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POSSIBILITIES OF MANUFACTURING THREE-LAYER WELDED HONEYCOMB PANELS FROM ALUMINIUM ALLOYS

L.V. PETRUSHINETS, Yu.V. FALCHENKO, V.E. FEDORCHUK and **V.S. SHINKARENKO**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

Three-layer honeycomb panels are widely applied in aircraft construction, ship-building, construction and others industries. In terms of design, they consist of a honeycomb core and two skins. At relatively small weight, these structures are characterized by high strength values, sound- and heat-insulating properties. The main problem in manufacturing a three-layer structure is welding the upper and lower skins to end faces of the honeycomb core. The work presents the results of development of the technology of manufacturing three-layer honeycomb panels of 150×150 mm size from aluminium alloys. The honeycomb core from AD1 aluminium alloy 0.150 mm thick was produced by joining the corrugated strips into blocks by spot welding. Flatness of end faces of the honeycomb core was achieved by grinding. The structure rigidity was ensured by filling the cells with colophony. Joining of the core to the skins from AMg2 alloy 1.0 mm thick was performed by diffusion welding in vacuum. The process was conducted in a fixture consisting of the lower and upper flanges and bushing. The flanges provided skin pressing to the honeycomb core end faces over the entire contact area, and the bushing allowed homogenizing the temperature field in the item and controlling the extent of its deformation during welding. 8 Ref., 1 Table, 6 Figures.

Keywords: *three-layer honeycomb panel, sheet aluminium alloys, spot welding, diffusion welding in vacuum*

Three-layer panels are widely applied at present in aircraft construction, ship-building and other industries. At a relatively small weight these structures have high characteristics of strength and rigidity. Load-carrying layers, reinforced by the core, take high compressive stresses, exceeding the material limit of elasticity. This kind of structures is characterized by good vibrational, radio engineering, sound and heat-insulating properties [1, 2].

A number of methods are used for joining the honeycomb core elements: adhesive bonding, resistance welding, brazing and diffusion welding. The most widely accepted manufacturing method is adhesive bonding (about 95 %). Three-layer honeycomb panels from aluminium alloys are mostly produced by adhesive bonding in modern industry. Panels produced by brazing, resistance and diffusion welding, are applied in structures, operating at high temperatures or in aggressive media [1]. Accordingly, nichrome, titanium alloys or stainless steels, are the materials used for such panels.

Honeycomb cores are produced by one of the two methods: pack stretching or its manufacture from profiled strips. With the second method, welding or brazing can also be applied, alongside adhesive bonding. The pack stretching method is used for manufacturing the cores, in which the honeycombs consist of just six faces. Here the thicknesses of metallic materials do not exceed 80 μm. The honeycomb cores, made from preprofiled strip in the form of foil, have more regular honeycomb geometry, that the cores produced by pack stretching. This technological process takes more time than the method of pack stretching. Therefore, the cores produced from profiled strips are usually more expensive [1].

The three-layer panel is designed to consist from two skins and honeycomb core, which differ essentially, both in their geometry and mechanical properties in different planes. This kind of structure requires development of individual approaches both to welding of profiled strips into the honeycomb core block, and to formation of the tee-joint of the skins with the core.

The objective of this work was development of the technology of producing three-layer honeycomb panels from aluminium alloys by diffusion welding in vacuum.

Three-layer panels were manufactured with application of AD1 aluminium alloy with foil thickness of 0.15 mm for the core, and AMg2 alloy of 1.0 mm thickness for the skins.

