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The effect of holding temperature on the strength of the diffusion bond of Ti-alloy and stainless steel through the ultrafine-grained interlayers of Ni and Ni-2%Cr alloy

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Abstract. The manuscript considers the effect of diffusion bonding pressure, as well as holding at different temperatures, on the strength of the joints between titanium alloy and stainless steel, formed by diffusion bonding through ultrafine-grained interlayers of Ni and the Ni-2%Cr alloy. In samples with an interlayer of nickel after holding at 25 °C, the maximum strength of 380 MPa is achieved after diffusion bonding in the pressure range of 4-8 MPa. In samples with an interlayer of Ni-2%Cr, after holding at 25 °C, the highest strength of 490 MPa is achieved after bonding at a pressure of 12 MPa at 700 °C for 20 minutes. In the case of Ni-2%Cr interlayer, the strength of the joint falls more slowly than in the case of Ni interlayer. The mechanical properties of the joints are discussed in terms of the effect of chromium doping of nickel interlayer on the temperature range of transformation of austenite to martensite of the formed TiNi intermetallic compound.

1. Introduction
The combination of high corrosion and mechanical properties of titanium alloy with the strength of stainless steel in one product will make it possible to expand the capabilities of the engineering, aerospace and chemical industries. Diffusion bonding (DB) is a promising method for obtaining a perfect permanent joint [1,2]. Direct DB of titanium alloy and stainless steel does not allow obtaining the necessary properties due to the formation of brittle intermetallics of the Ti-Fe system. To prevent the formation of Ti-Fe intermetallics, various interlayers are used in the joint zone [3].

The DB technique through nickel interlayer was well studied [4-8]. By means of DB through a nickel layer, a joint of pure Ti and stainless steel was obtained with the strength of 311 MPa [4]. In the study [4-8], coarse-grained nickel was used and the bonding temperature range was 750-950 °C. It was revealed that at the titanium alloy-nickel interface, the Ti2Ni, TiNi, and TiNi3 intermetallic layers were formed, over which failure occurred [7-10]. The application of nanocrystalline Ni reduces the temperature and duration of bonding while maintaining the strength of the joint and the character and site of fracture [9, 10]. In the study [9], the formation of a regular network of cracks in the Ti2Ni and TiNi3 layers adjacent to the TiNi layer was observed. It was assumed that the main cause of failure is the anomalous change in the coefficient of thermal expansion (CTE) as a result of austenite to martensite transformation (AMT) in the temperature range of 30-100 °C in the formed TiNi layer [9,
In this connection, in order to increase the strength of the joint, it seems promising to try, by doping the TiNi layer, to reduce the AMT temperature below the operating temperature of the product. It is known that chromium most strongly decreases the temperature of AMT in TiNi. With the addition of about 1 at.% Cr the temperature of TiNi AMT decreases by approximately 150 °C [12]. Reasoning from the character of the failure, one can assume that chromium alloying of nickel might cause a decrease in the temperature of AMT. In the case of nickel interlayer at the optimal temperature and holding time, the joint failed along the Ti-alloy/interlayer interface, and after DB through the Ni-2%Cr alloy, the joint failed along the stainless steel/interlayer interface [16,17].

An increase in the strength of the joint of the Ti64-type titanium alloys with microduplex or precipitation-hardening stainless steels when using nickel-based alloys with the additions of Cr, Fe, Mo, and Al was found earlier. However, these results were not analyzed in terms of lowering the temperature of AMT [13-15]. The alloying elements used by the authors [13-15] reduce the temperature of AMT, as evidenced by their high strength values. In addition, the effect of holding at low temperatures on mechanical properties at room temperature was not studied in [13-15]. The use of interlayers of nickel alloys with the additions of Cr, Fe, Mo and Al instead of pure nickel during DB of the Ti64-type titanium alloys with microduplex or precipitation-hardening stainless steels resulted in an increase in the strength of the joint [13-15]. The strength value 560 MPa of the joint was obtained using an interlayer of nickel alloy with 15.6% Fe and 4.9% Mo [13]. The strength in the range of 515-525 MPa was achieved after DB through an interlayer of nickel alloy with 8.6% Fe, 16.7% Cr, 0.4% Al [14,15]. The doping of TiNi with these elements reduces the temperature of AMT [12], therefore the increase in strength may be due to the AMT temperature decrease of the. However, the authors did not consider this fact. The assumption of the effect of AMT on strength can be verified by examining the mechanical properties of the joint after holding the samples at temperatures below the temperature range of AMT.

This work is aimed to study the effect of bonding pressure on the strength of diffusion bonding of titanium alloy and stainless steel through the fine-grained interlayer of the Ni-2%Cr alloy, as well as to determine the effect of holding at various temperatures on the strength of the joint.

