Structure and micromechanical properties of bimetal VT1-0 + AMg6 obtained by explosion welding

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Abstract. The weldability range of a VT1-0 + AMg6 bimetal without the traditional use of an intermediate layer of AD1 is determined. The phase composition of the melts on the interlayer boundary obtained by explosion welding of a titanium and an aluminum alloy at different values of the kinetic energy expended on the plastic deformation of the surface layers of metal was investigated. In the vortex zones, areas of melted metal with a hardness of 10-14 GPa were measured.

1. Introduction
Due to the formation of brittle titanium aluminides during fusion welding [1-3], it is possible to produce composites of aluminum and titanium alloys of sufficient thickness only by methods not related to long diffusion processes, one of which is explosion welding [4, 5]. The quality of the joint, as well as the properties of the main layers (titanium and aluminum alloy) of the composites obtained in this way, may vary depending on the welding conditions. So, with an increased energy of explosion welding, melted areas are formed between the metals being welded, leading to structural and mechanical inhomogeneity [6-11]. Usually, plasticity buffer from pure aluminum is introduced between the explosion-welded plates of aluminum and titanium alloys, providing a sufficiently large interval between the lower and upper weldability limits. However, the addition of a soft interlayer leads to a decrease in the strength of the composite under loading normally to the surface of the joint.

The aim of this work was to study the formation of structural-mechanical inhomogeneity at the interface of a bimetal junction titanium + aluminum alloy produced by explosion welding at various values of the kinetic energy expended on plastic deformation of surface metal layers ($W_2$).

2. Materials and methods
Studies were performed on an explosion-welded by an angular scheme bimetal titanium VT1-0 + aluminum alloy AMg6, at values of $W_2$ 0.5-2.0 MJ/m². Research samples were cut in the direction of detonation development. Metallographic studies were carried out using optical (modular motorized microscope Olympus BX-61) and electron (scanning electron microscope Versa 3D) microscopy. Microhardness test according to the restored imprint method was performed by indentation of a diamond indenter in the shape of a four-sided pyramid with a square base on a PMT-3M instrument under loads of 0.1-0.5 N.
3. Results and Discussion

The variation of the microstructure of the layered titanium-aluminum AMg6 alloy system of with varying collision speed and \( W_2 \) was investigated on transverse templates by optical microscopy. At \( W_2 = 0.5 \text{ MJ/m}^2 \), a waveless connection with a straight-line interface is formed (figure 1). An increase in \( W_2 \) to 0.6 \text{ MJ/m}^2 leads to the appearance of the first fragments of the wave profile, and at \( W_2 = 0.7 \text{ MJ/m}^2 \), a stable wave profile interface is formed. With an increase in \( W_2 \) from 0.7 to 1.5 \text{ MJ/m}^2 at the titanium – alloy AMg6 interface, the amplitude and wavelength increased, while their ratio remained unchanged at 0.26–0.3. When \( W_2 \) is above 1.5 \text{ MJ/m}^2, the wave amplitude begins to decrease at a constant length with destruction along the already formed wave profile of the interface.

![Figure 1. Change in the wave-like profile of the interface between layers at different specific energy \( W_2 \) (titanium on top).](image1)

It is known [12, 13] that the degree of fusion in compounds welded by the explosion is determined by the level of plastic deformation of the surface layers, and, consequently, by the specific energy \( W_2 \) spent on its implementation. At \( W_2 \geq 0.7 \text{ MJ/m}^2 \), zones of intense mixing of materials appear in the form of “vortices” at the lower point of the depression in the direction of the shock front (figure 2). The microhardness of the intensive mixing zone is 11.2-11.5 GPa, its area is \( \approx 0.01 \text{ mm}^2 \). A spot X-ray microanalysis allowed us to establish that the melt consists of \( \text{Ti}_3\text{Al(Mg)} \), \( \text{TiAl(Mg)} \), \( \text{TiAl(Mg)}_3 \) intermetallic compounds and areas of unreacted metal (see table 1).

![Figure 2. SEM image of intensive mixing the zone at \( W_2 = 0.7 \text{ MJ/m}^2 \).](image2)
Table 1. The chemical composition of the "vortexes" in the layered system obtained at $W_2 = 0.7$ MJ/m$^2$.

| Element | The content of the element (at. %) in points (see figure 2) |
|---------|-------------------------------------------------|
|         | 1            | 2            | 3            | 4    |
| Mg      | 3.0±0.3      | 4.5±0.3      | 6.9±0.3      | -    |
| Al      | 33.3±1.8     | 55.5±2.7     | 80.9±2.6     | -    |
| Ti      | 63.8±1.1     | 40.1±0.7     | 12.1±0.3     | 100  |
| Structural components | Ti$_3$Al(Mg) | TiAl(Mg) | TiAl(Mg)$_3$+Al(Mg) | Ti |

Intensification of the welding mode ($W_2$ above 1.0 MJ/m$^2$) leads to the formation of individual microcracks, which, as $W_2$ increases, merge into a single crack that passes along the wave-like interface of the joint and partially through the AMg6 boundary layer. The mixing zones remain after destruction in the titanium layer. When the specific energy reaches 1.2 MJ/m$^2$, the melt area increases to 0.058 mm$^2$, and its microhardness reaches a maximum value of 14 GPa (figure 3, table 2).

