Influence of Strain-Hardened Zones and Intermetallic Layers of Explosion Welded and Heat Treated Al/Cu Laminated Metal Composites on the Evolution of Thermal Conductivity Coefficient

Yuriy TRYKOV, Leonid GUREVICH *, **Dmitry PRONICHEV, Mikhail TRUNOV**

Volgograd State Technical University, Lenina ave. 28, Volgograd, 400131 Russia

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In this study laminated Al/Cu composite was obtained by explosion welding. The effect of strain-hardened zones and the intermetallic layer on thermal conductivity coefficient was investigated. For this purpose the specimens after explosion welding and after subsequent annealing to obtain the intermetallic layer were studied by X-ray methods and means of optical microscopy to determine the phase composition and the width of intermetallic layer. The microhardness tests were carried out to identify the width of the strain-hardened zones and the intermetallic layer. The thermal conductivity coefficient of the composite was experimentally measured to calculate the thermal properties of the strain-hardened zones and intermetallic layer. The width of the strain-hardened zone and the intermetallic layer was 80 μm and 160 μm respectively. The heat conductivity coefficients of the strain-hardened zones and intermetallic layer were 108 W/(m×K) and less than 35 W/(m×K) respectively.

Keywords: explosion welding, thermal conductivity, bimetal, intermetallic layer.

1. INTRODUCTION

Laminated metal composites (LMCs) are used in many industries: chemical process equipment, primary metal production, shipbuilding and others [1]. The variety of applications of LMCs can be explained by their appropriate advantages over isotropic materials: corrosion resistance, low cost [2], light weight and high strength [3]. Due to high electrical and thermal conductivity of aluminum and copper, Al/Cu bimetal can be applied for high direct-current bus systems [4] and parts of radiators [5, 6]. The electrical and mechanical properties of Al/Cu LMCs and the annealing process impact upon them have already been extensively studied by other researchers [7–11], while the thermal properties are insufficiently explored.

One of the methods to produce a bimetal is explosion welding (EW). Subsequent rolling and heat treatment can improve the bond properties of explosion welded composites [12, 13]. The weldability of aluminium to copper via explosion welding, and the impact of the subsequent rolling on composite's properties had already been investigated in previous studies [14–16].

Using different EW parameters (explosive rate, anvil, stand-off distance), it is possible to obtain various bond interfaces and various properties of adjacent to the bond areas [17]. Subsequent heat treatment causes growth of the intermetallic layer between bonded materials [7].

The thermophysical properties of LMCs depend on:

- crystal lattice distortion, caused by intense plastic deformation during explosive loading;
- the formation of zones with high strength adjacent to the bond;
- single layers or point inclusions of fused metal, formed during explosion welding;
- intermetallic layers, formed during heat treatment;
- hardening after cold rolling.

The purpose of this article is the experimental determination of the influence of LMC's obtaining parameters on their heat conductivity.

2. MATERIALS AND EXPERIMENTS

Parallel configuration of EW was used to obtain the composite. The chemical compositions of materials used in this study are given in Table 1.

The EW parameters were chosen to obtain high-quality bond without molten zones and gaps (Fig. 1, a).

To obtain an intermetallic layer between bonded materials the produced bimetal composite samples were heat treated at constant temperatures below 530 ºC. The limit temperature of 530 ºC was chosen to avoid liquid-phase diffusion between materials.

The microhardness distribution of the surface layers was measured using a standard microhardness tester (PMT-3) with the Vickers indenter test. The hardness tests were carried out with loads of 30 g for 15 seconds. Microhardness tests were performed to identify the width of strain-hardened zones (SHZ) and the intermetallic layer.

Optical images of the composites were investigated by AnaliSYS software in order to define the width and structure of the intermetallic layer.

XRD-patterns of the intermetallic layer were obtained using X-ray diffractometer Dron-3 (Russia) with CuK_α radiation with Ni-filter at an operating voltage of 30 KV and current of 20 mA. The X-ray recording was performed on both the Al side and Cu side of the intermetallic layer.

Heat conductivity of the composite was observed using the thermal conductivity measuring device KIT-02C.

