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APPLICATION OF MAGNETIC-PULSE WELDING TO JOIN PLATES FROM SIMILAR AND DISSIMILAR ALLOYS

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The paper provides analysis of the state-of-the-art and confirmation of the relevance of studying the process of magnetic-pulse welding (MPW) of flat parts from similar and dissimilar metals. Results are presented of studying the possibility of performance of magnetic-pulse welding of flat samples in a modified batch-produced N-126A unit, using an experimental flat rectangular inductor. Process scheme is given. Technology is described for producing joints of flat metal parts 1.0–1.5 mm thick of similar materials of A5N and AMG2 alloys, as well as dissimilar materials – copper, A5N alloy and ANG2 alloy to 12Kh18N10T stainless steel (cold-worked). Conducted metallographic studies showed that a common feature for MPW of similar and dissimilar metals is specific bonding of welded plates in the zones (regions) equidistant from the center of the inductor flat turn. Thickness of mobile plates becomes smaller, and microhardness in the welding zones becomes higher. Sound welding was found within the two-zone joint shape. Welded joint quality was assessed by the results of mechanical strength testing. 10 Ref., 1 Table, 9 Figures.

Keywords: magnetic-pulse welding, cold welding, solid-state welding, microstructure, microhardness

The objective of the work is to study the current tendencies in development of the technology of magnetic-pulse welding (MPW), investigation of the possibility of high-quality MPW of flat samples from similar and dissimilar metals and alloys produced locally, and metallographic examination of welded joint formation.

MPW (magnetic-pulse welding) is a relatively new technology, compared to the traditional welding methods. It is a process of solid-state cold welding of conductive metals, in which the impact of pulsed inductor magnetic field is used. At interaction of inductor current with induced current repulsion forces arise between the inductor and part. As a result, the part, gaining a high movement speed, moves towards the stationary part. Collision of the surfaces leads to considerable plastic deformations, which ensure the welded joint formation. Collision velocity is higher than 300 m/s, and pressure in the contact zone is up to 10^2–10^4 MPa [1].

Today there are already enough examples of industrial application of MPW in manufacture of hull structures of vehicles, in aerospace sector, nuclear power engineering, defense industry complex, etc. [2].

This technology is of special interest in manufacture of hull structures of vehicles, primarily due to the possibility of joining dissimilar metals. Here, the following advantages of the technology are pointed out: welding of similar and dissimilar materials to each other, complete absence of thermal deformation, high welding speed (pulse duration ~ 30 μs), high welding quality and repeatability of the results, low power consumption (~ 10 times less than in MIG welding), possibility of process automation, and of making rectilinear welded joints of up to 3 m length. At MPW there is no need for the operation of part scraping, for consumable materials (welding wire, gases) or local exhaust ventilation, due to the absence of harmful emissions.

Specialists say that deep introduction of MPW allows developing lighter weight frames and other elements of car structures from dissimilar metals that will lead to lowering of their weight to 70 %, as well as reduction of fuel consumption by 10 %. It will promote reduction of harmful emissions into the environment, also in car manufacturing («green technology») [3]. Experts also claim that MPW potential is very high, and real mass deployment is anticipated in the next few years [4]. At present, starting from the moment of invention of this technology, the majority of works have been related to MPW of the bodies of revolution. The process of MPW of flat parts was proposed relatively recently, and the number of publications on this subject over the last years has increased, but very slowly. In our opinion, researchers are not in a hurry to disclose the technicalities of the process.

This, however, does not diminish the relevance of the topic. This is indicated by creation within the EU framework of a major JOIN'EM project [5], aimed at studying the processes of welding dissimilar metals (predominantly copper-aluminium, including flat

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Figure 1. N-126A unit

items) by MPW. This project was founded in 2017, and operates within the EU Horizon 2020 Research and Innovation Programme [6]. That is, for the first time in modern welding history, a decision was taken on the European interstate level to support studies of MPW as a technology, which the most completely meets tomorrow's challenges.

Reduction of structure weight is one of the ways to achieve this correspondence. Successive replacement of traditional iron-based alloys by light and special alloys, as well as their combinations with the traditional materials is one of the main trends of modern industry. Technologically, this raises the problems of joining dissimilar metals, which cannot be done by the traditional fusion welding methods. Another significant factor that fuels the interest to technologies of dissimilar metal welding now is the problem of replacement of parts and products from copper and copper alloys by hybrid copper-aluminium products [7], which are joined by welding in the cold state. In this case, none of the fusion welding processes can guarantee a sound joint.

