PRESSURE WELDING OF MICRO-DISPERSED COMPOSITE MATERIAL AMg5 + 27 % Al_2O_3 WITH APPLICATION OF RAPIDLY SOLIDIFIED INTERLAYER OF EUTECTIC ALLOY Al + 33 % Cu

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Solid-phase weldability of micro-dispersed composite material AMg5 + 27 % Al_2O_3 by using rapidly solidified interlayer of eutectic alloy Al + 33 % Cu was studied. It was established that application of the rapidly solidified strip as an interlayer activates the mating surfaces and allows decreasing the temperature and time of diffusion welding of AMg5 + 27 % Al_2O_3 material. Employment of the techniques that accelerate diffusion processes in a butt joint (forced deformation, thermal cycling) made it possible to reduce the interlayer thickness to its almost complete dissolution and improve shear strength of the welded joint to the base metal strength level.

Keywords: *vacuum pressure welding, micro-dispersed composite material, interlayer, rapidly solidified strip, plastic deformation, welding temperature, strength of joints*

Topical task of development and practical operation of different types of equipment in modern machine building is reduction of friction and wear losses in movable joints of units and mechanisms. In this connection, of high interest are composite materials (CM) based on aluminum alloys, reinforced with dispersed ceramic particles of aluminum oxide Al_2O_3 or silicon carbide SiC. These CM are characterized by high specific elasticity modulus, increased heat resistance and rigidity at room and elevated temperatures, low values of coefficients of thermal linear expansion and friction, and high wear resistance. However, successful implementation of potential capabilities of these materials and their wide application are limited by the difficulties connected with their weldability.

Fusion welding of CM involves a number of problems, e.g. significant viscosity of the weld pool, decomposition or agglomeration of the reinforcing particles, complexity of quality formation of the welds as a result of poor wetting of reinforcing particle surfaces with aluminum, and porosity of the welds. Moreover, stirring of the base metal and filler is difficult in welding using filler wire and, as a result, strength of the weld metal [1, 2] is lower than that of a composite material.

In solid-state welding of alumocomposites, for example in a diffusion welding, all the processes take place at lower temperatures (in comparison with fusion welding), and the effect of increased toughness, welds porosity, reinforcer segregation are absent in the weld pool. Therefore, in welding of alumocomposites reinforced with Al_2O_3 (SiC) dispersed particles the preference is given to solid-state joining methods [3].

The main difficulties in pressure welding of dispersion-reinforced alumocomposites are related to the presence of a dense oxide film on the surface and high rigidity of the material, complicating deformation of its sub-surface layer.

It is hardly possible to remove the oxide film and join aluminum alloys over the «clean» surfaces. Therefore, in this case the trend is to destroy and disperse the thin oxide film remaining on the surface after etching and cleaning.

The aim of the present study was to develop a technological process for vacuum pressure welding of fine-dispersed alumocomposite, providing the welded joints with strength at a level of the base metal.

Weldability of CM based on aluminum alloy AMg5, reinforced with the dispersed particles of Al_2O_3 (AMg5 + 27 % Al_2O_3) was investigated. Thickness of the composite layer was 6 mm, and hardness was *HRB* 96–99 at a load of F = 600 N. This material is classified as difficult-to-weld and hard-to-machine.

The composite was manufactured by a casting method, i.e. mixing up the Al_2O_3 dispersed-reinforcing particles into a melt of the matrix material and subsequent pressing. Structure of the composite in the initial state consists of α-solid solution of aluminum, intermetallic inclusions characteristic of matrix aluminum alloy AMg5, and reinforcing particles of oxide aluminum Al_2O_3 of a dark-grey, almost black color, having an angular shape and size of 3–15 μm. They are sufficiently uniformly distributed in bulk of the matrix at a distance of 3–20 μm (Figure 1). The main defect in CM is an accumulation of particles, whereto the aluminum melt cannot penetrate during solidification, and where pores and discontinuities having a detrimental effect on the material properties are formed. Such defects of the base metal have a lower influence on the weld quality in solid-state welding, compared to fusion welding.

Welding of CM samples was carried out with no interlayer and with the aluminum alloy interlayer. The interlayer of aluminum alloy AD1 and interlayer in the form of a rapidly solidified strip of eutectic alloy Al + 33 % Cu were used.

