The structure and the phase composition of copper aluminide-based coatings formed on the aluminum surface under contact melting in the Al-Cu system joints

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Abstract. A contact melting mechanism in the Al-Cu system is proposed and experimentally verified. The impact of contact melting thermal and temporal conditions on the phase composition, structure and properties of coatings produced on aluminum surfaces is investigated.

1. Introduction

Wear-resistant coatings based on intermetallic compounds are used to increase the wear resistance of the electrically conductive material surface [1-5]. Complex technologies are employed to obtain these surfaces, and they include a preliminary coating of a component surface with a layer of the metal which can form intermetallic joints with the base metal accompanied by a subsequent diffusion annealing of the composite material produced [6].

A significant increase of diffusion interaction between dissimilar metals can be achieved through contact melting at the metal interface [7-9]. The process consists in the transition of contacting dissimilar hard materials to the liquid state at temperatures below their melting points. This phenomenon is typical of eutectic systems and the systems which form solid solutions with a minimum on the liquidus curve.

The use of explosion welding in this technology is substantiated by a number of advantages which this method has for joining dissimilar metals. The main advantage is the production of a composite with a firm-and-impervious joint of layers with the thickness required.

The paper aims at establishing the regularities in structure formation and the properties of aluminide copper-based coatings which form on the aluminum surface under contact melting in the Al-Cu system joints produced by explosion welding.

2. Materials and methods

Explosion welded specimens of grade AD1 of aluminum with grade M1 of copper (16 + 0.1-0.5 mm) were used as experimental material. The specimens were heat treated in the SNOL heater ‘8.2/1100’ at temperatures of 560°C and 580°C. A metallographic study was performed with the Olympus BX-61 metallurgical microscope. The interaction zone phase composition was evaluated by comparing the data obtained with the DRON-3 diffractometer and the Versa 3D DualBeam electronic microscope. Microhardness measurements were performed using the PMT-3M instrument with the 100 gram indentor load.
3. Results and discussion
The Al-Cu system (Figure 1) belongs to heavily degenerated eutectic systems with the eutectic point in the phase diagram shifted in the direction of Al. Hence, the decisive role in the liquid phase formation in the Al-Cu contact should be played by the melting point depression [7]. The analysis of the Al-Cu phase diagram made it possible to suggest the following sequence of interaction zone formation in contact melting at the interface of explosively welded bimetal AD1+M1.

The contact melting process in the Al-Cu system starts at temperature above 548 °C (Figure 1) and is initiated by the reciprocal diffusion which leads to the formation of the Al(Cu)-based solid solution of maximum concentration at the interface of the explosively welded metals; this solution deliquesces easily.

Upon the achievement of a certain critical Cu concentration in Al(Cu), separate small areas of the solid solution turn out to be “blocked” from each other by Cu atom ‘partitions’ as a result of breaking Al-Al interatomic bonds. It leads to the formation of nano-sized clusters where melting point depression shows up [7].

Further, the chaotically distributed clusters merge upon the contact and form a liquid matrix with separate Al(Cu) solid-phased particles (microcrystals). With time, the solid particles, surrounded with the liquid, dissolve and the entire solid solution area turns into a thin liquid film.

The liquid interlayer thickness growth is accompanied by a decrease in the Cu concentration as per the liquidus line in the Al-Cu phase diagram. In doing so, the copper concentration falls in the interlayer part adjoining the Al-based solid solution (points ‘I’ and ‘II’). The concentration growth is observed in the interlayer part adjoining the Cu-based solid solution (points ‘I’ and ‘II’).

The nonequilibrium crystallization in the interaction zone may be followed by the formation of Al(Cu) and CuAl2 subsequent phases. In case of a prolonged heat treatment, a complete Cu dissipation is to be followed by the liquid phase coming into equilibrium as per the points ‘I’ and ‘II’.

In order to experimentally verify that the interaction zone structure complies with the predictions, based on the phase diagram, the real structure obtained under heat treatment as per the contact melting regime at hold times which provide the presence or absence of the non-reacted Cu layer; heat treatment of a set of specimens was performed at 560°C and 580°C (Figures 2, 3).
It was established that the interaction zone thickness (Figure 2), formed at the AD1+M1 interface (16 ± 0.1 mm) after heat treatment at 560°C, changes from 55 µm (5 min) to 690 µm (20 min). The
quantity of Al and Cu in the interaction zone, expressed on a percentage base and calculated by the amount of the components which took part in the reaction (thickness loss compared with the initial values after welding considering component densities), ranges from 30 to 42 wt.% for Cu and 58 to 70 wt.% for Al. For the hold time of 5 min, which is insufficient for complete Cu melting (Figure 2, a), the copper concentration in the interaction zone (42 wt.%) somewhat exceeds the eutectic concentration (33 wt.%). The hold time increase to 10 min ensures Cu melting in the interaction zone and reduces the copper concentration to the eutectic value (Figure 2, b). When the hold time equals 20 min, the Cu concentration continues to decrease and is accompanied with the emergence of Al(Cu) inclusions in the interaction zone structure (Figure 2, c).