The relevance of this topic is due to copper being a more expensive metal, compared to, for instance, aluminium (approximately 2 to 4 times). Its cost is rising continuously because of a rapid growth of the demand for it practically in all the sectors of economy, particularly, in electric engineering, electronic and power generation industry. At the same time, aluminium is very close to copper in terms of heat conductivity and electric conductivity (~ 60 %), at much lower specific density (~ 30 %) and cost.

Research work performed at PWI resulted in development of MPW techniques for flat metal parts and producing samples, using this process. Realization of MPW process on locally produced metals and alloys is also relevant, their composition and properties often differing from their foreign analogs.

In order to conduct the experiments, batch-produced unit N-126A (Figure 1), manufactured by PWI Pilot Plant of Welding Equipment, was upgraded for MPW of cylindrical parts. In particular, changes were made in the electric diagram, design of high-voltage current conduits and arc discharger.

Experiments were conducted at charge voltage of 10–18 kV, at maximum current of 200–500 kA. Current was switched using controlled arc discharger of «trigatron» type. Total capacitance of the capacitors was equal to 115 μF. Width of inductor working turn was 5 mm. Current was measured, using super high-speed USB oscilloscope DATAMAN 570 and respective software for processing and post-processing of the obtained data.

General scheme of the process of MPW of flat parts from one side with application of single-turn E-shaped inductor is given in Figure 2, and the scheme of movement of the part being welded is shown in Figure 3.

Flat samples of metal alloys 1.0–1.5 mm thick were used in the work. Qualitative approach was applied for evaluation of the results.

Appearance of some samples joined by MPW, is shown in Figure 4.

Plates of aluminium alloys A5N and ANG2, copper of grade M1 and cold-worked stainless steel 12Kh18N9T were used to produce joints of similar and dissimilar metals by MPW method.

A5N is a ductile, corrosion-resistant alloy, with minimum content of additives. Alloy composition is

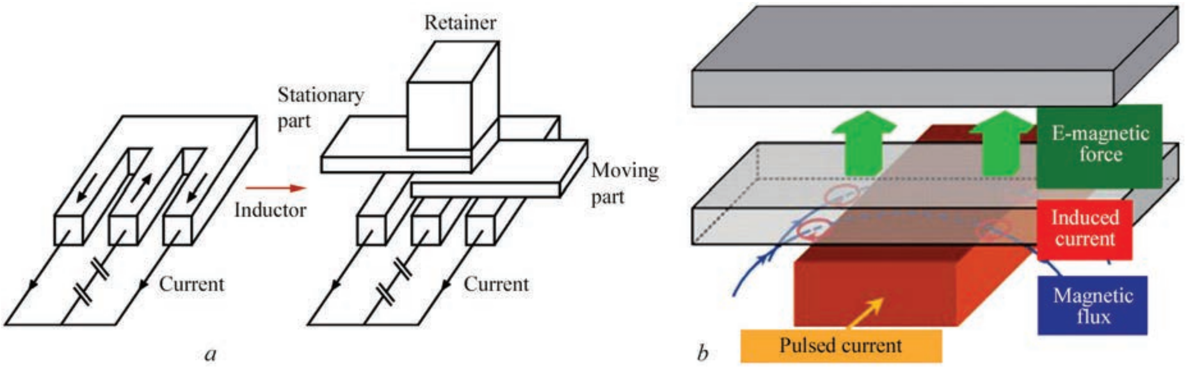

Figure 2. General scheme of the process of MPW of flat parts

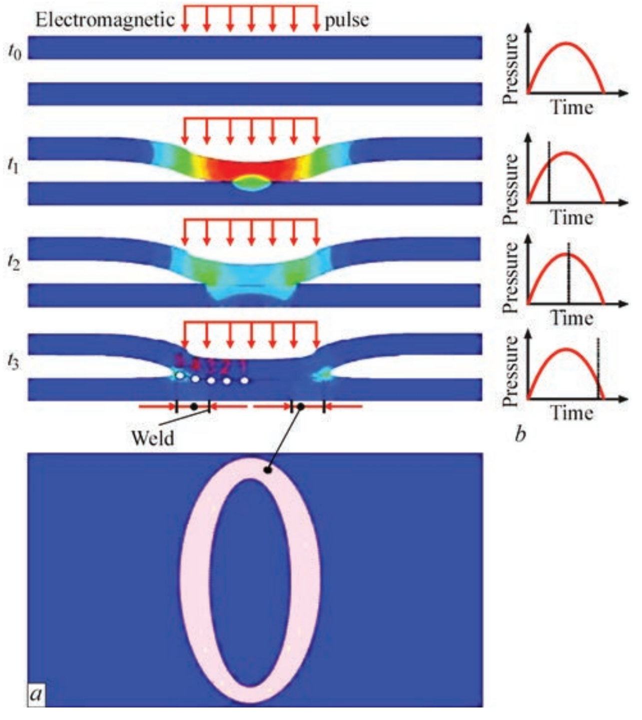

Figure 3. Scheme of movement of the part being welded (*a*) and welded zone shape (*b*)

