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LAMINATED COMPOSITE MATERIALS BASED ON ORTHORHOMBIC ALUMINADE/TITANIUM ALLOY

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Abstract

Laminated composite materials consisting of an orthorhombic Ti₂AlNb based alloy and an (α + β) titanium alloy have been fabricated at a laboratory scale using a two-step process involving diffusion bonding and hot-pack rolling. The feasibility of fabrication of two- and three-layered materials with high quality bonding between layers has been demonstrated. Preliminary assessment of the tensile mechanical properties of the obtained composite materials at room and elevated temperatures showed that, on the whole, they were superior to those of the titanium alloy and insignificantly inferior to the orthorhombic alloy.

Keywords :

Laminated composite material, bonding zone, tensile mechanical properties

1 INTRODUCTION

1.1 SECTION PROCESSING

The progress in the aerospace industry depends on the development of new structural materials providing a higher level of service properties against to currently exploited materials and/or lightening of parts due to using materials with a lower specific weight. In this regard, involving of light intermetallic alloys based on the γ -TiAl, α_2 -Ti₃Al and O-Ti₂AlNb phases, possessing high creep and oxidation resistance in the temperature range of 600-800°C, high specific strength and modulus elasticity persisting up to high temperatures, is of great interest because these materials may replace the heavier high-temperature steels and nickel-based superalloys having appreciably higher specific weight. However, poor ductility and low fracture toughness in a wide temperature range impede widespread engineering applications of titanium aluminides. To overcome these deficiencies optimizing the alloy composition/processing are now the main research targets. Another alternative way can be associated with the development of composite materials based on titanium aluminides and, for instance, titanium alloys. Indeed, titanium alloys having relatively a low specific weight and reasonable heat resistance up to 400-600°C possess appreciably better ductility, fracture toughness and processing characteristics in contrast to the intermetallic counterparts. Therefore, composition materials based on titanium aluminide and titanium alloy constituents may provide a good combination of both high-temperature properties and ductility/fracture toughness. In this regard, the concept of laminated composite materials consisting of alternating layers of the intermetallic and titanium alloy constituents seems to be very promising. It should be expected that the metallic ductile phase can improve fracture toughness and ductility in contrast to a pure intermetallic material whereas the intermetallic layer(s) is to be responsible for improved high-temperature properties.

In the literature there is not so much information on composite materials like titanium alloy – titanium aluminide [1-8]. V.V. Rybin and co-workers investigated the bonding zone obtained by diffusion bonding and explosion welding in the case of bimetallic materials based on titanium and orthorhombic alloys [1-3]. The bonding zone between Ti-6-4 and γ -TiAl based alloys was investigated by authors after diffusion bonding [4]. The manufacturing of laminated composites based on titanium alloy – orthorhombic alloy is considered in the papers [5, 6]. It is worth noting that there is not a clear understanding how to better produce laminated composite metal – intermetallic and whether it is interesting from point of view of mechanical properties.

The institute for metals superplasticity problems has developed a number of processing methods for manufacturing of bulk and sheet materials with a homogeneous fine-grained structure out of titanium and titanium aluminide alloys as well as for diffusion bonding as applied to these materials [9-13]. On this basis, new laboratory-scale processes are now being developed to produce laminated composite materials based on titanium and intermetallic alloys using different titanium and titanium aluminide components.

The present work aimed at a study of microstructure in the bonding zone and a preliminary evaluation of tensile mechanical properties of the laminated composite material prepared on the base of titanium alloy VT25U (Russian appellation) and orthorhombic O-Ti₂AlNb-based intermetallic alloy.

2 EXPERIMENTAL FACILITY

The intermetallic alloy Ti-23Al-22.7Nb-1.1V-0.6Zr-0.2Si-0.3C (hereafter in at. %) and titanium alloy Ti-12Al-0.7Sn-2.17Zr-2Mo-0.26W-0.34Si were used as components of the laminated composite material. For the sake of simplicity, in what follows the alloys will be referred to the O- and Ti-alloys.

The wrought bar of the titanium alloy with a diameter of 270 mm had a size of transformed β grains in the range of $d=1-1.5$ mm. The O-based alloy was supplied as an ingot with $\varnothing 115 \times 155$ mm, a grain size was varied in the range of $d=0.5-3$ mm. The β -transus temperature of the titanium alloy is about $T_{\beta}=1000^{\circ}\text{C}$, the β -transus temperature of the O-based alloy is about $T_{\beta}=1130^{\circ}\text{C}$.