The heat treatment temperature increase facilitates the contact melting velocity increase. The interaction zone thickness after heat treatment at 580°C (copper layer thickness is 0.5 mm) changes from 1.6 (5 min) to 5.2 mm (50 min (Figures 3, 5, a). The quantity of Al and Cu in the interaction zone expressed on the percentage basis is within the range of 59 to 74 wt. % and from 26 to 41 wt.% respectively. For hold times insufficient for Cu complete melting (from 5 to 10 min), the Cu concentration is somewhat higher (38 to 41 wt. %) than the eutectic one. An increase in the hold time after Cu complete melting leads to the coagulation of the structural components and the formation of flake-like homogenous insertions in the coating (Figures 3, d, 3, e).

The analysis of the interaction zone surface XRD patterns, the study of chemical element distribution throughout the interaction zone thickness and point energy-dispersion microanalysis (Figure 4, Tables 1, 2) made it possible to conclude that after heat treatment at 560°C, the interaction zone major structural components are structurally free intermetallic CuAl2 and eutectic Al(Cu)+CuAl2. Intermetallic Cu2Al3 was additionally found at the Cu boundary after heat treatment at 580°C.

![Figure 4. The SEM image of the coating structure (heat treatment at 580°C, 5 min) from the copper side (a) and from the aluminum side (b) with point location for element composition analysis.](image)

| point | element | wt. % | at. % | error, % | phase  |
|-------|---------|-------|-------|----------|--------|
| 1     | Al      | 5.78  | 12.62 | 10.35    | Cu(Al) |
|       | Cu      | 94.22 | 87.38 | 2.02     |        |
| 2     | Al      | 1.55  | 3.57  | 13.57    | Cu(Al) |
|       | Cu      | 98.45 | 96.43 | 1.96     |        |
| 3     | Al      | 22.53 | 40.64 | 8.46     | Al2Cu3 |
|       | Cu      | 77.47 | 59.36 | 2.06     |        |
| 4     | Al      | 22.71 | 40.89 | 8.47     | Al2Cu3 |
|       | Cu      | 77.29 | 59.11 | 2.09     |        |
Table 2. Point energy dispersion microanalysis results (Figure 4, b)

| point | element | wt. % | at. % | error, % | phase       |
|-------|---------|-------|-------|----------|-------------|
| 1     | Al      | 93.89 | 97.31 | 2.3      | Al(Cu)      |
|       | Cu      | 6.11  | 2.69  | 5.23     |             |
| 2     | Al      | 53.16 | 72.77 | 6.77     | CuAl₂ + эвт |
|       | Cu      | 46.84 | 27.23 | 2.23     |             |

The interaction zone microhardness after heat treatment at 560°C is approximately 1.5 GPa. Microhardness mean values in the interaction zone obtained at 580°C diminish with the Cu concentration gradient from 2.7 GPa (5 minutes) to 1.4 GPa (50 minutes) (Figure 5, b).

![Figure 5](image)

Figure 5. Variations of interaction zone thickness (a) and microhardness mean values (b) depending on the hold time at 580°C.

4. Conclusions
The contact melting process in the Al-Cu system is initiated by reciprocal diffusion which leads to solid solution formation in Al, and this solution deliquesces easily. Diffusion interaction in the liquid phase presence results in intermetallic coating formation on the Al surface. The coating structure and the phase composition are conditioned by thermal and temporal heat treatment regimes and the weight content of the components which participated in the reaction.

The major structural components of the system Al-Cu coating obtained on the Al base after heat treatment as per the contact melting regime which provides total melting of the copper layer are CuAl₂+Al(Cu) eutectics and Al(Cu) solid solution.

An increase in heat treatment temperature leads to an increase of the contact melting velocity and the interaction zone thickness while an increase in the hold time brings about the coagulation of the structurally free solid solution and a decrease in the coating hardness.

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