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MODERN METHODS OF MANUFACTURING THREE-LAYER PANELS OF ALUMINIUM ALLOYS (Review)

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Three-layer panels with periodic cellular core from aluminium alloys are promising for application in aerospace products, ground and water transportation. The uniqueness of the three-layer panel design consists in that they are characterized by high values of strength and rigidity at a relatively small mass. The work deals with the main types of three-layer panels, design features of manufacturing the cores, methods to join the honeycomb core strips to each other, as well as the three-layer panel elements into one structure. The objective of the presented review is analysis of modern methods of manufacturing three-layer panels from aluminium alloys. Analysis of published data showed that such methods of joining the three-layer panel elements as adhesive bonding and brazing became the most widely applied. Their main disadvantage, however, is increase of the structure mass due to application of an adhesive or braze alloy. Application of diffusion welding with manufacture of honeycomb core from a stronger titanium alloy for joining three-layer panels or application of a specialized fixture, which allows limiting the degree of plastic deformation of the structure, are promising for welding three-layer panels. 28 Ref., 1 Table, 9 Figures.

Keywords: *aluminium alloys, three-layer panels, core, adhesive bonding, brazing, welding*

Three-layer panels became widely applied in aircraft manufacturing, shipbuilding, construction and other industrial sectors owing to their unique properties, namely at a relatively small mass these structures are characterized by high values of strength and rigidity. Moreover, they have good vibration and radio engineering characteristics, and sound and heat insulation properties.

«Three-layer panel» term should be understood as a structure consisting of two thin skins (load-carrying layers) with the core placed between them (Figure 1) [1].

The uniqueness of the three-layer panels consists in that the skins reinforced by the core, take up high compressive stresses, exceeding the material elasticity limit. Separation of the load-carrying layers by a certain distance from each other, through application of the core, enables achieving a significant ratio of the structure rigidity to its mass.

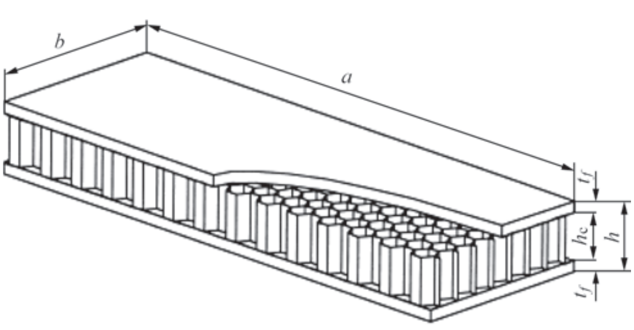

Figure 1. Schematic of a three-layer honeycomb panel [1]

The core applied in the three-layer panels, can be divided into the following groups:

- solid from homogeneous material;
- solid from anisotropic material;
- lightweight (perforated) core;
- ribbed structures.

Designs of three-layer structures with corrugated (Figure 2) and honeycomb cores (Figure 3) were also developed.

Core density is one of its main characteristics. It is determined by material mass and volume, taken by it between the load-carrying layers. Core density influences the mass of the three-layer structure, and value of strength and rigidity of the core.

In the case of application of the honeycomb core from metal, its density depends on the cell shape, wall (face) width and its thickness, density of material from which the core is made, and method to produce the core [2].

$$\rho_c = k_b(\delta_w/a_w)\rho_m,$$

where k_b is the coefficient allowing for cell forming; δ_w is the thickness of the wall of single face of the cell; a_w is the width of the honeycomb wall; ρ_m is the density of core material.