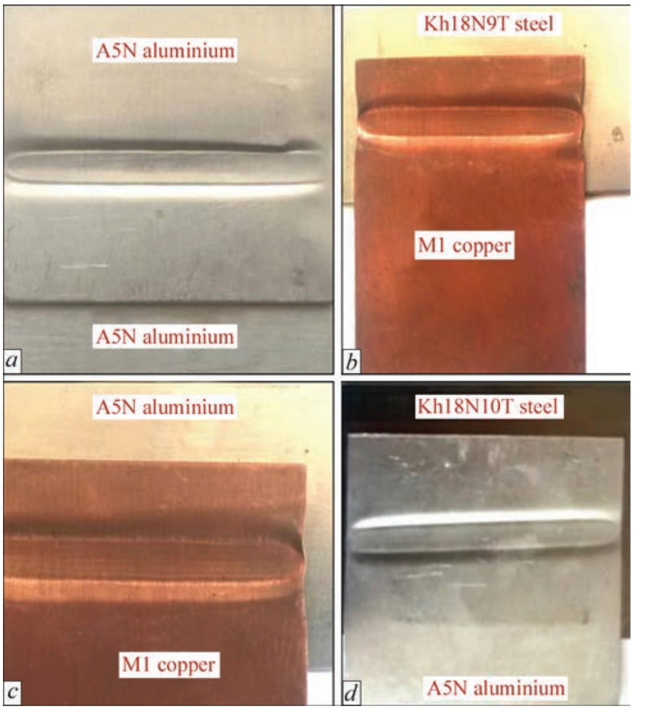

Figure 4. Appearance of flat samples, bonded by MPW: *a* — similar; *b–d* — dissimilar metals

as follows, wt.%: > 99.5 Al; < 0.3 Fe; < 0.25 Si and other additives (Ti, Mn, Cu, Mg, Zn, Ga). «N» means the cold-worked state, i.e. owing to additional treatment the sheets acquire higher rigidity, but have lower elasticity. Alloy microhardness is equal to 465 MPa. AMG2 is a wrought aluminium alloy. It composition is as follows, wt.%: > 95.7–98.2 Al; 1.7–2.4 Mg and other additives (Fe, Ti, Mn, Cu, Cr, Zn), 0.15 all together. Alloy microhardness is equal to 605 MPa. M1 is oxygenfree copper, which contains, wt.%: 99.95 Cu; 0.003 O_2, 0.002 P. Copper microhardness is equal to 890 MPa. Cold-worked 12Kh18N9T is stainless steel, which is corrosion- and heat-resistant, containing the following alloying elements and additives, wt.%: ≤ 0.12 C; 17.0–19.0 Cr; 8.0–9.5 Ni; 0.80 Ti; ≤ 0.8 Si; ≤ 2.0 Mn; ≤ 0.020 S; ≤0 .035 P. Steel microhardness is equal to 4630 MPa.

Investigations were conducted with application of a procedure, including metallography — NEOPHOT-32 optical microscope, durometric analysis — hardness meter M-400 of LECO at 0.098 and 0.249 N load. Chemical etching of metallographic sections was conducted using the following reagents: 50 % aqueous solution of HNO_3 (detection of copper struc-

