Features of creation and properties of steel-aluminum composite with diffusion barrier

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Abstract. The paper presents the results of developments to create a new composite steel-aluminum material with a diffusion barrier. It is shown that the creation between the aluminum and steel of the diffusion barrier made from the nitrated steel layer makes it possible to significantly increase the heat resistance of the steel-aluminum composite due to the inhibition of the diffusion processes. The results of the investigation of the effect of a nitrated layer on the structure, strength and electrophysical properties of a steel-aluminum composite are presented.

1. Introduction
In recent years, steel-aluminum composite materials find wide application in various industries and engineering as transition elements, parts and units of power and electrical equipment [1–3]. In obtaining a steel-aluminum compound, the main problem is the formation of brittle intermetallic compounds at the metal interface, which sharply reduce the strength of the welded joint [4, 5]. Explosion welding allows one to receive not only high-quality steel-aluminum compounds without intermetallics and practically zero transient electrical resistivity, but also to obtain composite materials with a different combination of layers, thicknesses and sizes [6, 7].

However, the exploitation of such composites from dissimilar metals has limitations on the permissible heating temperature. This is due to activation of diffusion processes at elevated temperatures and the formation on the border of welded joints brittle intermetallic compounds, which reduce the strength and performance properties of the composite [8, 9]. To suppress diffusion and improve thermal stability of composite materials creating a diffusion barrier between dissimilar layers of the composite, which helps prevent the formation of brittle intermetallic compounds [10, 11].

The aim of this work was to improve thermal stability of the composite steel-aluminum by creating on the border of the weld of the diffusion barrier.

2. Materials and methods
In experiments, the authors used as the objects of investigation aluminum A5 and low-carbon steel St.3. Nitriding of steel samples was carried out with heating 600 °C and holding in an ammonia medium for 5 to 24 hours, which made it possible to obtain on the steel surface a thin nitrated layer of various thicknesses. Mechanical tests on the separation of the layers was carried out on a tensile testing machine R-500. Metallographic studies were performed on optical microscope OLYMPUS BX61. The distribution of microhardness was measured on the device Metkon DUORLINE-M. Transient electrical resistivity at the border of the connection of aluminium to steel was estimated by...
the method [12], based on direct measurement of the voltage drop in steel-aluminum samples A5+St3 and A5 +St3 (nitrated) by passing through them a constant current of 1 A.

3. Results and discussion
On the basis of the results of these studies created a new heat-resistant composite steel-aluminum material with a diffusion barrier, allowing one not only to slow down significantly the flow of diffusion processes between steel and aluminum, but also to shift the temperature interval of the beginning of their course to higher temperatures. A diffusion barrier is achieved by creating on the

![Graph](image1)

**Figure 1.** Effect of the thickness of the nitrated layer on the strength of the explosive welded composite steel-aluminum material:
1 - after welding, 2 - after welding and heat treatment at $T = 500 \, ^\circ C$, $\tau = 1 \, h$.

![Graph](image2)

**Figure 2.** Influence of heating temperature and exposure time on the strength of composite steel-aluminum material:
1 – A5+St3(nitrated), $\tau = 1 \, h$; 2 – A5+St3(nitrated), $\tau = 5 \, h$; 3 – A5+St3(nitrated), $\tau = 10 \, h$;
4 – A5+St3, $\tau = 10 \, h$. 
surface of the steel plate thin nitrated layer.

It was established experimentally that the optimum thickness of the nitrated layer is 0.4-0.6 mm, which allows one to provide a reliable diffusion barrier by thermal effects on the steel-aluminum composite (Figure 1). When one performs a nitrated layer of a lesser thickness, subsequent heating of the composite reduces the strength of the welded joint due to the partial removal of the thin nitrated layer of a cumulative jet. Increasing the thickness of the nitrated layer is impractical because of the substantial growth of time of thermochemical treatment. Numerous experiments have shown that the presence of the thin nitrated layer on the steel surface has virtually no effect on weld strength.

**Figure 3.** Microstructure of the compound A5 + St3 (nitrated) composite interface with a diffusion barrier (a) and composite A5 + St3 without a barrier (b) after explosion welding and heat treatment at $T = 500^\circ C$, $\tau = 10$ h
To assess the thermal stability of the steel-aluminum composite material with a nitrated diffusion, a barrier was produced by heating samples in the temperature range from 250 to 550 °C with an exposure of 1-10 hours. The results showed that the creation on the steel surface a thin nitrated layer will significantly slow down the diffusion processes between aluminum and steel, durable to maintain a healthy connection at the temperature of heating to 500-520 °C, while in explosion welded steel-aluminum samples with no diffusion barrier, the tensile strength of the layers sharply decreased to $\sigma_{\text{pull}} = 20$ MPa (Figure 2).