*Corresponding author. Tel.: +7-8442-248094, fax: +7-8442-239941.
E-mail address: *mv@vstu.ru.* (L. Gurevich)

Table 1. Chemical composition of materials before EW

Material	Composition (wt.%)							
Al plate	Fe <0.3	Si <0.3	Mn <0.025	Ti <0.15	Zn <0.1	Cu <0.05	Mg <0.05	Al >99.3
Cu plate	Fe <0.005	Ni <0.002	O <0.05	Sn <0.002	S <0.004	Pb <0.005	Zn <0.004	Cu+Ag>99.9

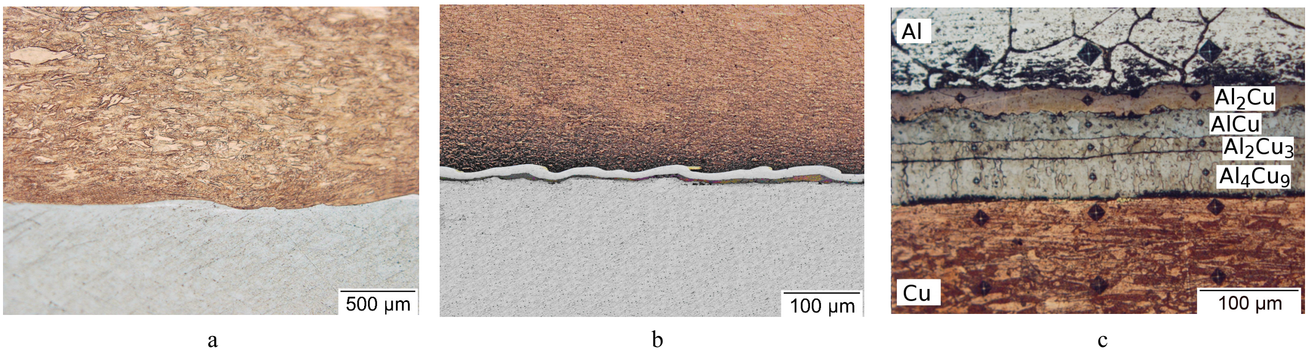

Fig. 1. Optical image of Al/Cu interface (a) after EW (b) after EW and after annealing at 380 ºC for 1 hour (c) after EW and after annealing at 530 ºC for 30 hours

To measure heat conductivity the device uses integral non-stationary method, developed by authors [18], suitable to measure heat conductivity of metals, cermet, items of nanotechnology, composites and other materials in the range from 1 W/(m×K) to 400 W/(m×K). The measurements of heat conductivity coefficient of the composite were undertaken 8 times. The obtained thermal conductivity coefficient value was the average of all measurements.

3. RESULTS AND DISCUSSION

The microhardness distributions across the bond interface after EW and after heat treatments are shown on Fig. 2.

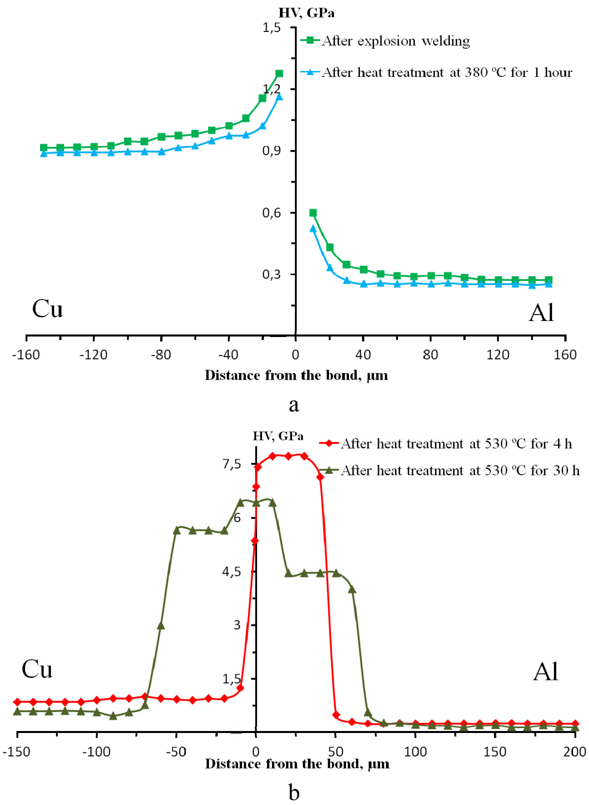

Fig. 2. Microhardnes distributions (a) after EW, after EW and annealing at 380 ºC for 1 hour (b) after EW and after annealing at 530 ºC for 4 hour and 30 hours

After EW the thickness of the SHZ near the bond interface was about 110 µm and 120 µm for copper and aluminum respectively.

