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INVESTIGATION OF HEAT TREATMENT IMPACT ON THE STRENGTH OF Al–Ti BIMETAL HONEYCOMB CORE

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The effect of heat treatment on the strength of aluminium-titanium bimetal honeycomb structures is considered. Aluminium-titanium bimetal was produced by vacuum diffusion welding of strips of AD1 aluminium and VT1-0 titanium low alloys. The possibility of spot welding of bimetal strips 12 mm wide for producing the honeycomb core was studied with different combinations of titanium and aluminium layers. It is shown that the optimal variant is welding the strips in Al/Ti + Al/Ti combination. Here, the average compressive strength of the honeycombs is equal to 41.1 MPa. Annealing of bimetal honeycombs was performed at temperatures of 600 °C and 700 °C. Annealing time at 600 °C was 60–1200 min, at 700 °C it was 10–30 min. It is found that annealing for 60 min at 600 °C leads to formation of individual sites of an intermetallic interlayer up to 1 μm thick in the butt joint between the aluminium and titanium layers that results in increase of compressive strength of the honeycomb samples by 11.7 %, compared to the initial condition. Further increase of annealing time leads to growth of the intermetallic interlayer in the butt joint and to lowering of the compressive strength of the honeycomb samples. It is shown that the honeycomb samples after annealing for 60–600 min at 600 °C at compression with the maximum deformation level of 50 % deform without fracture of the welding location or bimetal material walls. Increase of annealing time leads to embrittlement of both the welding locations, and the material as a whole. 9 Ref., 3 Tables, 7 Figures.

Keywords: aluminium, titanium, foil, bimetal joints, diffusion welding, annealing, intermetallic interlayer, compressive strength

Three-layer aluminium panels with honeycomb core have become widely accepted in aircraft- and ship-building, construction and other industries due to their unique properties, owing to the fact that these structures with their relatively small weight are characterized by high values of strength and rigidity. More over, they have good vibration and radiotechnical characteristics, sound and heat-insulating properties. Such structures can be used as load-bearing elements in the wing, fuselage, flooring, as well as thermal shielding elements [1, 2].

Improvement of service properties of honeycomb panels, as well as increase of resistance of three-layer panel core can be achieved through application of a stronger material, for instance, titanium. So, authors of work [3] proposed installing box-shaped profile elements from a titanium alloy between the skin sheets and transverse stiffeners from an aluminium alloy, which prevent buckling during welding. Box-shaped profile in such panels acts as the main load-carrying structural element, while aluminium alloy sheets are the skin. However, considering that the weight of titanium is almost two times greater than that of aluminium, its application will lead to an essential increase of the total weight of the structure, which is undesirable for the aerospace industry.

An optimal variant between minimum weight and maximum strength of the honeycomb structures, in our opinion, is application of a honeycomb core, produced using bimetal materials. The possibility of producing Al–Ti bimetal by vacuum diffusion welding (VDW) was shown in work [4].

Investigations conducted in [5] lead to the assumption that application of layered composite materials (LCM), which could include foil-based bimetals, can greatly improve the properties of honeycomb structures. Considering the possibility of wide adjustment of LCM structure and composition at the stage of joint formation, investigations on producing such materials with a controlled content of the intermetallic phase in the butt joint are quite relevant.

The good prospects for application of aluminium-titanium bimetal produced by vacuum diffusion welding, to make three-layer honeycomb panels, as well as the possibility of their operation at higher temperatures, will be determined by the strength and intensity of intermetallic phase growth in the bimetal during manufacture of honeycomb structures and their service.

The objective of this work was studying the heat treatment impact on the strength of Al–Ti honeycomb core.

Investigation procedures, materials and sample preparation. The honeycomb core was produced using Al–Ti bimetal blanks of 130×130×0.180 mm size, earlier made by VDW method. Used as initial materi-

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Table 1. Chemical composition of AD1 and VT1-0 alloys [6], wt.%

Alloy	Al	Ti	Fe	Si	Mn	Cu	Mg	Zn	Amount of additives
AD1	Base	0.15	0.3	0.3	0.025	0.02	0.05	0.1	–
VT1-0	–	Base	0.025	0.10	–	–	–	–	0.30