Density of honeycomb core with a hexagonal cell, provided $a_w = \delta_w$, $\beta = 60°$, can be found from the following formula

$$\rho_c = 1.54(\delta_w/a_w)\rho_m.$$

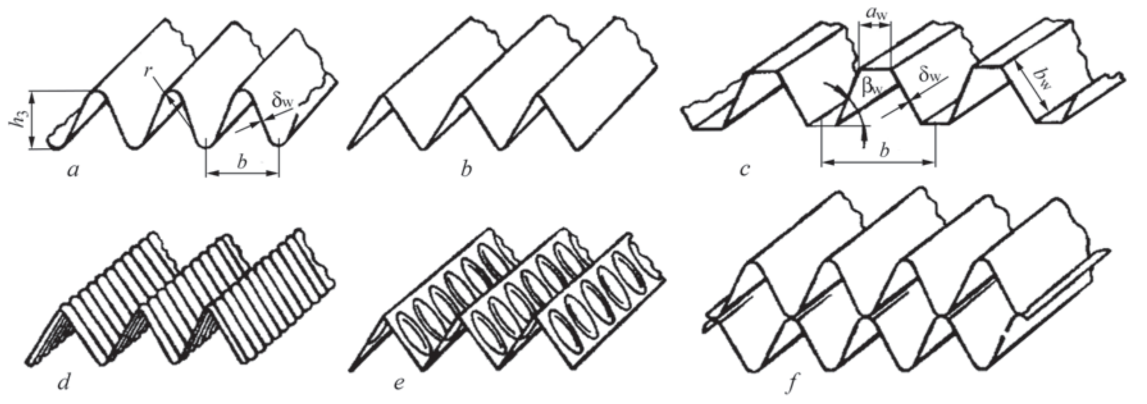

Figure 2. Examples of structures with a corrugated core: *a* — sinusoidal; *b* — triangular; *c* — trapezoidal; *d* — wavy truss; *e* — rift truss; *f* — double truss

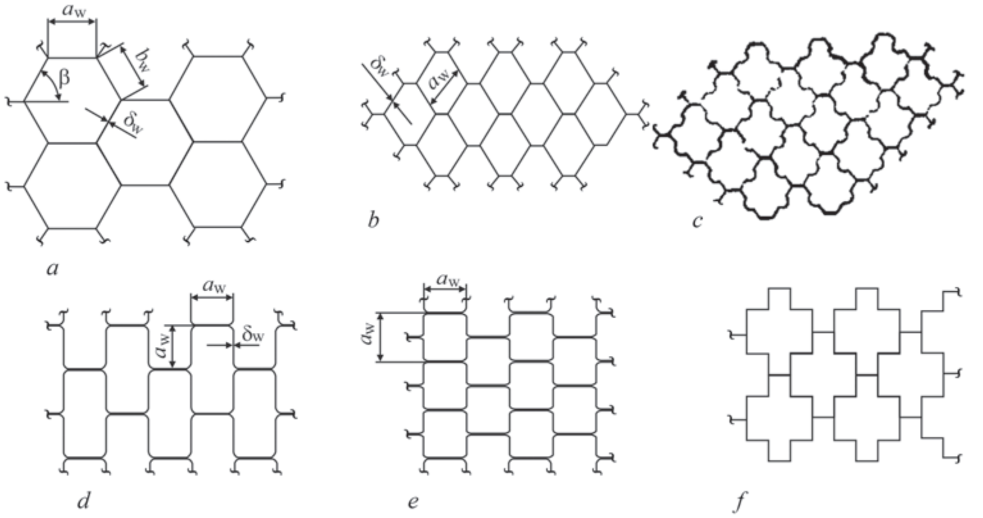

Figure 3. Examples of honeycomb core structures: *a* — with hexagonal cell; *b* — with square cell; *c* — with square rifted cell; *d*, *e* — with rectangular cell; *f* — with cruciform cell [2]

Three-layer panels, particularly those with a honeycomb core, are used in space vehicle structures, as well as in aircraft of various classes and purposes. Such structures can be applied as load-carrying elements in the wing, fuselage, particularly in assemblies, taking up a local load (flaps, fairings) and transverse distributed load (flooring), as well as non load-carrying elements [2, 3]. Application of honeycomb structures from aluminium alloys in the internal layer of a high-speed train nose, as an element, absorbing a considerable amount of energy at frontal collision, is promising [4].