Figure 3. SEM image of intensive mixing the zone at $W_2 = 1.2$ MJ/m$^2$.

Table 2. The chemical composition of the "vortexes" in the layered system obtained at $W_2 = 1.2$ MJ/m$^2$.

| Element | The content of the element (at. %) in points (see figure 3) |
|---------|-------------------------------------------------|
|         | 1            | 2            | 3            | 4    |
| Mg      | 8.1±0.3      | 3.5±0.3      | 2.9±0.3      | -    |
| Al      | 84.0±2.5     | 49.3±2.6     | 36.4±2.3     | -    |
| Ti      | 7.9±0.2      | 47.2±0.6     | 60.7±1.0     | 100  |
| Structural components | TiAl(Mg)$_3$+Al(Mg) | TiAl(Mg) | TiAl(Mg)$_2$ | Ti |
The zone of intensive mixing of the second type is located in the form of a strip of various thickness directly at the interface of titanium and aluminum alloy. The structure of such layers in layered systems obtained at different values of the impact velocity and specific kinetic energy \( W_2 \) is shown in figure 4. By energy dispersive analysis, it was found that the zone of intensive mixing of the second type is a eutectic TiAl\(_3\)(Mg) + Al(Mg) and separate inclusions of aluminides.

![Figure 4](image)

**Figure 4.** Appearance of crystallized structures in zones of intense vortex formation at various values of specific energy \( W_2 \).

Thus, when the energy \( W_2 > 1.0 \text{ MJ/m}^2 \) in the "vortex" structure exists all intermetallics which are present on the phase diagram of a binary Ti-Al system. The most thermodynamically stable aluminide of the type TiAl\(_3\) [14] was detected only in a mixture with a solid solution of Al(Mg).

By analyzing the micromechanical properties in the border zone, it was found that in the \( W_2 \) interval from 0.5 to 0.7 MJ/m\(^2\), an increase in the impact velocity caused a slight increase in the microhardness of the border layers VT1-0 and AMg6 (figure 5, a). In the interval of \( W_2 \) 0.8–1.6 MJ/m\(^2\), the microhardness values stabilize. A further increase in \( W_2 \) reduced the microhardness, which is associated both with the intensification of recrystallization processes due to an increase in the temperature of thin joined layers and a decrease in first-type stresses at the boundary of the connected layers when the mechanical connection between them breaks down when cracks form.

The dependence of the average hardness of the "vortices" on the specific energy \( W_2 \) is shown in figure 5, b. The maximum hardness of mixing zones reaches 14 GPa at \( W_2 = 1.0 \text{ MJ/m}^2 \), which is significantly higher than the microhardness of the vortices in the titanium-aluminum system [6 - 8].

![Figure 5](image)

**Figure 5.** Microhardness of layers of aluminum alloy AMg6 (1) and titanium VT1-0 (2) near the interface in the zone of maximum plastic shear deformation (a) and sections of vortexes near the depression (b).
Conclusions

During explosion welding of an aluminum alloy with titanium without technically pure aluminum plasticity buffer, structural-mechanical heterogeneity is formed from, which is determined by the energy expended on plastic deformation of the surface metal layers. At $0.7 < W_2 < 0.9$ MJ/m$^2$, at the border of the VT1-0 + AMg6 junction, a clearly defined wave profile is formed without visible microcracks with areas of local melting of the material. An increase in the specific energy $W_2$ from 0.5 to 2.0 MJ/m$^2$ leads to an increase in the area of local inclusions of the melted metal formed on the interlayer boundary from 0.01 to 0.06 mm$^2$. When the specific energy $W_2$ is more than 1.0 MJ/m$^2$, a crack is formed along the wave-like boundary of the joint and partially through the AMg6 boundary layer.

When the energy $W_2 > 1.0$ MJ/m$^2$ in the "vortex" structure, there are all intermetallic compounds that are present on the phase diagram of the Ti-Al binary system. The most thermodynamically stable aluminide of the type TiAl$_3$ was detected only in a mixture with a solid solution of Al(Mg).

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