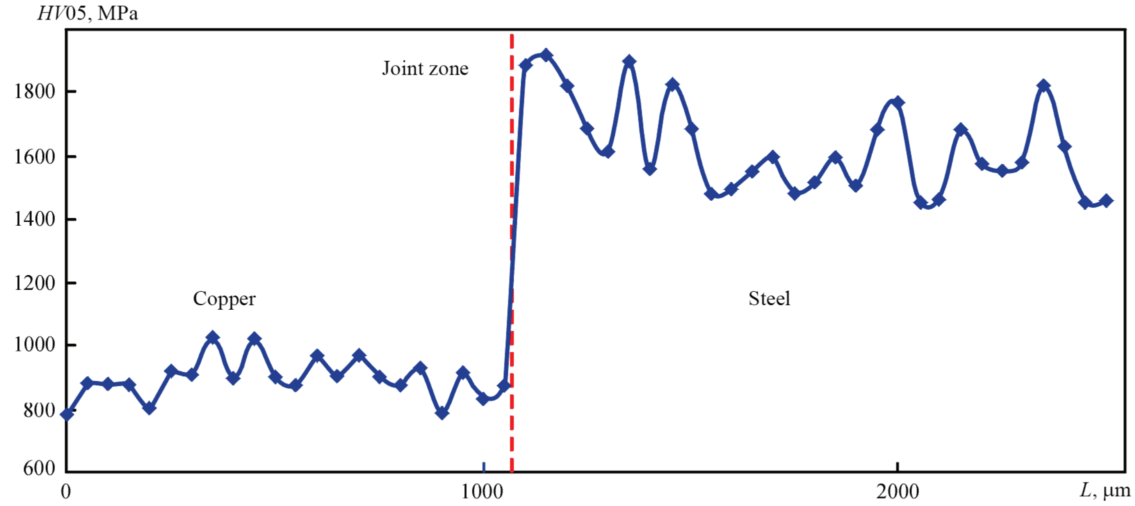

Figure 9. Diagram of change of microhardness of copper-steel specimen after MPW

geometrical characteristics of the joint line area depend on the welding process parameters (discharge energy, gap between parts, etc.) and design of the inductor [10, 11]. The height of teeth in the joint area was 10–30 μm (Figure 8, *a*). The thickness of the welded-on copper layer was 0.96–1.16 mm. This difference in thickness is caused by the influence of the nonuniform magnetic field of the working zone of the inductor. In the joint zone on the side of copper, changes in the metal structure were recorded — rounded grains with a diameter of 20–80 μm at a distance of 270–500 μm from the joint zone are observed. Rounded grains are located near the joint area. Moving further from this area, their number decreases and the structure turns into large deformed copper grains with twins (Figure 8, *c*).

The microhardness of copper in the joint area is 1344 MPa (Figure 9), which almost does not differ from the total hardness of the copper layer — 1361 MPa, the microhardness of rounded grains is 3–5 % higher (~1382 MPa) than that of large deformed grains (~1361 MPa).

In the joint area on the side of steel to a depth of ~ 50 μm, a ferrite band was recorded. Its average microhardness in the joint area is 2058 MPa, which is 16 % higher than the microhardness in the centre of a steel part, being 1777 MPa. Further changes in the banded ferrite-pearlite structure are not observed (Figure 8, *b*).

CONCLUSIONS

The weldability of copper rings to steel rods was investigated in order to study the possibility of using a single-turn inductor. A high-quality joint of copper rings of 1 mm wall thickness with steel cylinders was produced with the use of discharge energy of up to 18 kJ.

Metallographic analysis revealed a high-quality joint of copper rings with steel parts with a two-zone shape of joining, as well as structural changes in the weld zone, while the microhardness of steel within this zone increases in average by 16 %.

In the future, investigations will be conducted to study the effect of different process parameters (gap between parts, energy and discharge frequency) on the strength and metallographic characteristics of Cu–Fe welds.

To gain a better understanding of exact mechanisms of welding, effect of ring wall thickness on weld formation, and deformation of components, numerical simulation should also be performed.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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