The ability of the core to take the load in the direction of loading of the load-carrying layers depends on the position of its fibers or walls. If the latter are located normal to this direction, the core does not take the load. If they are parallel, the core is loaded. At present, honeycomb cores are used in the majority of cases for three-layer panels from light alloys. They have the following advantages: honeycomb walls are located normal to the load-carrying layers, so that the core does not take the load from the skin, and, as a result, does not buckle out at load increase. Load-carrying layers are reinforced by the honeycomb walls as though in a «continuous» manner (ratio of the honeycomb size to the load-carrying layer thickness ≤25), so that the buckling stress of load-carrying layers between the walls is in the plastic region [5]. This

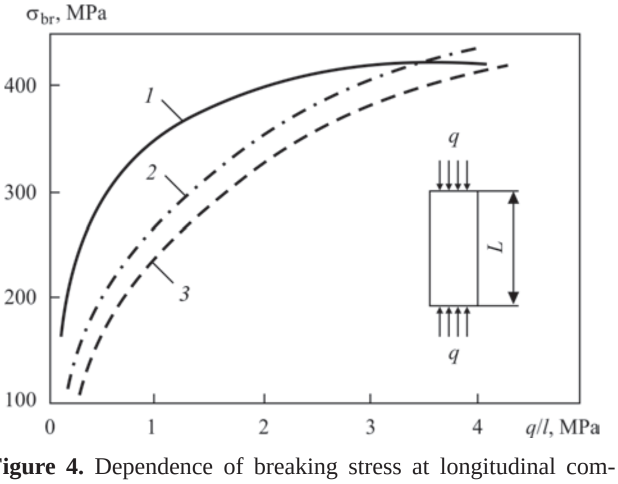

Figure 4. Dependence of breaking stress at longitudinal compression on intensity factor for different designs of the three-layer panels: *1* — panel with honeycomb core; *2* — solid panel; *3* — stringer riveted panel

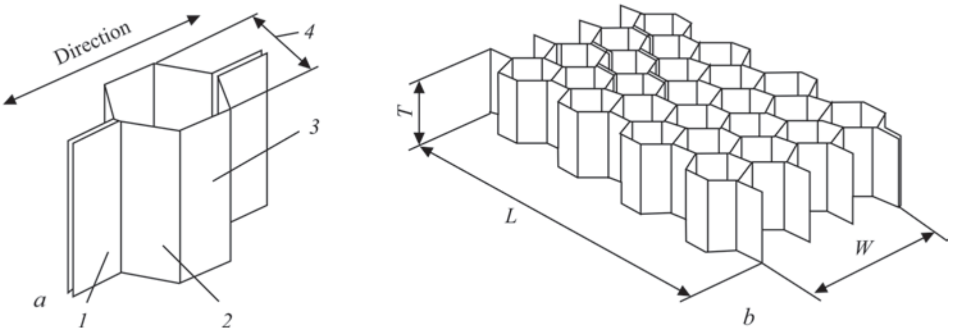

Figure 5. Honeycomb core with hexagonal cells: *a* — view of isolated cell (*1* — corrugated strips; *2* — cell faces of single thickness; *3* — cell faces of double thickness; *4* — cell size); *b* — main parameters of the honeycomb core (*L* — length; *T* — thickness; *W* — width) [8]

is confirmed by high breaking stresses of honeycomb structures at compression (Figure 4) [6].

Despite the large number of honeycomb core structures developed so far, their mass production all over the world has been mastered only for honeycomb core with smooth hexagonal cells. Its output volumes greatly exceed those of production of the other honeycomb core structures taken together. This is attributable to good service characteristics, simplicity of manufacturing and relatively inexpensive process equipment for manufacture of the core with such a type of cells [7].

Honeycomb core (Figure 5) [8] is formed from corrugated strips of material, connected to each other along the outer planes of the corrugations. Each corrugation has the configuration of half of a hexagon, and forms half of the honeycomb cell. Connected to each other corrugated strips form rows of hexagonal cells. Each cell has four faces of single thickness (initial thickness of honeycomb core material) and two faces of double thickness [2].

Honeycomb core can be made from a broad range of aluminium alloys. So, 3003 alloy is often used for manufacture of honeycombs of the commercial class, alloys 5052, 5056 and 2024 are applied in specific structures. Alloy 2024 is used at increased operating temperature (up to 216 °C), while cores from other aluminium alloys can operate only up to 177 °C.