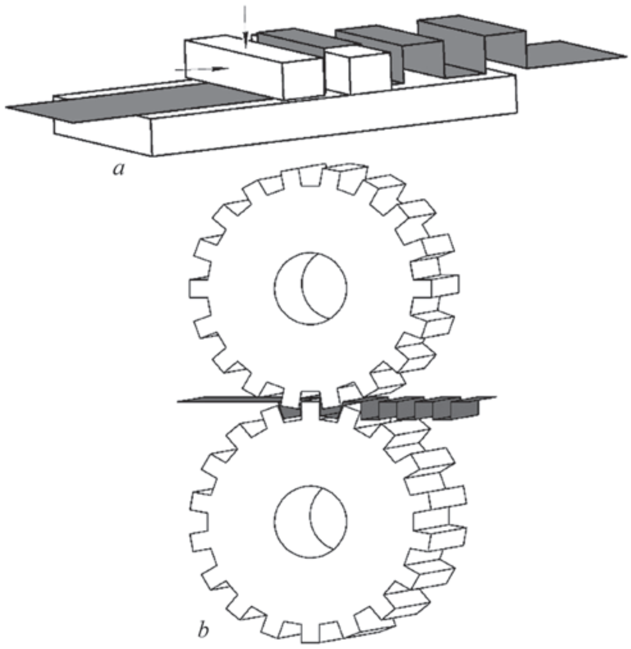

Figure 1. Schematic of moulding the honeycomb core strips using rectangular inserts (*a*) or a gear set (*b*)

Based on the earlier performed literature survey [3], it was shown that profiled strips for the honeycomb core can be produced by successive moulding of foil with the specified step in the form of halves of honeycombs in the fixture consisting of rectangular inserts (Figure 1, *a*) or using a gear set (Figure 1, *b*).

The first type of fixture is simple to manufacture, but forming the profiled strips takes considerable time. The fixture, consisting of a gear set, is more expensive to manufacture, but it is rational when preparing large batches of profiled strip.

Spot and diffusion welding methods were applied to join the elements of profiled strips into the honeycomb core block. Spot welding was conducted on a support strap made from steel in the form of a «comb» (Figure 2). Fixture, consisting of a set of «combs» was used for diffusion welding, respectively.

Mechanical tensile tests of welded joints of foil were performed in versatile MTS 810 machine. Mechanical compression characteristics of the honeycomb structure were studied with application of digital controller of KOLI Company, XK3138T1 model, and pressure sensor of CAS Company, MNC-1 model, with operating range from 0 up to 1000 kg.

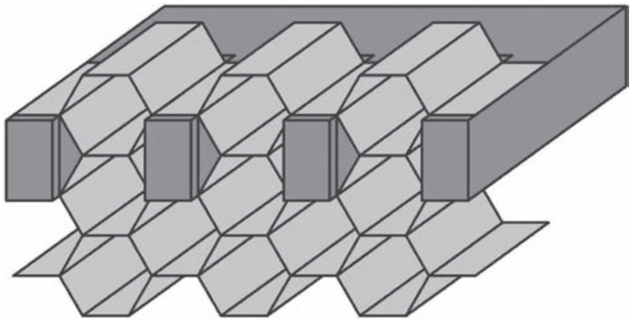

Figure 2. Appearance of «comb» fixture for welding the honeycomb core

Tensile strength of joints

Sample	Welding mode			Fracture site	σ, MPa	σ_{av}, MPa
	T_w, °C	P_w, MPa	t_w, min			
BM	–	–	–	–	67.9	68.0
				–	58.9	
				–	77.3	
Welded joint	600	40	20	Grips	59.7	64.0
				Same	56.1	
				Joint zone	76.1	

Vacuum diffusion welding was performed in P-115 system by the procedure, described in detail in [4].

Investigation of welded joint microstructure was conducted on transverse microsections, using scanning electron microscope, fitted with energy-dispersive spectrometer ENERGY 200 and optical metallographic microscope MMT-1600V.

Vacuum diffusion welding of AD1 aluminium alloy was performed at temperature T_w = 480–600 °C, pressure P_w = 10–40 MPa, process duration t_w = 10–20 min, vacuum in the chamber was maintained on the level of $1.33\cdot10^{-3}$ Pa. Oxide film was removed by mechanical scraping, which was followed by degreased the surfaces to be welded in alcohol. The size of overlapping of the samples to be welded was 10 mm.

As shown by investigations, in foil welding in the mode, which corresponds to the optimal one according to published data [5], individual adhesion areas are observed in the sample joint zone. It is found that pressure increase up to 40 MPa and process duration of up to 20 min provided physical contact over the entire surface of the sample. At increase of welding temperature from 480 up to 600 °C the quantity of defects in the joint zone is reduced.