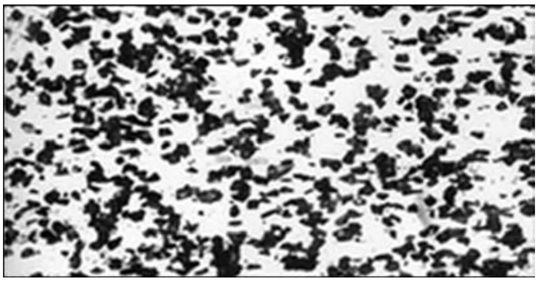

Figure 1. Microstructure (×400) of the AMg5 + 27 % Al_2O_3 CM in the initial state

Samples measuring 15 × 15 × 4 mm were manufactured to optimize the technology and choose the optimum welding parameters. Preparation of the samples for welding consisted in removal of the work-hardened layer around 0.2–0.3 mm thickness and cleaning of the surface with a scraper. Shear tests of the samples were carried out for evaluation of strength of the welded joints. Cutting of the samples after welding was carried out using the EKh-1331P electroerosion machine tool. Examinations of microstructure were performed by the optical microscopy method using microscopes MIM-8 and «Neophot-32». Element composition was determined by using X-ray microanalyzer CAMEBAX. Hardness of the samples was measured with the «Rockwell» device at F = 600 N (ball), and microhardness — with the PMT-3 device at F = 0.2 N.

Production of joints with a high strength and crack resistance is a difficult problem in pressure welding of high-strength, difficult-to-weld metallic and, in particular, metal-ceramic materials. In welding of such materials, development of joint plastic deformation of the mating surfaces is complicated due to significant non-uniformity of the activation process and physical-chemical interaction on the contact area [4]. As follows from studies [5, 6] and results of our investigations, when welding CM to CM, welded joints in dispersion-reinforced CM have low strength because of its significant rigidity. Shear strength of such joints is σ_{sh} = 8–9 MPa. Metallographic examinations showed that the reinforcing particles, matrix intermetallics and oxides are concentrated in a joining line. The interface is well recognized, in particular, in the places of accumulation of the reinforcing particles, where pores and discontinuities occur (Figure 2, *a*).

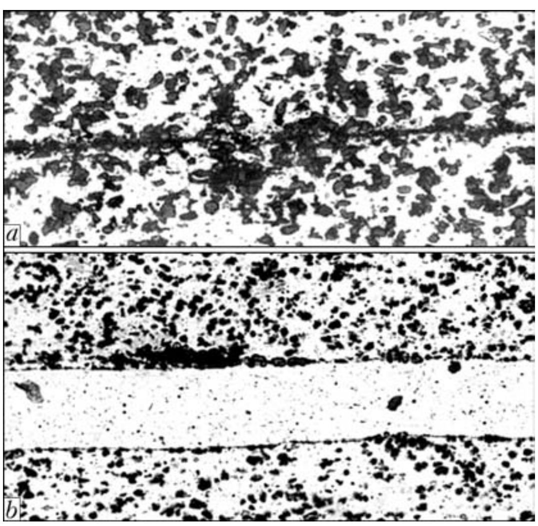

Figure 2. Microstructure of the welded joint on AMg5 + 27 % Al_2O_3 CM produced by vacuum pressure welding without interlayer (*a* — ×400) and with aluminum interlayer 0.15 mm thick under free deformation conditions (*b* — ×250)

It is well known that interlayers in the form of solid materials [7, 8] of plastic alloys, such as aluminum, copper, nickel and silver, are widely used for activation of plastic deformation. In welding of dispersed-reinforced CM using a plastic interlayer eliminates such type of the contact as particle-to-particle, which weakens the joint, and replaces it by a stronger one, i.e. metal-to-particle. Besides, due to a plastic flow during the welding process, the soft solid interlayer placed in the joint provides destruction of the oxide film at the contact surfaces of the composite and improves the process of plastic deformation for near-contact volumes of the metal welded.

To optimize the technology and select the optimum welding parameters, the samples of dispersed-reinforced CM AMg5 + 27 % Al_2O_3 were welded using the 0.15 mm thick interlayer of pure aluminum (AD1 alloy) under the free deformation conditions. At that, the used optimum temperature was T = 560 °C, time was t = 20 min, welding pressure was P = 40 MPa, and vacuum in the working chamber was $B = 1.3 \cdot 10^{-3}$ MPa. The overall plastic deformation of the samples under the free deformation conditions was set at a level of ε = 25 % by using steel inserts limiting the deformation.