The main methods of manufacturing the honeycomb core are as follows: adhesive bonding, resistance welding, brazing and diffusion welding. Adhesive bonding is the most widely accepted manufacturing method (about 95 % of the total volume of three-layer panel manufacture). In view of the high cost of the process, resistance welding, brazing and diffusion welding are used in manufacture of cores, operating at high temperatures or in aggressive media [3].

There exist two main methods applied for transformation of sheet material into the honeycomb: pack stretching and its manufacturing from profiled strips.

Method of pack stretching is applicable for manufacturing honeycomb cores, the cells of which consist of only six faces. Thicknesses of metallic materials cannot exceed 80 μm. Here, more favourable conditions for pack stretching are created with increase of the cell side and decrease of initial material thickness, as well as the height of honeycomb core cell. Joining of sheet material is performed by adhesive bonding method. Figure 6 gives the schematic of realization of the method. In order to lower the honeycomb core mass, the adhesive strips are applied on the material from one side of the sheet in most cases. Then, the sheet material is cut to length with subsequent assembly of honeycomb core packs and their adhesive bonding.

Stretching of honeycomb pack or billet is performed in a special unit. At force application to the sections of the pack external sheets, which are located in the place of faces of the future honeycomb cells, the pack will be stretched as a result of bending of the unbonded sections of its sheets. Cells of a hexagonal

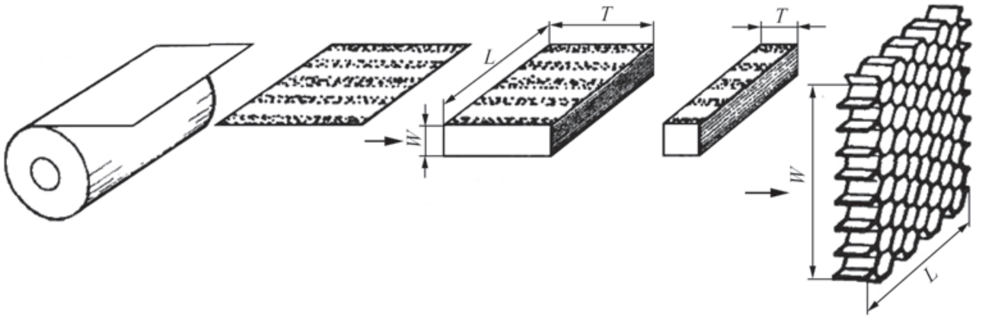

Figure 6. Process of manufacturing the honeycomb core by pack stretching [3]

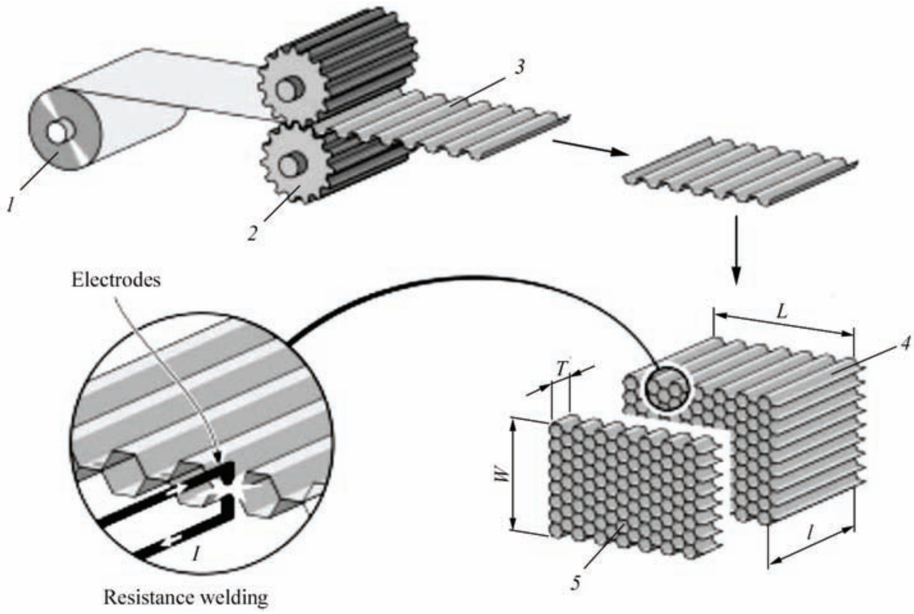

Figure 7. Process of honeycomb core manufacture from profiled strips [9]: *1* — foil coil; *2* — forming rollers; *3* — corrugated foil; *4* — pack of honeycomb cores; *5* — honeycomb core