The study of the microstructure of the connection zone showed that the reduction of strength of steel-aluminum samples without a diffusion barrier due to the presence on border of connection of aluminum to steel a thin layer of brittle intermetallic compounds Fe$_2$Al$_5$ (Figure 3 a), formed as a result of flow diffusion. In steel-aluminum samples with a diffusion barrier from the nitrated layer, the formation of brittle intermetallic compounds was not observed (Figure 3 b). It is connected with education at the interface of a thin film of aluminum nitride AlN, which allows one to slow down the flow of diffusion processes and increases the heat resistance of the composite material.

The study of the distribution of microhardness on the border of the compound of aluminum with steel has shown that after the explosive welding, the microhardness value for steel-aluminum samples with diffusion barrier a little higher compared to conventional steel-aluminum samples without a nitride layer. At the same time, as the boundary between aluminum and steel was bound to the interface in samples with a diffusion barrier, the microhardness increased from 205 to 290 MPa, and in ordinary steel-aluminum samples the value of microhardness increased insignificantly from 200 to 250 MPa (Figure 4). Directly the measurements of microhardness of the melted areas showed that after the explosive welding of the ordinary steel-aluminum samples its value was about 4000-4500 MPa, and the steel-aluminum samples with a diffusion barrier value of microhardness was more and amounted to 8500-8800 MPa, which is associated with the formation of solid solution based on iron nitrides Fe$_4$N, Fe$_3$N and Fe$_2$N, which have high microhardness.

![Figure 4. Distribution of microhardness on the border of explosive welded steel-aluminum composite material](image-url)
One of the main requirements in the operation of the composite transition elements is their low transitional resistance. For this purpose, studies were carried out to study the effect of the heating temperature and the amount of molten metal on the electrophysical properties of the composite steel-aluminum material. It is established that in the absence or presence of compound in a small amount of fragile melted metal ($K_{\text{fus}} < 10\%$), the proportion of transient electrical resistivity $\rho_l$ of steel-aluminum composite was not more than $25 \ \mu\Omega\cdot\text{mm}^2$. Increasing the amount of melted metal leads to the straight ascending $\rho_l$. So, when the content in weld molten metal $K_{\text{fus}} > 50\%$ specific transient electrical resistivity increases more than 2 times (Figure 5). This leads to a decrease in the operational properties of the transition element, its overheating and premature failure. It should also be noted that during explosive welding of aluminum with nitrated steel amount of melted metal is smaller in comparison with welding of the composite material without the diffusion barrier.

An investigation of the influence of the heating temperature on the change in its specific transient electrical resistivity showed that the electrophysical properties of a steel-aluminum composite with a diffusion barrier from a nitrated layer are significantly higher than those of a composite without a diffusion barrier. Thus, after heating at $T = 500 \ ^\circ\text{C}$ for steel-aluminum samples with a nitrified layer, the value of the specific transient electrical resistivity did not exceed $28-30 \ \mu\Omega\cdot\text{mm}^2$, and in samples without a diffusion barrier the transition resistance was significantly increased to $\rho_l = 60-65 \ \mu\Omega\cdot\text{mm}^2$ (Figure 5).

4. Conclusions

1. Creation a diffusion barrier of a thin nitrated layer between aluminum and steel allows one to increase the resistance of steel-aluminum composites due to the inhibition of the flow of diffusion
processes on the boundary of the welded joint and displacement of the temperature interval of the beginning of the formation of intermetallic compounds at higher temperatures.

2. It was established experimentally that the optimum thickness of the nitrided layer is 0.4-0.6 mm, which allows one to provide a reliable diffusion barrier by thermal effects on the steel-aluminum composite.

3. The application of the new heat-resistant composite steel-aluminum material with diffusion barrier allows one to reduce transient electrical resistance of more than 2 times in comparison with the composite without a protective nitrided steel layers.

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References

[1] Findik F 2011 Mater. Des. 32 1081-093
[2] Li X J et al 2016 Hanneng Cailliao/Chin. J. Energ. Mater. 24 188-93
[3] Young G 2005 Hydrocarbon Engin. 10 109-10
[4] Banker J G, Nobili A 2002 Light Met. TMS Annual Meeting 439-45
[5] Shiran M R K G et al 2017 Mater. Res. 20 291-302
[6] Mynors D and Zhang B 2002 J. Mater. Process. Techn. 125 1-25
[7] Carpenter S H and Wittman R H 1974 SME Tech Pap MF74-819 18
[8] Greenberg B A et al 2015 Metallur. Mater. Transac. A: Phys. Metall. Mater. Sci. 46 3569-580
[9] Trykov Yu P, Trudov A F and Stepanishev I B 2002 Met. Sci. Heat Treat. 44 524-28
[10] Kiz’min V I et al 2015 Phys. Met. Metallog. 116 1096-102
[11] Tcherdyntsev V V et al 2002 Mater. Manuf. Process. 17 825-41
[12] Peev A P et al 2002 Fiz. Khim. Obrab. Mater. 3 60-3