Mechanical tensile properties were determined both for aluminium foil in the initial condition, and for welded joints (see Table). It is found that strength of initial metal from AD1 alloy is equal to σ_t = 68.0 MPa. Average strength of welded samples is equal to σ_t = = 64.0 MPa, i.e. coefficient of joint strength is equal to 0.94 of the initial material level.

Spot welding was performed at room temperature in air. Before welding, the foil contact surfaces were mechanically scraped and degreased. The process was conducted in the following modes: U_w = 3 V, current I_w = 270–300 A. The intensity of heating in welding was determined by process duration, which was set by time switch in the range of t_w = 0.2–5.0 s. Visual inspection of the surface and tensile testing of the joints showed that the optimum duration of the welding cycle is t_w = 0.5–1.0 s.

In samples produced at less that 0.5 s pulse duration, partial melting of the joined surfaces under the electrode is observed with formation of weld spots of a small diameter (Figure 3, *a*). Increase of welding time up to 1 s allows improving the welding quality and promotes formation of a tight joint over the entire electrode surface (Figure 3, *b*).

Considering that the diffusion welding process is more labour-consuming, furtheron spot welding was used for welding the honeycomb core elements.

Resistance of the honeycomb core to the impact of external loads was determined by compression tests, in keeping with the procedures given in studies [6, 7]. It is found that deformation of the honeycomb core from AD1 alloy occurs at the average value of the compressive force equal to 23.3 MPa. Analysis of honeycomb core elements after compressive testing showed that no delamination of the walls occurs during deformation.

During manufacture of the three-layer panel it is necessary to join the honeycomb core to the skins, thus ensuring formation of tee-joints. Diffusion welding in vacuum is the most suitable for these purposes, as it allows maximum accurate control of all the process parameters.

One of the main requirements in diffusion welding is the plane-parallelism of the surfaces being welded. However, the technology of producing the honeycomb core from profiled strips does not ensure it. Stresses arising during spot welding, result in distortion of the honeycomb core block. Therefore, we developed the technology of grinding its contact surfaces. Considering that the honeycomb core is made of an aluminium alloy 0.15 mm thick, its direct machining is impossible in view of its high ductility. To provide the stability of the cell walls, it is necessary to ensure their rigidity by filling them with another material. The material for honeycomb filling should meet the following requirements:

- have low melting temperature;
- be sufficiently rigid and strong;
- be inert to the material of honeycomb core — aluminium;
- be readily treatable by grinding;
- be easy to remove.

Applicability of colophony, sulphur and paraffin as material for filling the honeycomb core was studied.