The results of metallographic examinations showed that the sufficient adhesion of metal of the interlayer with matrix aluminum of the composite was provided in a welded joint under the free deformation conditions in vacuum pressure welding using the 0.15 mm thick interlayer of pure aluminum. There was no accumulation of the reinforcing particles at the interface. However, individual regions contained micropores and extended oxides (see Figure 2, *b*). Thickness of the aluminum interlayer in the welded joints reduced from 150 to 100–120 μm. Shear strength of the joints was σ_{sh} = 40 MPa.

As shown by investigations [4], deformation of solid interlayers take place only in a short edge area in a case of using the free-state welding scheme, this being in agreement with our investigation results. To produce stronger joints, the authors of studies [4, 9] recommend using such techniques and parameters of pressure welding, at which the joining zone material experiences plastic deformation by the pressure + shear scheme. This process was called welding with forced deformation [9], which is the case of cold welding, friction welding, resistance butt welding, etc.

In our investigations we used the scheme of welding with forced deformation for activation of plastic deformation in the joining zone. A forming device, providing a directed shear plastic deformation of metal in the joint and preset deformation of welded samples as a whole, was employed for this purpose. The forming device consisted of two dies and a guide bushing. The degree of plastic deformation of the joints at a level of ε = 15–25 % was set by depth of the channels.

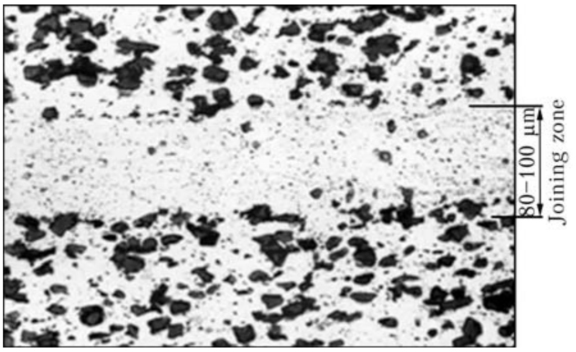

Figure 3. Microstructure (×400) of CM welded joint produced by vacuum pressure welding using aluminum interlayer 0.15 mm thick under forced deformation conditions

Metallographic analysis of the welded joints produced in the forming dies using the aluminum interlayer showed the absence of defects that usually take place during welding in the free state (oxide inclusions, pores) (Figure 3).

The aluminum interlayer had non-uniform thickness along the length of a sample. In welding with the solid interlayer, thickness of aluminum was 80–100 μm in the central part of a joint and 30–60 μm at its ends, i.e. it was smaller at ends of the welded joint than in its central part. This is explained by the fact that the deformation processes on the periphery of the joint take more time than in the central part, and that the shear (tangent) deformations are longer and more intensive [10]. Microhardness of the aluminum interlayer in the welded joints is 650–750 MPa. One of the differences of the welded joints produced in the forming dies from those produced in the free state is the presence of flash no more than 1 mm thick, whereto not only the soft aluminum interlayer but also the adjacent CM layers go during welding.

In welded joints of the composite material, the character of distribution of the reinforcing particles within the welding zone, their morphology and dispersion do not change both under the free deformation conditions and when using the forming dies. Shear strength of the joints produced by welding in the forming dies using the 150 μm thick aluminum interlayer is σ_{sh} = 91 MPa. This is approximately 50 % of that of the composite in the initial condition.

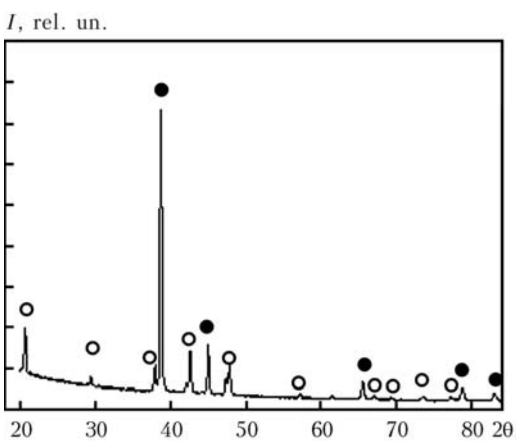

Figure 4. Spectrum of X-ray diffraction of rapidly solidified strip of Al + 33 % Cu: ● — Al; ○ — Al_2Cu