shape form at a certain degree of stretching, and rectangular cells form at further stretching.

The process of producing the honeycomb core from profiled strips is schematically represented in Figure 7 [9]. Honeycomb cores manufactured by this method, have a more correct geometry of cells, than those produced by pack stretching.

After corrugation, adhesive is applied on the respective surfaces of the sheets. Then they are stacked one upon the other and curing in the oven is performed. Brazing, diffusion or resistance welding can also be used instead of adhesive bonding. These joining techniques allow a significant increase of operating temperature of the honeycomb structure, for instance, up to 700 °C for stainless steel and Inconel [3].

In three-layer panels joining of the load-carrying layers with the core is performed by different technological processes: adhesive bonding, brazing and welding. Here, bonding of the structural elements takes a leading position.

Producing three-layer honeycomb panels by adhesive bonding. By the data of [10], adhesives have become widely applied in practice in aeronautical products. Film and pastelike adhesives for structural applications have a wide range of strength and deformation properties. The adhesives are designed for manufacture of honeycomb and laminated load-carrying structures from metals and polymer composite materials. Adhesive bonds have high long-term strength, vibration resistance, resistance to cracking, impact of climatic factors, and aggressive media. The Table gives the characteristics of film adhesives for structural purposes.

Specifics of producing three-layer panels by adhesive bonding method consists in application of intermediate materials — prepregs, which are sheets of woven or non-woven fibrous materials, impregnated by uncured polymer binders.

In work [11] the influence of preparation of the honeycomb surface on core bonding to the skin, as well as nature of organic solvents, was assessed. It is noted that in order to produce a reliable bond, the resin should flow out of the prepreg (or adhesive) and create symmetrical fillets between the skin external sheet and honeycomb walls. Here, the core edge should be straight and sharp. It should slightly recede from the skin surface, creating an interface between the prepreg, resin and core wall. As noted by the authors, ap-

Characteristic of film adhesives for structural purposes [10]

Adhesive	Working temperature range, °C	Strength characteristics					
		τ_t, MPa	σ_t, MPa	S_{del}, N/mm	γ, %	$\sigma_{l.s}$, MPa (time — 500 h)	τ_{max} at $N = 10^7$ cycles, MPa
VK-25	–60–200	27	22	5–6	140–200	18.5	9
VK-36	–130–160	37 ± 2.5	50	2–3	80–100	34	8
VK-50	–60–150	25 ± 5	25 ± 5	10	135–150	17	10
VK-51	–60–80	40 ± 2.5	–	3	70–120	32.4	9
VK-51A	–69–80	37.5 ± 2.5	–	3	40	22.4	9

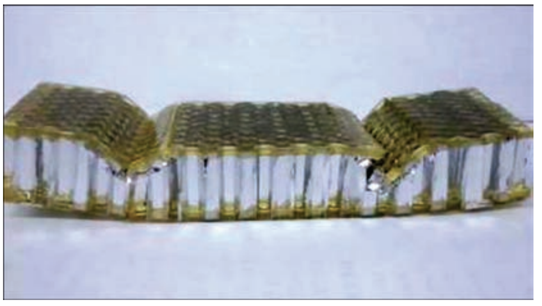

Figure 8. View of the sample after compression tests [14]

plication of wet grinding over 320 emery paper allows achieving the best quality of bonding. The quality of the bond can also be influenced by the nature of organic solvent. Aggressive solvents can leave a layer of oligomers on contact surfaces that adversely affects the strength characteristics of the three-layer panel.