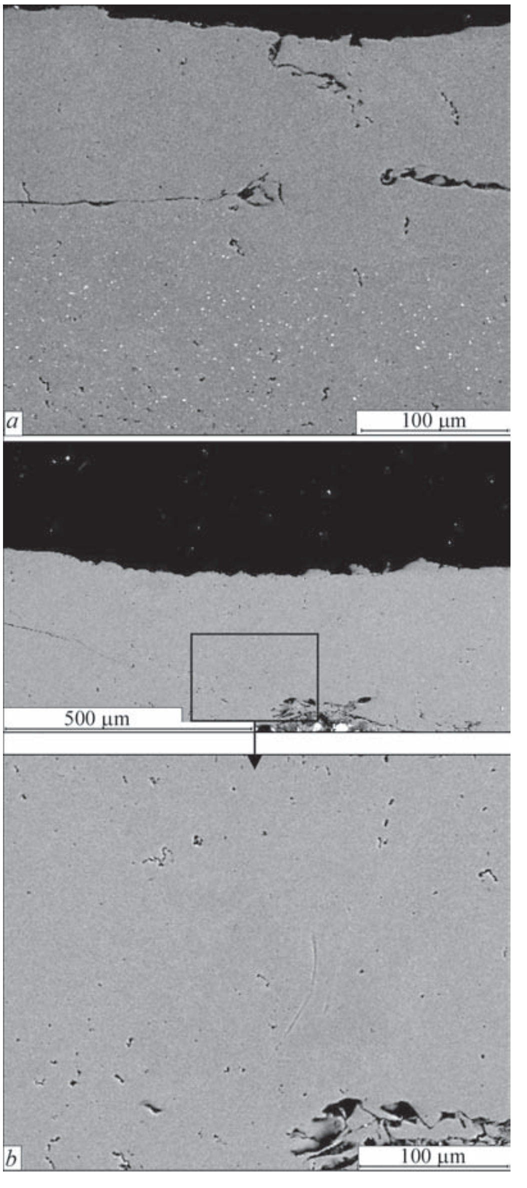

Figure 3. Microstructure of joints produced by spot welding at process duration of 0.2 (*a*) and 1 s (*b*)

When sulphur is used (T_m = 115 °C), one should take into account that it has a higher viscosity above 160 °C, that makes it unsuitable for application. Sulphur melt acquires the highest viscosity at the temperature of 190 °C. Further temperature rise is accompanied by lowering of viscosity and above 300 °C the fluidity of molten suphur increases again. Therefore, cell filling should be performed at the temperature of 300–350 °C.

Paraffin has melting temperature T_m = 45–65 °C, but shows considerable shrinkage at solidification, so that filling has to be conducted in several stages.

Colophony melts at temperature T_m = 100–130 °C. It has a sufficiently low viscosity in the molten state that has a positive effect on adaptability to fabrication (fillability of the form). More over, shrinkage of colophony at solidification is minimal.

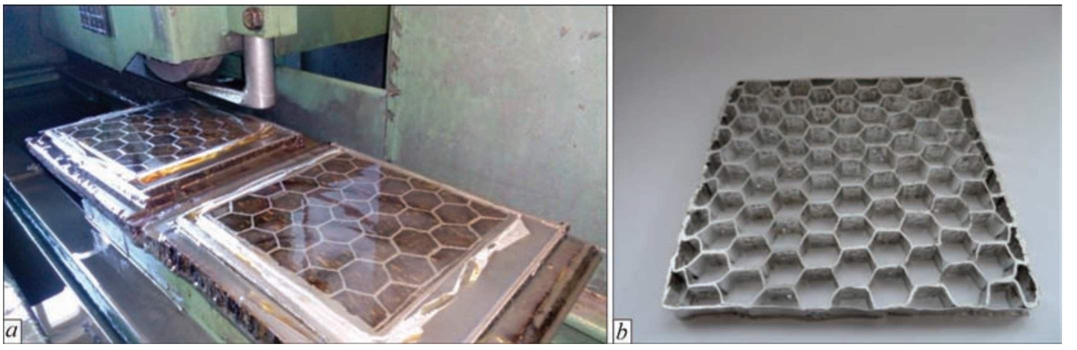

Figure 4. Appearance of honeycomb core during grinding (*a*) and after removal of colophony (*b*)

Honeycomb core samples were filled with the respective substance (colophony, sulphur, paraffin) in the molten state, and left to solidify for 20–30 min, which was followed by grinding of the contact surfaces (Figure 4, *a*).

As followed by the conducted experiments, the samples filled with colophony, have the best grindability. When paraffin is used, it sticks to the abrasive tool, making the grinding process more difficult. At application of sulphur, some surface areas, where it has delaminated, are observed, that leads to deformation of the core walls.

Technological operation of removing the material poured into the honeycomb core cells was conducted using sample reheating. Experiments showed that paraffin remains are readily removed from the cells, if final rinsing is performed in boiling water. In samples filled with sulphur, a small deposit remains on cell surface after its removal, which is difficult to remove after washing in benzene. In the case of colophony application, its remains are readily removed by washing in organic solvents: alcohol, benzene and turpentine.

Performed research leads to the conclusion that it is the most rational to apply colophony as material for filling the honeycomb core cells. It allows performing high-quality machining and subsequent scraping of all the faces of honeycomb cells (Figure 4, *b*).