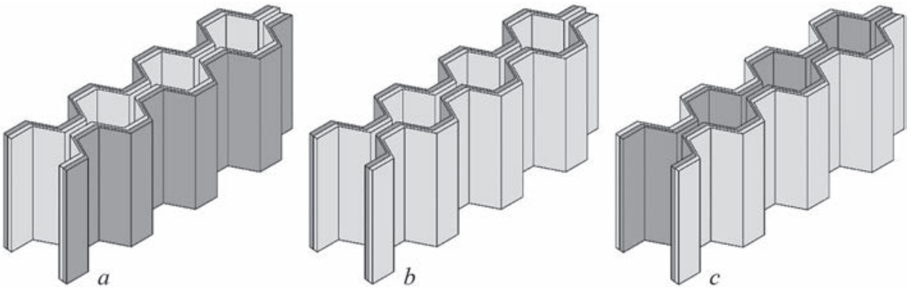

Figure 1. Schematic image of possible variants of joining two corrugated Al–Ti bimetal strips: *a* — Ti/Al + Al/Ti; *b* — Al/Ti + Al/Ti; *c* — Al/Ti + Ti/Al

als were aluminium AD1 and titanium VT1-0 alloys, the composition of which is given in Table 1 [6]. Bimetal sheets were used to make 12 mm wide strips, which, in their turn, were used to form the corrugated strips with 10 mm corrugation pitch.

Unlike the monolithic material, certain difficulties may arise in spot welding of bimetal strips, which are due not only to material heterogeneity by thickness, but also to different physico-mechanical properties of titanium and aluminium. Titanium has low electro- and thermal conductivity, and it is very active towards gases, contained in the atmosphere. Its welding is conducted at relatively small parameters of current, compression force and heating duration. Aluminium has a high heat conductivity, low electric resistance and refractory film on the surface. Therefore, before welding, the part surfaces should be thoroughly cleaned to remove the thick oxide film, in order to prevent lacks-of-penetration [7].

To obtain sound joints from corrugated strips and determine optimal configuration of the layers relative to each other, experiments with three variants of combination of bimetal samples (Figure 1) were conducted:

- Ti/Al + Al/Ti due to welding aluminium layer to aluminium layer;
- Al/Ti + Al/Ti due to welding aluminium layer to titanium layer;
- Al/Ti + Ti/Al due to welding titanium layer to titanium layer.

Spot welding was conducted at room temperature in air. Before welding the contact surfaces of corrugated strips were cleaned mechanically and degreased. Welding was conducted at constant values of voltage U_w = 3 V and current I_w = 270–300 A, heating intensity was here determined by pulse duration t_w = 0.5–5.0 s and number N = 1–20.

Investigations of the impact of heat treatment on formation of an interlayer of intermetallic between titanium and aluminium were conducted under normal conditions in a specially developed stand, which was made up of a muffle furnace and system of temperature control, which consisted of thermocontroller REX C-100, solid-state relay SSR-40 DA and chromel-alumel thermocouple (Figure 2). The sample was placed inside a furnace on a ceramic support. Heat treatment parameters were assigned in the following ranges: temperature T_{an} = 600–700 °C, soaking duration t_{an} = 10–1200 min.

Analysis of structural characteristics of foil and welded joints was performed on sections, using scanning electron microscope CAMSCAN 4, fitted with a system of energy dispersive analysis EDX INCA 200 for local chemical composition on flat samples.

Preparation of transverse microsections of welded joints was conducted by a standard procedure using grinding-polishing equipment of Struers Company.

Mechanical properties of the samples were determined at their compression testing that corresponds to the procedure given in works [1, 8].

Mechanical compression tests of the honeycomb structure were conducted using a digital pressure controller of XK3118T1 grade of KOLI Company, and

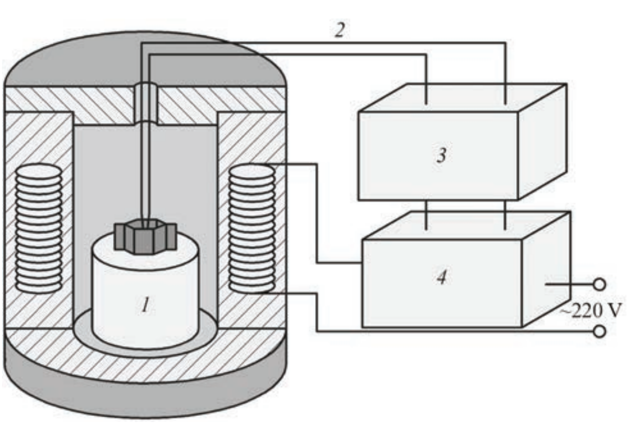

Figure 2. Scheme of a set-up for heat treatment of samples: *1* — ceramic support; *2* — thermocouple; *3* — thermocontroller REX C-100; *4* — solid-state relay SSR-40 DA