One hour annealing at 380 ºC reduces the hardness of SHZ both in aluminum and copper and leads to the growth of an intermetallic layer between bonded materials. The thickness of the intermetallic layer reaches 10 µm after annealing (Fig. 1, b).

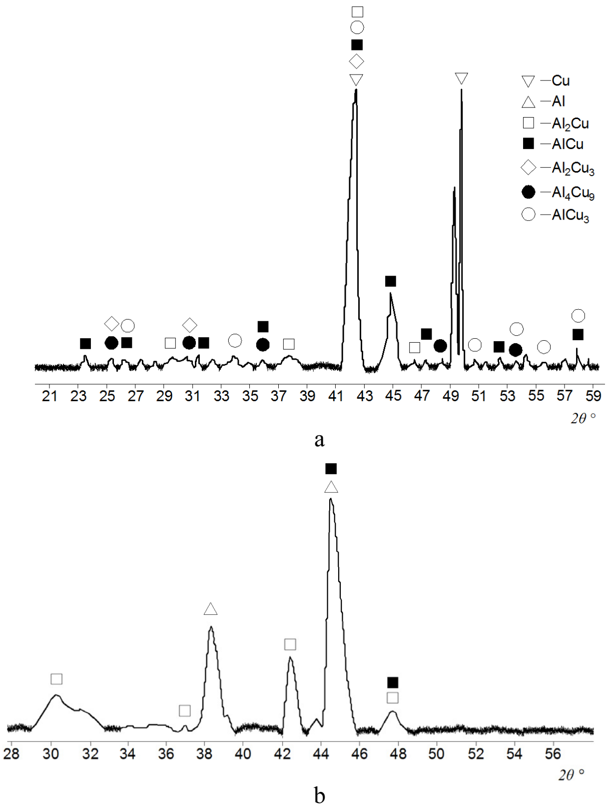

Fig. 3. XRD-patterns of the intermetallic layer phases grown at explosion welded Al/Cu bond during annealing at 530 ºC for 30 hours (a) Cu side of the intermetallic layer (b) Al side of the intermetallic layer

After the subsequent annealing at 530 ºC for 4 hours strain hardened zones were completely reduced. Microhardness of Cu and Al after 20 h annealing at 530 ºC

Table 2. Experimentally obtained values of thermal conductivity coefficients

Annealing at 530 ºC time, h	Layer width, μm				Heat conductivity coefficient, W/(m×K)				
	Cu	Al	SHZ	Intermetallic layer	Cu[1]	Al[1]	LMC	SHZ[2]	Intermetallic layer[2]
0	5500	4200	230	–	410	220	287	108	–
3	5485	4163	–	52	410	220	287	–	36
10	5465	4151	–	84	410	220	280	–	35
20	5438	4139	–	123	410	220	269	–	31
30	5415	4124	–	161	410	220	267	–	37

[1] values obtained before bonding; [2] values calculated from eq. (4).

was 0.87 GPa – 0.9 GPa and 0.26 GPa – 0.27 GPa respectively. The microhardness values of intermetallic layers after 20 h and 30 h annealing at 530 ºC were 7.5 GPa – 7.8 GPa and 6.3 GPa respectively, which in line with [19].

The 30 hour annealing at 530 ºC results in formation of 4 visible different intermetallic layers (Fig. 1, c), while after 1 hour annealing at 380 ºC only one layer was identified. The X-ray micro-structural analysis revealed the following phases: Al_2Cu, Al_2Cu_3, AlCu, Al_4Cu_9 and $AlCu_3$, which were indentified in [20]. The XRD-patterns taken from Al and Cu sides of the intermetallic layer of the annealed at 530 ºC sample are presented on Fig. 3.

The kinetics of the intermetallic growth is presented on Fig. 4. The thickness of intermetallic layers after 30 hour annealing at 530 ºC was 160 μm.