Diffusion welding of three-layer honeycomb panel of 150×150 mm size was conducted in a specialized device, which is designed to consist of the lower and upper flanges and limiting bushing (Figure 5, *a*). Flanges ensure pressing of the skins to the honeycomb core over the entire contact area during welding. The purpose of the limiting bushing consists in equalizing the temperature field and ensuring the specified level of overall plastic deformation on the item [8]. The welding mode corresponded to the following parameters: T_w = 540 °C, P_w = 5 MPa, t_w = 20 min. Figure 5, *b* shows the appearance of the three-layer honeycomb panel manufactured by the developed procedure.

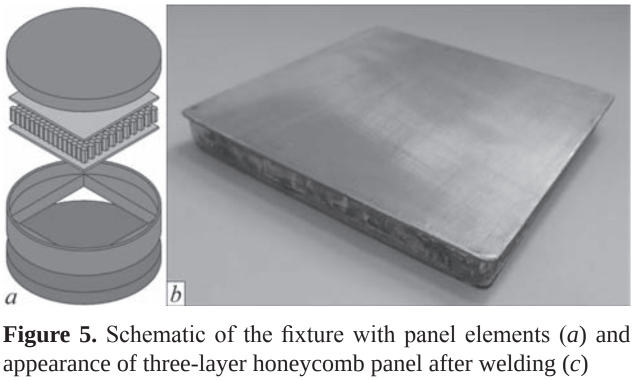

Figure 5. Schematic of the fixture with panel elements (*a*) and appearance of three-layer honeycomb panel after welding (*c*)

As shown by the results of optical microscopy, there are no defects in the form of cracks or pores in the zone of the joint of honeycomb core wall and the skin (Figure 6, *a*).

Compressive testing of the three-layer panel elements was performed to assess the strength of their joining. For this purpose, individual elements corresponding to an isolated hexagonal cell by their dimensions were cut out of the three-layer panel.

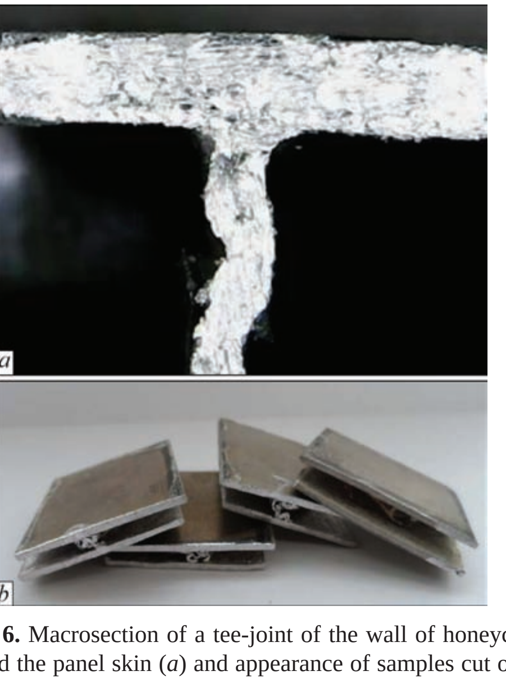

Figure 6. Macrosection of a tee-joint of the wall of honeycomb core and the panel skin (*a*) and appearance of samples cut out of the three-layer panel after their compressive testing (*b*)

The dimension of the honeycomb core cells was 10×10 mm, its height was 11 mm, thickness of AMg2 aluminium alloy skins was 1 mm, and thickness of honeycomb core from AD1 alloy was 0.15 mm. Total area of the sample surface was about 670 mm^2, and the cross-sectional area of the honeycomb core was 12 mm^2.

As is seen from Figure 6, *b*, at compression with the degree of deformation of about 50 %, deformation of vertical walls of the core proceeds without fracture of the sections of welding the honeycomb core to the panel skins. Average value of compressive force, at which deformation of the honeycomb core in the three-layer panels takes place, is equal to 58.12 MPa.

Thus, performed investigations showed the theoretical possibility of manufacturing welded three-layer panels from aluminium alloys. Developed technology of grinding the honeycomb core enabled producing the joint over all the contact surfaces of the three-layer panel. Analysis of mechanical testing results showed that the panels with the honeycomb core in the form of hexagonal cells can stand compressive loading with the degree of deformation of the order of 50 % without fracture of tee welded joints.

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