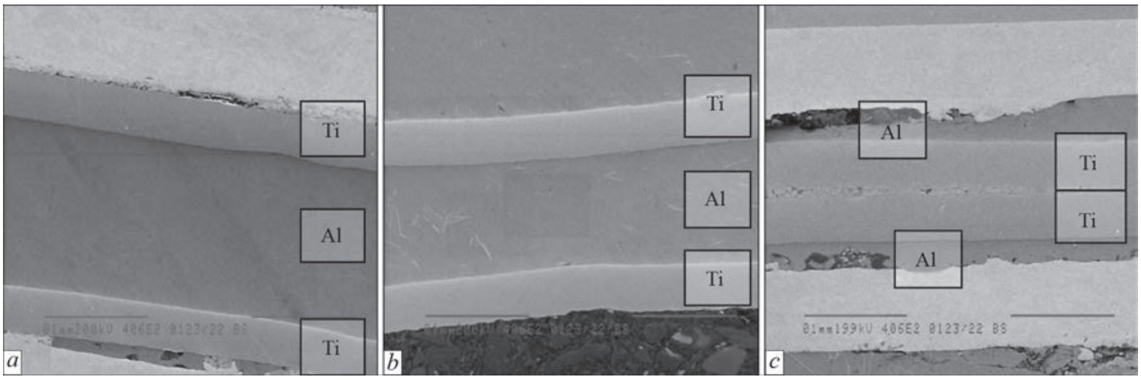

Figure 3. Microstructure of spot joints of Al–Ti bimetal foil: *a* — Ti/Al + Al/Ti; *b* — Ti/Al + Ti/Al; *c* – Al/Ti + Ti/Al

Figure 4. General view of samples of individual honeycombs before (*a*) and after mechanical compression tests (*b*)

pressure sensor of MNC-1 grade of CAS Company with working interval from 0 up to 1000 kg.

Investigation results. In order to produce a honeycomb structure of the core, a technology of welding bimetal profiled strips was developed. It was found that in order to obtain joints of bimetal samples in welding of an aluminium layer to aluminium layer (Ti/Al + Al/Ti), it is enough to use a welding cycle from 2 current pulses of duration t_w = 3 s. In order to produce a core at contact of the aluminium and titanium layer (Ti/Al + TiAl), the number of pulses rises up to 4, while the duration remains constant, t_w = 3 s. In order to produce a core at contact of the titanium layer with titanium layer (Al/Ti + Ti/Al), pulse duration rises up to t_w = 5 s, while their number increases up to 20. Here, excess overheating of aluminium interlayer under the electrodes with its flowing out of the joint zone, is observed. The joint microstructure is given in Figure 3.

Analysis of the modes of welding the honeycomb cores suggests that the variant of welding the aluminium layer to aluminium layer is the least power- and labour-consuming. However, considering that at production of the honeycomb core there is a need for contact between the aluminium and titanium layers, the optimal variant is welding the aluminium layer to the titanium one.

Compression tests of individual honeycomb samples were conducted to assess their strength (Figure 4, *a*). Honeycomb upsetting was specified on the level of 50 % from the initial height. It was established that in the case of joining Ti/Al + Ti/Al and Ti/Al + Ti/Al metal layers (Figure 4, *b*), deformation of the honeycomb core walls takes place at compression without breaking of the spot welds, and in the case of joining Al/Ti + Ti/Al layers (Figure 4, *c*) delamination between the titanium layers is observed. The average strength of the

Table 2. Results of compression testing of bimetal samples of a honeycomb core

Combinations of bimetal strip surfaces	Sample testing	Compressive strength, MPa	Average value of compressive strength, MPa
Ti/Al + Al/Ti	Without fracture	42.1	44.5
		54.1	
		37.4	
Ti/Al + Ti/Al		40.3	41.1
		38.5	
		44.6	
Al/Ti + Ti/Al	With fracture	38.2	35.2
		32.2	
		35.1	

Table 3. Dependence of the intermetallic interlayer thickness and strength of Al–Ti bimetal on heat treatment mode

Sample	Sample heating temperature, T_{an}, °C	Sample soaking duration, min	Average	
			Intermetallic interlayer thickness, μm	Compressive strength, MPa
1	–	–	–	41.1
2	600	60	–	45.9
3	600	150	2	39.9
4	600	300	4	35.6
5	600	600	10	32.4
6	600	1200	11	29.8
7	700	10	4	33.3
8	700	30	14	27.2