In study [12] it is established that the main cause for failure of panels produced by adhesive bonding, is loosening of the adhesive under the impact of load and its subsequent failure. Investigations, described in [13], also show that increase of the amount of the adhesive up to 2.5 times (from 0.4 up to 1.0 kg/m^2) does not influence the nature of its behaviour under load, and practically does not lead to increase of fatigue strength of the three-layer honeycomb panel.

By the data of work [4], at shear testing of panels (Figure 8) the combination of aluminium core with a binder from a layer of epoxy resin does not exhibit instability — the sample does not undergo any catastrophic changes under load. At load increase, the aluminium of the honeycomb core was compressed because of rigidity of the composite layer. The authors note that cracks in the composite layer and core initiated after the pressure applied by the press exceeded the yield limit of the aluminium core that led to decrease of the load-carrying capacity of the three-layer panel.

Brazing three-layer panels. Braze alloys for brazing aluminium and its alloys can be applied in the form of wire, powder, paste, foil, cast rods, washers, and cladding layer. The most technologically advanced method is cladding of the brazed metal with it. Here, the layer of the braze alloy is relatively uniform, and there is no need for fastening the braze alloy at item assembly for brazing, or adding to the flux the chlorides, containing a servicing agent, as the braze alloy has already been applied in the sites of joint formation on the surface of the parts being brazed and there is no need to improve its flowability.

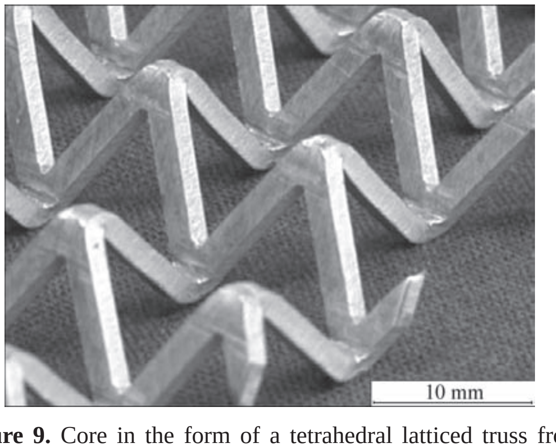

Figure 9. Core in the form of a tetrahedral latticed truss from 6061 alloy [18]

In order to ensure making sound brazed joints of aluminium and its alloys, the braze alloys should meet the following main requirements: braze alloy melting temperature should be below that of aluminium alloys; molten braze alloys should readily wet the base metal and fill the gaps between the parts being brazed; braze alloys should ensure the required strength and corrosion resistance of brazed joints; thermal expansion coefficients of the brazed metal and braze alloy should be approximately the same.

Main braze alloys applied for brazing aluminium and its alloys, can be conditionally divided into three groups:

- aluminium-based braze alloys, ensuring high strength of brazed joints and high corrosion resistance, with melting temperature in the range of 450–630 °C;
- zinc-based braze alloys, characterized by sufficiently high strength and being relatively corrosion-resistant, with melting temperature in the range of 300–450 °C;
- low-melting braze alloys, based on tin, lead, cadmium, gallium, with melting temperature below 300 °C. These braze alloys have a low strength and corrosion resistance. The advantage of these alloys is their low melting temperature, and, therefore, also brazing temperature [15].

In brazing, similar to adhesive bonding, the braze alloy should form symmetrical fillets in the point of contact of the skin with honeycomb core. Here it should be noted that application of both the adhesive, and braze alloy results in increase of the three-layer panel mass. Another factor, limiting application of brazing when joining three-layer panel elements, is braze alloy interaction with base metal in service, leading to thinning of the honeycomb core walls, and formation of cracks at its base [16].

For joining complex-shaped items the authors [17] recommend applying a mixture of Nocolok flux with Si particles on the conjugated surfaces, instead of the traditional cladding with Al–Si system braze alloy, which should be followed by brazing in a vacuum furnace.