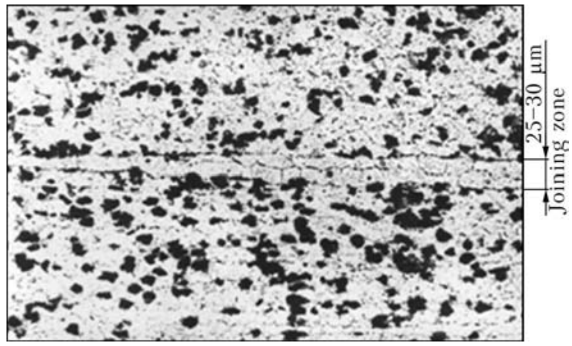

Figure 5. Microstructure (×300) of the CM joining zone in vacuum pressure welding using rapidly solidified strip (Al + 33 % Cu) 0.07 mm thick under free deformation conditions

Joints with sufficiently high strength characteristics can be produced by vacuum pressure welding providing that interface between the mating surfaces stops acting as a separate structural element [11]. This can be achieved by using thin interlayers, capable of intensifying diffusion processes in the joint, dispersing and redistributing remainders of the oxide film. For this, the diffusion processes have to be activated and maximum possible dissolution of the interlayer has to be achieved during the welding process, which, in our opinion, should promote significant improvement of strength of the joints. For this purpose, low-melting point interlayers of eutectic aluminum alloy, including the rapidly solidified ones, which activate the mating surfaces and easily diffuse into the base metal during welding [12], can be used.

It is also well known that the diffusion processes significantly accelerate with the grain size refinement, i.e. with increase in length of the grain boundaries, as the diffusion coefficient along the grain boundaries is several orders of magnitude higher than in the bulk of grains [13].

In this connection, the rapidly solidified strip of the Al–Cu (Al + 33 % Cu) system and eutectic composition, 0.07 mm thick and 10 mm wide, developed and manufactured by the I.M. Frantsevich Institute of Problems of Materials Science of the NAS of Ukraine, was used for welding of CM AMg5 + 27 % Al_2O_3. Structure of the strip consists of α-solid solution of aluminum and dispersed particles of intermetallic phase Al_2Cu, uniformly distributed in the matrix volume. An X-ray diffraction pattern of the rapidly solidified trip of Al/Cu system eutectic alloy

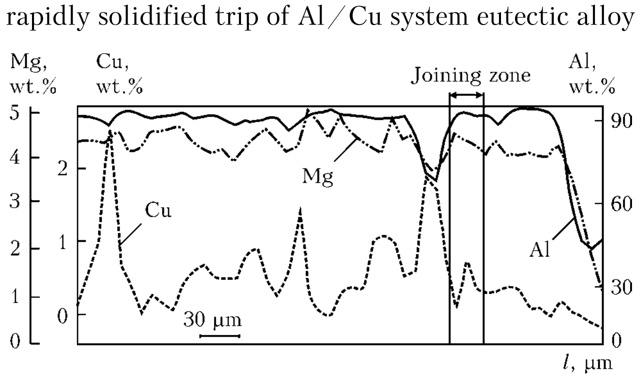

Figure 6. Character of distribution of copper, magnesium and aluminum in the CM joining zone in welding under free deformation conditions

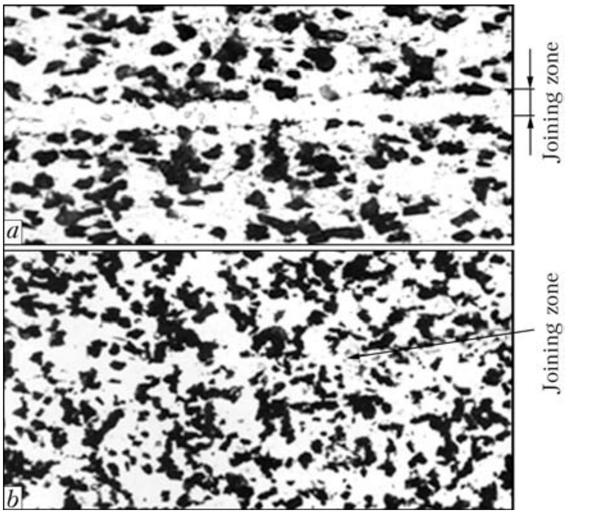

Figure 7. Microstructure of the CM joining zone (δ = 8–10 μm) in vacuum pressure welding using rapidly solidified strip (Al + 33 % Cu) under forced deformation conditions (*a* — ×600) and with subsequent thermal cycling (*b* — ×400)