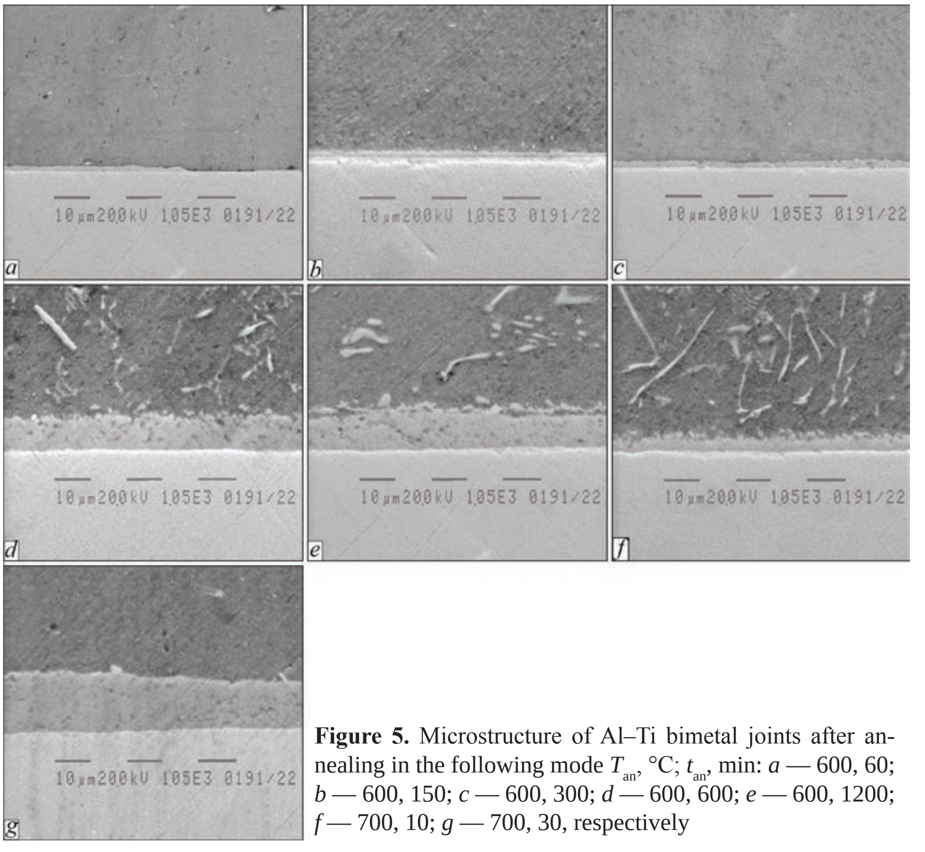

Figure 5. Microstructure of Al–Ti bimetal joints after annealing in the following mode T_{an}, °C; t_{an}, min: *a* — 600, 60; *b* — 600, 150; *c* — 600, 300; *d* — 600, 600; *e* — 600, 1200; *f* — 700, 10; *g* — 700, 30, respectively

joints, when joining Ti/Al + Al/Ti and Ti/Al + Ti/Al bimetal is close in its value, and is equal to 44.5 and 41.1 MPa, respectively. Combining Al/Ti + Ti/Al leads to decrease of the average strength value to 35.2 MPa and breaking of the joints (Table 2). A possible cause for drop in strength is oxidation of the surfaces of titanium during welding, and formation of a large number of defects in the butt joint (Figure 3, *c*).

In order to study the features of growth of the intermetallic interlayer between the titanium and aluminium layers during heat treatment, Al–Ti bimetal joints were heated up to temperatures of 600 and 700 °C. Analysis of the microstructure of Al–Ti bimetal showed that formation and growth of the intermetallic interlayer takes place during heating, while increase of its thickness depends primarily on the temperature and duration of heat treatment (Table 3).

In the structure of Al–Ti bimetal foil after diffusion welding the intermetallic interlayer is not identified [4]. Investigations of the impact of heat treatment showed that soaking at the temperature of 600 °C for 60 min does not lead to formation of a continuous intermetallic interlayer (Figure 5, *a*), but formation of individual intermetallic areas of up to 1 μm thickness is observed in the zone of aluminium-titanium joint. At increase of the annealing duration up to 150 min formation and growth of a continuous intermetallic interlayer of up to 2 μm thickness is observed on aluminium/titanium boundary (Figure 5, *b*). Further increase of annealing duration up to 300 min leads to growth of intermetallic interlayer thickness up to 4 μm that is two times greater than the previous result (Figure 5, *c*). Conducting heat treatment for 600 min leads to formation of an intermetallic interlayer about 10 μm thick (Figure 5, *d*). Increase of the time of soaking at 600 °C temperature up to 1200 min only slightly influences the thickness of the intermetallic interlayer. Average thickness of the intermetallic layer is equal to 11 μm (Figure 5, *e*).