2. Experimental
DB was performed using a titanium-based PT3V alloy (Ti-2%V-4.5%Al) and 12Kh18N10T stainless steel (0.12%C-18%Cr-10%Ni-1%Ti). The sizes of the joint parts were 4x4x16 mm³, the interlayers were made of 0.2 mm thick plates of pure Ni and the Ni-2%Cr alloy. To obtain an ultrafine grained structure in Ni and the Ni-2%Cr alloy, they were deformed by torsion under quasi-hydrostatic pressure of 5 GPa in 5 revolutions [18]. The DB regimes were as follows: the pressure range was $P = 4$-16 MPa, the temperature was $T = 700$ °C, the duration was $t = 20$ minutes, the residual gas pressure was did not exceed $2x10^{-3}$ Pa. The microstructure was analyzed using a Tescan Vega scanning electron microscope with an X-act Oxford Instruments detector for energy dispersive analysis with shooting mode in the BSE contrast. Tensile tests of samples with the dimensions of the working part 1x1x5 mm³ were performed at room temperature with a mobile grip speed of 1 mm/min. Three samples were used to measure the main ultimate tensile strength $\sigma_u$.

3. Results and discussion
After DB at a pressure of 4 MPa, the thicknesses of the intermetallic layers are: Ti$_2$Ni ($0.63 \pm 0.16$ µm), TiNi ($1.82 \pm 0.14$ µm) and TiNi$_3$ ($1.22 \pm 0.15$ µm) (figure 1). The chemical composition at the interface of Ni-2%Cr/stainless steel changes smoothly, and there are no sharp differences in phase contrast. In this layer, the Ti:Cr ratio is close to 1:2, which indicates the formation of TiCr$_2$ intermetallics [16,17].

In the samples with Ni interlayer after holding at 25 °C, the maximum strength of 380 MPa is achieved after DB at the pressure range of 4-8 MPa. A further increase in the pressure of DB results in a decrease in the strength of the joint to 300 MPa (figure 2a). After holding the DB samples at 10 °C, the joint strength drops to 150-250 MPa (figure 2a). In samples with an interlayer of Ni-2%Cr, after
holding at 25 °C, the highest strength of 490 MPa is achieved after DB at a pressure of 12 MPa (figure 2b). After holding the DB samples at -10 °C, the joint strength drops to 150-300 MPa, while the maximal strength is also observed after DB at a pressure of 12 MPa (figure 2b). As we see, lowering the holding temperature results in a decrease in the strength of the joint when using a layer of both Ni and Ni-2%Cr alloy. However, as the holding temperature decreases, the strength of the joint through Ni-2%Cr interlayer falls more slowly than in the case of Ni. Even after holding at the temperature of -10 °C, i.e. 20 degrees lower than 10 °C, the strength of the joint through Ni-2%Cr interlayer is approximately the same as in the case of Ni interlayer.

Figure 1. Microstructure (a, b) and chemical composition (c) of joint zones of titanium alloy and stainless steel through Ni-2%Cr interlayer after 4 MPa DB at 700 °C for 20 min.

The samples, subjected to DB through Ni interlayer, irrespective of the holding temperature, were always fractured with "participation" of the TiNi layer: either along the Ti$_2$Ni/TiNi interface or along the TiNi/TiNi$_3$ one [9, 16]. The fracture of the samples bonded through Ni-2%Cr interlayer at 4 MPa, 700 °C for 20 minutes occurred along the Ni-2%Cr/stainless steel interface (figure 3a). After DB under a higher pressure and holding at 25 °C, the fracture passed along the Ti$_2$Ni + TiNi / TiNi$_3$ intermetallic interfaces (figure 3c). After holding at -10 °C, the samples bonded through Ni-2%Cr interlayer were fractured along the Ti$_2$Ni + TiNi/TiNi$_3$ intermetallic interfaces (figure 3b).

An increase in the strength of the joint through Ni-2%Cr interlayer after holding at 25 °C, as well as a slower decrease in strength with a decrease in the holding temperature, can be explained by shifting the temperature of the onset of the TiNi martensitic transformation to lower temperatures. In the case of Ni-2%Cr, the martensitic transformation of TiNi apparently begins just above room temperature and its negative effect on strength is less than in the case of Ni interlayer, where the austenite to martensite transformation begins much higher than room temperature and at room temperature the degree of transformation is already essential. A further increase in strength at room temperature is possible by increasing the concentration of elements reducing the temperature range of the austenite to martensite transformation of TiNi below the room temperature.

Figure 2. Influence of DB pressure on the joint strength of the titanium alloy and stainless steel through a layer of (a) Ni, (b) Ni-2%Cr alloy. DB was performed at 700 °C for 20 min.
Figure 3. Fracture surfaces of the samples, subjected to DB through Ni-2%Cr interlayer at 700 °C for 20 min under pressure (a, b) 4 MPa and (c) 16 MPa after holding at (a, c) 25 °C and (b) 10 °C and failed during tensile deformation at 25°C.

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