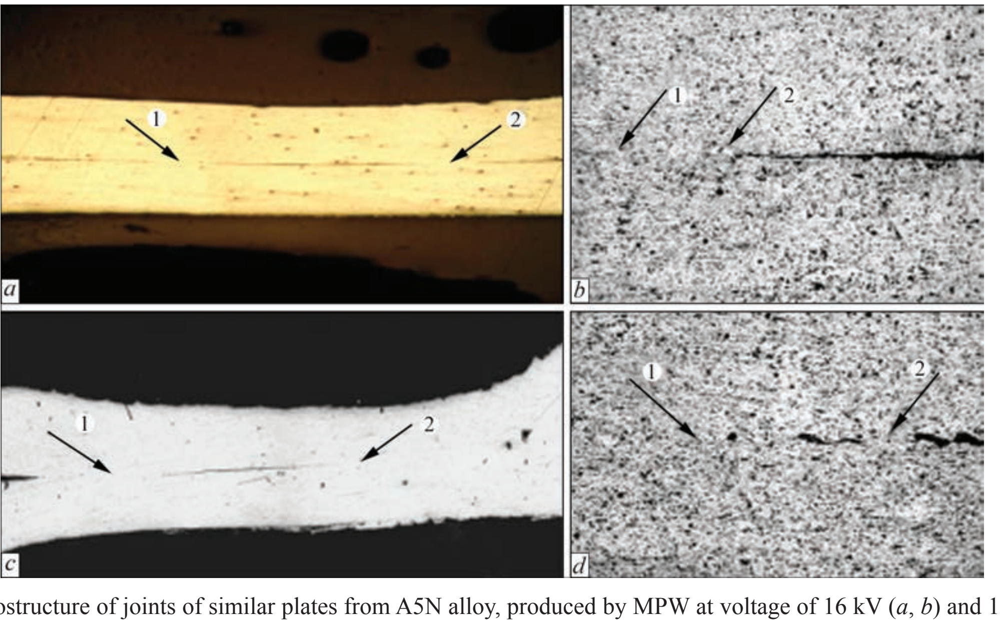

Figure 5. Microstructure of joints of similar plates from A5N alloy, produced by MPW at voltage of 16 kV (*a*, *b*) and 18 kV (*c*, *d*): *a*, *c* — ×25; *b, d* — ×400 (etched)

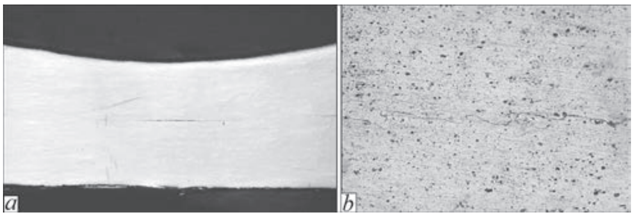

Figure 6. Microstructure of joints of similar plates of AMG2 alloy at voltage of 18 kV: *a* — ×25; *b* —×400 (etched)

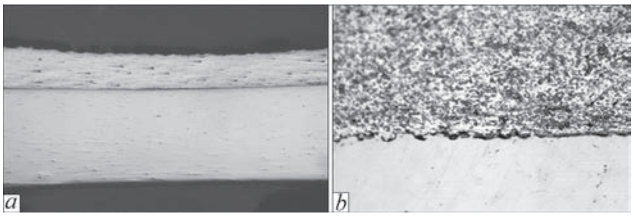

Figure 7. Microstructure of a joint of dissimilar plates of alloy AMG2 and stainless steel Kh18N10T, produced by MPW at 18 kV voltage: *a* — ×25; *b* —×400 (etched)

ture); HNO_3:HCl:H_2O in the ratio of 3:1:1 (detection of aluminium alloy structure).

A common feature for MPW of plates of similar and dissimilar metals is specific bonding of welded plates (Figure 3, *b*; Figure 5, zones 1, 2) in two zones (regions), equidistant from the center of inductor flat turn [8–10].

In welding plates of aluminium alloy A5N at 16 kV voltage, bonding occurred in two regions of 0.52 mm length, located at 1.02 mm distance from the center of inductor flat turn. Plate thickness in these regions was reduced for the upper and lower plates by 20 and 24 %, respectively, compared to initial thickness (1.0 mm). Microhardness of the moving and stationary plates increased by not more than 3 %, compared to initial state of the alloy (*HV*0.1 – 465 MPa, see Table). At MPW higher voltage (18 kV), the length of bonding regions increases up to 1.72 and 2.32 mm. Thickness of both the plates is reduced by 30 %, hardness increases up to 9 % (Figure 5, see Table).

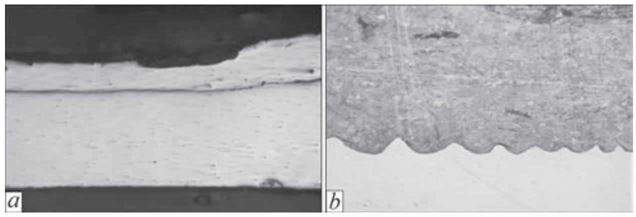

Figure 8. Microstructure of a joint of dissimilar plates of copper M1 and stainless steel Kh18N10T, produced by MPW at the voltage of 18 kV; *a* — ×25; *b* — ×400 (etched)