Chemical analysis conducted using a scanning electron microscope showed that the intermetallic interlayers are of the following composition, wt.%: 55.58–58.93 Al and 41.07–44.42 Ti. According to Al–Ti binary diagram, this composition corresponds to an alloy based on a mixture of Al_2Ti and Al_3Ti intermetallics.

Dependence of intermetallic interlayer thickness on annealing duration at 600 °C is shown in Figure 6.

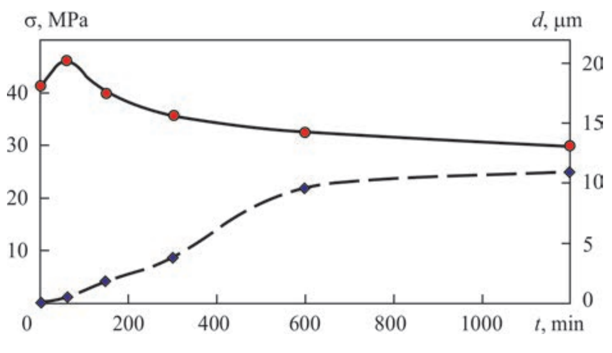

Figure 6. Dependence of compressive strength σ (*1*) and thickness σ (*2*) of intermetallic interlayer on sample annealing duration at 600 °C temperature

Figure 7. General view of samples of individual honeycombs after annealing and mechanical compression testing, T_{an}, °C; t_{an}, min: *a* — 600, 150; *b* — 600, 600; *c* — 600, 1200

Increase of soaking temperature up to 700 °C leads to acceleration of the growth of intermetallic interlayers (Table 3, Figure 5, *f*, *g*).

Determination of the strength of samples after heat treatment was conducted on individual honeycombs (Figure 3, *a*). It was established that after annealing for 60 min at 600 °C 11.7 % increase of compressive strength of honeycomb samples takes place, compared to the initial condition (45.9 against 41.1 MPa) (Table 3, Figure 6). Such an increase of strength can be related to formation of individual centers of the intermetallic phase in the zone of titanium-aluminium joint. Sample annealing for 150 min, in keeping with the results of metallographic studies, leads to formation of a thin intermetallic layer (~ 2 μm) in the butt joint, the presence of which has a minor influence on the load-carrying capacity of the honeycomb, while the strength remains almost on the level of the initial values (39.9 MPa). Further increase of soaking time to 1200 min at 600 °C has a negative impact on strength, the values of which drop to 29.8 MPa. The cause for it is the nonuniformity of the growth and defectiveness of the intermetallic layer that can be associated with the change of its formation mechanism [9], as well as intensive recrystallization of aluminium.

Increase of heat treatment temperature to 700 °C leads to a considerable drop of strength as a result of degradation of the aluminium layer structure (Table 3).

Analysis of the honeycombs after conducting mechanical investigations shows that at compression of samples annealed at 600 °C for 300 min inclusive, deformation of the honeycomb core walls takes place with formation of individual cracks without destruction of the welded spots (Figure 7, *a*). Increase of the heat treatment duration up to 600 min leads to partial destruction of the honeycomb material and welded spots (Figure 7, *b*). After soaking at 600 °C for 1200 min the honeycomb material decomposes into individual elements (Figure 7, *c*).

Thus, obtained results of research conducted on samples consisting from an individual honeycomb, show that use of Al–Ti bimetal core, compared to aluminium one allows increasing its compressive strength four times from 9.8 up to 41.1 MPa, respectively.

Conclusions

1. Studied was the possibility of spot welding of bimetal strips for producing honeycomb core with different combinations of titanium and aluminium layers. It is shown that an optimal variant is welding strips, which corresponds to Al/Ti +Al/Ti joints, the average strength of which is equal to 41.1 MPa.

2. It is shown that annealing of the honeycomb core at the temperature of 600 °C for 60 min leads to formation of individual particles of the intermetallic phase of up to 1 μm size in the butt joint between aluminium and titanium layers that results in 11.7 % increase of compressive strength of the samples, compared to the initial condition.

3. Further increase of annealing time from 60 up to 1200 min leads to formation and growth of the intermetallic layer in the butt joint and lowering of the compressive strength of honeycomb samples.

4. It is shown that samples of the honeycomb core after annealing at 600 °C for 60–600 min at compression with maximum level of deformation of 50 %, deform without destruction of the welded spot and the bimetal material walls. Increase of annealing time leads to embrittlement of both the welded spots, and the honeycomb material as a whole.

5. Use of bimetal honeycomb core, compared to aluminium one, allows increasing its compressive strength from 9.8 up to 41.1 MPa.

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