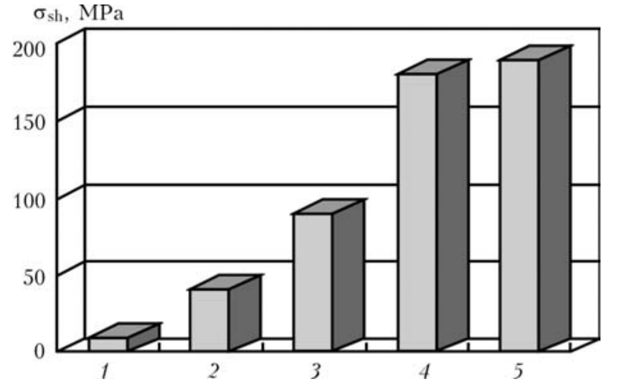

Figure 8. Diagram of changes of shear strength σ_{sh} for welded joint on AMg5 + 27 % Al_2O_3 CM depending on the technological peculiarities of vacuum pressure welding (*1–4*) and in the initial state (*5*): *1* — free state using no interlayer (σ_{sh} = 8–9 MPa); *2* — same by using aluminum interlayer of δ = 150 μm (σ_{sh} = 40 MPa); *3* — forming die by using aluminum interlayer of δ = 150 μm (σ_{sh} = = 91 MPa); *4* — same by using rapidly solidified strip Al + 33 % Cu of δ = 70 m (σ_{sh} = 180 MPa); *5* — σ_{sh} = 190 MPa

Al + 33 % Cu is shown in Figure 4, in which only the Al and Al_2Cu peaks are present.

The optimal temperature in vacuum pressure wielding of AMg5 + 27 % Al_2O_3 CM using the rapidly solidified strip of Al/Cu system eutectic alloy Al + 33 % Cu as an interlayer was T_w = 500 °C (t = 10 min, P = 40 MPa) both under the free and forced deformation conditions. It is likely that a 60 °C decrease in the welding temperature, compared with welding using the solid aluminum interlayer, is related to an increased activity of the rapidly solidified strip.

The metallographic examination results showed that thickness of the interlayer in the joint reduces from 70 up to 20–30 μm (Figure 5) in vacuum pressure welding (T_w = 500 °C) under the free deformation conditions. According to the data of X-ray spectrum microanalysis, the interlayer contains 4.35 wt.% Mg, 2.3 wt.% Cu and 93.4 wt.% Al (Figure 6). During the welding process more than 4 wt.% Mg transfers to the interlayer from alumocomposite AMg5 + 27 % Al_2O_3. Hardness of the interlayer is virtually at a level of that of the composite matrix.

Welding in forming devices allows reducing the interlayer thickness to 8–10 μm (Figure 7, *a*). Subsequent heat treatment (thermal cycling), consisting of five cycles of heating to 500 °C under pressure and cooling to 200 °C, provided practically complete dissolution of the interlayer (Figure 7, *b*). Shear strength of the welded joint after welding and heat treatment was σ_{sh} = 180 MPa.

Therefore, application of the rapidly solidified strip of Al/Cu system eutectic alloy Al + 33 % Cu, as well as techniques aimed at acceleration of the diffusion processes in the joint, in vacuum pressure welding of composite AMg5 + 27 % Al_2O_3 allowed decreasing the welding temperature and reducing thickness of the interlayer in the welded joint to its practically complete dissolution. Shear strength of the welded joint reaches 180 MPa (Figure 8, pos. *5*), which corresponds to the strength level of composite in the initial state.

CONCLUSIONS

1. In vacuum pressure welding, a change of the pure aluminum interlayer to the interlayer of the rapidly solidified strip of the Al/Cu system eutectic alloy Al + 33 % Cu allowed producing the quality welded joints on composite AMg5 + 27 % Al_2O_3 at a lower temperature and shorter time of welding.

2. Application of the rapidly solidified strip of the Al/Cu system eutectic alloy provides strength of the joints at a level of that of the base metal.

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