In [18] the brazing method was used to join a tetrahedral latticed core (Figure 9) from AA6061 aluminium alloy to skins from AA6951 alloy. AA4343 alloy with 6.8–8.2 % silicon, was applied on panel surfaces as braze alloy. Then, the assembly was coated by Handy Flo-X5518 flux and placed into a muffle furnace. Brazing was performed at the temperature of 595 ± 5 °C. Brazing duration was not more than 5 ± 1 min, that allowed lowering the negative impact of silicon diffusion from the braze alloy on the joint strength properties. Subsequent heat treatment at 500 °C, soaking for 30 min with quenching in water and ageing at 165 °C for 1140 min, allows increasing the core strength up to maximum values, and thus increasing the compressive strength of the panel from 9 up to 20 MPa.

Authors of work [19] applied ultrasonic soldering with Sn–Pb–Zn solder (Sn–29.2Pb–6Zn–1Ag–0.38Cu–0.42Bi wt.%) for joining a three-layer honeycomb panel from 6061 aluminium alloy. Solder melting temperature was 190.68 °C. Heating of the assembly was performed at the rate of 15 °C/s at ultrasonic vibration of 100–980 W at 20 kHz frequency. Increase of ultrasound power to 980 W at simultaneous reduction of mounting gap to 0.1 mm allowed minimizing the angle of wetting by the solder. Optimum soldering time is 45 s. After soldering the solder exhibits four zones: zone enriched in Sn; zone enriched in Pb; Sn–Pb eutectic phase and zone, enriched in Al. Despite the relatively low temperature of the process, soldering leads to partial dissolution of aluminium in the solder.

Methods of three-layer panel welding. *Laser welding.* Laser welding can be used to join relatively thick elements (from 0.5 mm) of the three-layer panels. This method is applicable for joining the trapezoidal core to the skins [20].

Application of this kind of welding, particularly, when joining sheet elements, is associated with formation of a number of defects (pores, splashes, convexities and craters), prevention of which requires following a number of recommendations. Welding is performed in the pulsed mode. To prevent splashes, the authors [21] point to the need to ensure a larger surface of the weld pool in the initial period of welding by smoothly increasing the laser power at the start of the pulse. Appearance of cavities can be avoided by smoothly lowering the power that allows setting the speed of the beam exit from the channel below that of the channel filling with the melt. Maintaining laser power on the level, which corresponds to channel appearance threshold, also prevents formation of the convexity and crater.

Diffusion welding. Chemical treatment of the surfaces before welding is given a special place in diffusion welding of aluminium and its alloys. The oxide film can be removed by etching or mechanical cleaning methods. Chemical etching is the most widely spread method of preparation of the surfaces of aluminium and its alloys to be welded. After removing oxides from the surfaces of aluminium parts to be welded, it is believed to be rational to cover them by resins, lacquers or polymers based on styrene, decomposing without residue at heating in vacuum.

Welding of aluminium and its alloys without interlayers is performed at the temperature of 500–600 °C [22].

By the data of [23], the temperature of vacuum diffusion welding of wrought aluminium alloys after mechanical cleaning of surfaces to be joined is usually lower than that of the alloy heating for quenching. Optimum parameters of welding AMg5 and AMg6 alloys are as follows: T_w = 500 °C; P_w = 10 MPa, t_w = = 10 min, vacuum of $1.33\cdot10^{-3}$ Pa. Here, as noted by the authors, the interface between the welded parts is absent on welded joint microstructure, that is indicative of formation of a monolithic joint. Welding of the alloys in the above modes does not lead to degradation of their mechanical properties, as coagulation of intermetallics in the joint zone is absent, that improves the mechanical properties and increases the ductility of metal.

Application of interlayers which form eutectics with aluminium and other alloy components at heating, enables breaking up the oxide film, activating the processes of diffusion interaction of aluminium alloys and lowering the welding temperature [24]. Copper, magnesium, and zinc in the form of foils or coatings can be used as interlayer materials. In the case of interlayers from zinc, the temperature of welding the joints is equal to 480–500 °C, those from magnesium 470–490 °C, and from copper — 400–450 °C. Joint quality largely depends on the thickness of interlayers. At more that 3 μm thickness the quantity of the eutectic is quite high. The eutectic is partially removed from the joint zone due to deformation. Reduction of interlayer thickness to 1–2 μm allows producing joints of a higher strength, reaching 0.85–0.95 % of that of welded wrought alloys.