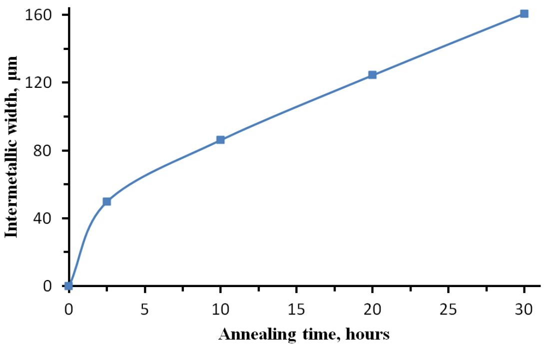

Fig. 4. Relationship between thickness of intermetallic compound layers and annealing time at 530 ºC

The total thermal resistance R_C of a composite is given by:

$$\frac{1}{R_C} = \sum_{i=1}^{n} \frac{1}{R_i}, \quad (1)$$

where n denotes the number of the components of the composite with thermal resistances R_i:

$$R_i = \frac{\delta_i}{\lambda_i}, \quad (2)$$

where δ_i and λ_i are the thicknesses and heat conductivity coefficients of the layers in the composite respectively.

Using eqs. (1) and (2) we find:

$$\lambda_{LMC} = \frac{\sum_{i=1}^{n} \delta_i}{\sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}}, \quad (3)$$

where λ_{LMC} – heat conductivity coefficient of the composite.

Using eq. (3) we can calculate the thermal conductivity coefficient of SZH or intermetallic layer (IL) assuming the heat conductivity coefficients of all the other composite's components and the entire thicknesses to be known:

$$\lambda_{(SZH)IL} = \frac{\delta_{(SZH)IL}}{R_{LMC} - (R_{Cu} + R_{Al})}, \quad (4)$$

The value of the heat conductivity coefficient of an explosion bonded Cu-Al specimen, observed from thermal conductivity experiments (287 W/(m×K)), is lower, than calculated using eq. (3) without considering the effect of strain hardened zone.

Heat treating at 380 ºC of a composite leads to a small increase in the value of heat conductivity coefficient (302 W/(m×K)), despite the appearance of thin intermetallic layer. Diffusion annealing at 530 ºC for 30 hours reduces the value of heat conductivity coefficient λ_{LMC} to 267 W/(m×K).Both the calculated and measured parameters are listed in Table 2.

The value of heat conductivity coefficient of intermetallic layer is 31 W/(m×K) – 37 W/(m×K), and it varies depending on the chemical composition of the diffusion layers (Fig. 5)

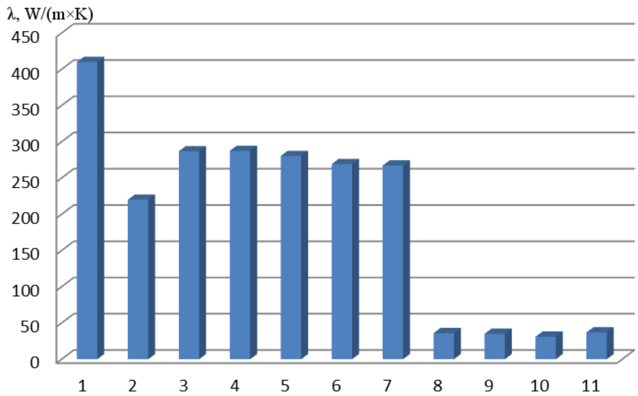

Fig. 5. Heat conductivity of Al/Cu bimetal and its components (1) Cu, (2) Al, (3–7) Al/Cu bimetal (3 – after EW, 4 – after annealing at 530 ºC for 3 hours, 5 – 530 ºC for 10 hours, 6 – 530 ºC for 20 hours, 7 – 530 ºC for 30 hours), (8–11) intermetallic layers (8 – 530 ºC for 3 hours, 9 – 530 ºC for 10 hours, 10 – 530 ºC for 20 hours, 11 – 530 ºC for 30 hours)

4. CONCLUSIONS

The thermal conductivity coefficients of the intermetallic layer containing Al_2Cu, Al_2Cu_3, AlCu, Al_4Cu_9 and $AlCu_3$ phases in the bond of heat treated explosion welded Al-Cu bimetal and of the strain hardened zone in explosion welded Al-Cu bimetal were measured to be less than 40 W/(m×K) and 110 W/(m×K) respectively. The intermetallic layers formed during annealing increase the thermal resistance of the laminated Al/Cu composite. This effect can be used to manufacture thermal protective elements in Al/Cu components. Multi-layered Al/Cu composites with thin Cu layers and high volume fraction of intermetallics improve thermal resistance of the composite.

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