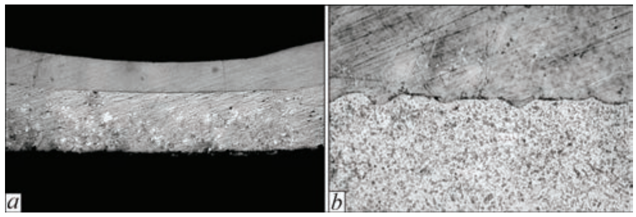

Figure 9. Microstructure of a joint of copper (M1) and aluminium alloy A5N

In welding AMG2 alloy, having a higher hardness (607 MPa) than that of A5N alloy, two bonding areas of the length of 1.28 and 1.04 mm at 1.06 mm distance from the center of pulse impact are found. Compared with the initial state, thickness in the bonding zones decreased by 20 %, and microhardness increased to 32 % (Figure 6, see Table).

In welding dissimilar metals — aluminium alloy AMG2 to stainless steel 12Kh18N10T, two wavelike bonding regions of 1.4 and 1.0 mm length were observed at 1 mm distance from the center of discharge initiation. Microhardness of moving plate of AMG2 somewhat increases (3 %), and that of stainless steel remains practically unchanged. Thickness of moving plate decreases by 38 %, and that of stationary plate does not change (Figure 7, see Table).

At MPW of plates from copper of grade M1 (moving) and stainless steel 12Kh18N10T (stationary), bonding is observed in two regions of 0.5 and 0.4 mm

Characteristics of MPW joints

Joined materials (grade)	*U*, kV	Gap between the plates, mm	Plate thickness, mm		Distance from the center, mm	Joint regions, mm		*HV*01 BM, MPa	*HV*01, in joint regions, MPa
			Before MPW	After MPW		I	II		
Al A5N / Al A5N	16	0.8	1 / 1	0.80 / 0.72	1.02	0.52	0.52	465	(I) 478 (II) 468
Al A5H / Al A5H	18	0.8	1 / 1	0.44 / 0.44	1.00	1.72	2.32	462	(I) 502 (II) 478
Al AMG2 / Al AMG2	18	1.0	1 / 1	0.80 / 0.88	1.06	1.28	1.04	607	(I) 804 (II) 736
Al (AMG2) / Steel (12Kh18N9T)	18	1.0	1.0 / 1.5	0.62 / 1.50	1.00	1.40	1.00	515 / 4630	(I) 530 (II) 496
Cu (M1) / Steel (12Kh18N9T)	18	0.8	0.8 / 1.5	0.46 / 1.50	1.20	0.50	0.4	891 / 4630	(I) 1078 (II) 1200
Cu (M1) / Al (A5N)	18	0.8	0.8 / 1.2	0.45 / 0.90	1.70	0.57	0.57	768 / 376	(I) 1216 (II) 1188

length, at the distance of 0.1 and 0.2 mm from the center of discharge initiation. Bonding region is of wave-like shape. Thickness of moving copper plate was reduced by 43 %, and its microhardness in bonding zones increased by 22 %. Thickness and microhardness of the stationary plate did not change (Figure 8, see Table).

If the moving plate metal is copper, and that of the stationary plate is aluminium alloy A5N, two wavy regions of metal bonding 0.57 mm long are observed, at 1.7 mm distance from the center of discharge initiation. Thickness of moving copper plate was reduced by 44, and that of the stationary aluminium plate — by 25 %. Copper microhardness in the bonding regions increased by 50 %, and that of aluminium — by ~ 13 % (Figure 9, Table 1).

Welded joint quality was evaluated by the results of mechanical strength tests. Evaluation of the joints was conducted with separation of the moving plate from the stationary one (base). Samples which demonstrate an acceptable quality of the joint broke through the moving plate metal, usually softer and less strong, than that of the base.

Conclusions

1. MPW of flat samples of similar and dissimilar metals and alloys produced locally was performed at PWI in upgraded N-126A unit.

2. Metallographic examination showed that bonding of parallel metal plates occurs in two regions located at the same distance from the center of the inductor flat turn.

3. Formation of a sound welded joint within the mentioned regions was detected. Samples broke through moving plate metal, which was usually softer than that of the base.

4. Relevant tendencies in development of technologies and investigations in MPW field allow us making the following statements:

● MPW is an effective technology, with high scientific-practical potential and it requires performance of further research on the technique and technology of welding similar and dissimilar metals;

● Objects of investigation and development will be MPW technological aspects for improvement of weldability of both existing and new materials; reduction of the process power consumption; and experimental-design developments for improvement of the tools (special kinds of inductors, etc.).

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