The technological aspects of diffusion welding of aluminium alloys are considered in greater detail in [25]. Sufficiently strong joints of aluminium alloys were produced through application of thin interlayers from low-melting metals, namely zinc and gallium. Gallium was applied by mechanical rubbing in the solid or liquid state. Diffusion welding was conducted at the temperature of 420–500 °C. As stated by the authors of [25], gallium is completely dissolved in the base material during the time of isothermal soaking of 240 min. Shear strength of the joints from aluminium-magnesium alloys AMg6 and 01570 through gallium underlayer is equal to 180–210 MPa.

More effective is application of a copper interlayer of 0.8–1.0 μm thickness. At isothermal soaking for 20–30 min and diffusion welding temperature of 500 °C, the process of material recrystallization is actively developing in the joint zone.

Analyzing the results of Auger spectral analysis the authors come to the conclusion that Al–Mg–Cu alloy of eutectic composition forms on the contact boundary as a result of interdiffusion at the stage of isothermal soaking. Presence of the liquid phase promotes breaking up of the oxide film.

Effect of superplasticity is realized in welding 01570 alloy. Recrystallization of the alloy joint zone occurs at the temperature of 472–477 °C and proceeds actively at contact with thin copper interlayer. Strength at shear testing of the joint of 01570 alloy through an interlayer of copper 1 μm thick reaches 260 MPa. Readily reproducible values (± 15 MPa) are achieved in the case, if the coating is applied on both the surfaces being joined (0.5 μm on each).

Work [26] gives the results of studies on diffusion welding in vacuum of three-layer panels with plate-like, cellular and corrugated cores, produced with application of forming devices. Investigations were conducted on alloys of Al–Mg, Al–Zn–Mg, and Al–Cu–Mg systems. Sheet thickness was equal to 2 mm, panel size was 500x500 mm, building height was up to 30 mm. Prior to welding the blanks were degreased with subsequent chemical etching in 70 % nitric acid. Then ion etching was performed on the respective surfaces of the skins and core, which was followed by deposition of copper (or mechanical cleaning by a metal brush). Diffusion welding was conducted in the following mode: welding temperature of 500–510 °C, pressure of 5–10 MPa, and welding time from 30 to 60 min. In welding sheet blanks common grains form in the joint zone in all three cases, and isolated discontinuities are also observed in the alloy of Al–Mg system. Subsequent heat treatment of the joints from alloys of Al–Zn–Mg and Al–Cu–Mg systems (quenching + ageing) allows increasing strength up to the level close to the base material. Shown is the possibility of producing a sound joint of aluminium alloys without a copper underlayer, due to increasing the degree of deformation. Samples in which metal deformation in the joint zone was equal to 70–90 % (370–420 MPa) had maximum shear strength.

Proceeding from the above, one can come to the conclusion that diffusion welding in vacuum is a promising method for joining the skins to the thin-walled core, as this process does not have the weighting and weakening effect of the adhesive and braze alloy on the performance of the three-layer panel. However, as was shown above, at diffusion welding of aluminium alloys the recommended parameters are temperature T_w = 500–600 °C, and specific pressure P_w = 5–10 MPa. These parameters of the process cannot be applied in welding the three-layer panels from aluminium alloys, because of the loss of stability by the thin-walled core, that makes it necessary to lower the heating temperature and search for technological solutions, that would provide a permanent joint. Solution of the arisen problem can be application of forming devices that will allow avoiding unlimited deformation of the core [27], or welding of combined panels, in which the honeycomb core is made of a stronger material, for instance, titanium alloy, and the skin is from aluminium alloy [28]. During welding at the respective temperature under pressure the titanium alloy ribs are embedded into the aluminium alloy, and the aluminium fills all the gaps between the protrusions due to creep. This process is accompanied by fragmentation of the brittle oxide film on aluminium, thus promoting formation of a strong joint.

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