Using the method of multi-directional isothermal forging [8] bulk pancakes with a homogeneous fine-grained microstructure were produced for the both alloys. The plates with thickness of 4-8 mm were cut out of the workpieces, mechanically polished, stacked together, canned using a low carbon steel to protect against oxidation and then subjected to hot pressure at about $T=950^{\circ}\text{C}$. The pressed pack was soaked in a furnace at about $T=950^{\circ}\text{C}$ and then rolled on cold rolls with intermediate reheats at the same temperature between each pass. After finishing rolling the packet was cooled in a furnace then decanned and used for microstructure examination and preparation of flat samples for subsequent tensile tests. Applying described technique two- (Ti+O-alloy) and three-layered (Ti+O+Ti-alloy) laboratory scale composite materials were produced. The rolled composite materials had approximate sizes $150 \times 50 \times 1.5-2$ mm for two- and $150 \times 50 \times 4.5-5$ mm for three-layered composites.

Scanning electron microscopy (SEM) in the back-scattering electron (BSE) mode was performed in a Leo-1550 (Zeiss SMT) microscope, which was equipped with an energy-dispersive X-ray (EDX) analysis system calibrated using ternary TiAl-Nb based alloy standard. Microstructure examination and EDX analysis were performed in the bonding zone. To evaluate the quality of interlayer bonding the special tests for defining the shear strength in the bonding zone were carried out. The results were compared with the shear strength of

the Ti- and O-alloys in a fine-grained condition after annealing at $T=950^{\circ}\text{C}$, that is of the composite constituents. The tests were performed at room temperature using special samples as described in detail elsewhere [13]. A mean value obtained as a result of three tests was taken into consideration.

The tensile mechanical tests were carried out using flat samples with a gauge section of $20 \times 5 \times (2-3)$ mm, where the thickness was variable and dependent on thickness of the rolled composite material. Before testing the samples were ground, mechanically polished and the thicknesses of metallic/intermetallic constituents were measured for each sample to define the volume fraction of the both constituents. The tests were performed in air at $T=20, 500-700^{\circ}\text{C}$ and an initial strain rate of $\dot{\epsilon}=8.3 \times 10^{-4} \text{ s}^{-1}$. For comparison the flat samples prepared from the fine-grained pieces of the both alloys after annealing at $T=950^{\circ}\text{C}$ having approximately the same geometry as mentioned above were also tensile tested.

3 RESULTS AND DISCUSSION

The titanium alloy under study is a two-phase alloy consisting of the α and β phases which are solid solutions based on titanium having close-packed hexagonal and base centered cubic lattice respectively. The phase constitution of the orthorhombic alloy was earlier investigated by XRD analysis of water quenched samples. To do it, the samples were heated up to $T=600-1200^{\circ}\text{C}$ in each 50°C , annealed during 1 hour and then water quenched [4]. XRD measurements and microstructural analysis revealed the following temperature ranges of the phase fields: $T < 750^{\circ}\text{C}$ – $\text{O} + \beta(\text{B}2)$, $T = 750-900^{\circ}\text{C}$ – $\text{O} + \beta(\text{B}2) + \alpha_2\text{-Ti}_3\text{Al}$, $T = 900-1080^{\circ}\text{C}$ – $\beta(\text{B}2) + \alpha_2\text{-Ti}_3\text{Al}$, $T > 1080^{\circ}\text{C}$ – $\beta(\text{B}2)$, where O is the intermetallic phase based on the orthorhombic Ti_2AlNb lattice, $\alpha_2\text{-Ti}_3\text{Al}$ is the intermetallic phase DO_{19} , β is the solid solution based on Ti and B2 is the intermetallic $\text{L}2_0$ phase having bcc lattice and ordered from the β phase under cooling.

After preliminary multi-directional forging fine-grained microstructures were obtained in the both alloys. A typical colony size was $d=5-8 \mu\text{m}$ for the titanium alloy and $d=1-2 \mu\text{m}$ for the O alloy.

Fig. 1 represents the BSE images of the laminated composite material in the bonding zone. Tables 1 and 2 show the results of EDX analysis. After rolling and furnace cooling the intermetallic constituent contains the O phase (grey) and $\beta(\text{B}2)$ phase (bright) (Fig. 1c,d). Note that the O phase contains some dark regions depleted in niobium (Table 1). The titanium alloy contains the β -transformed phase (grey) and grains of the α phase (dark) (Fig. 1c,d).

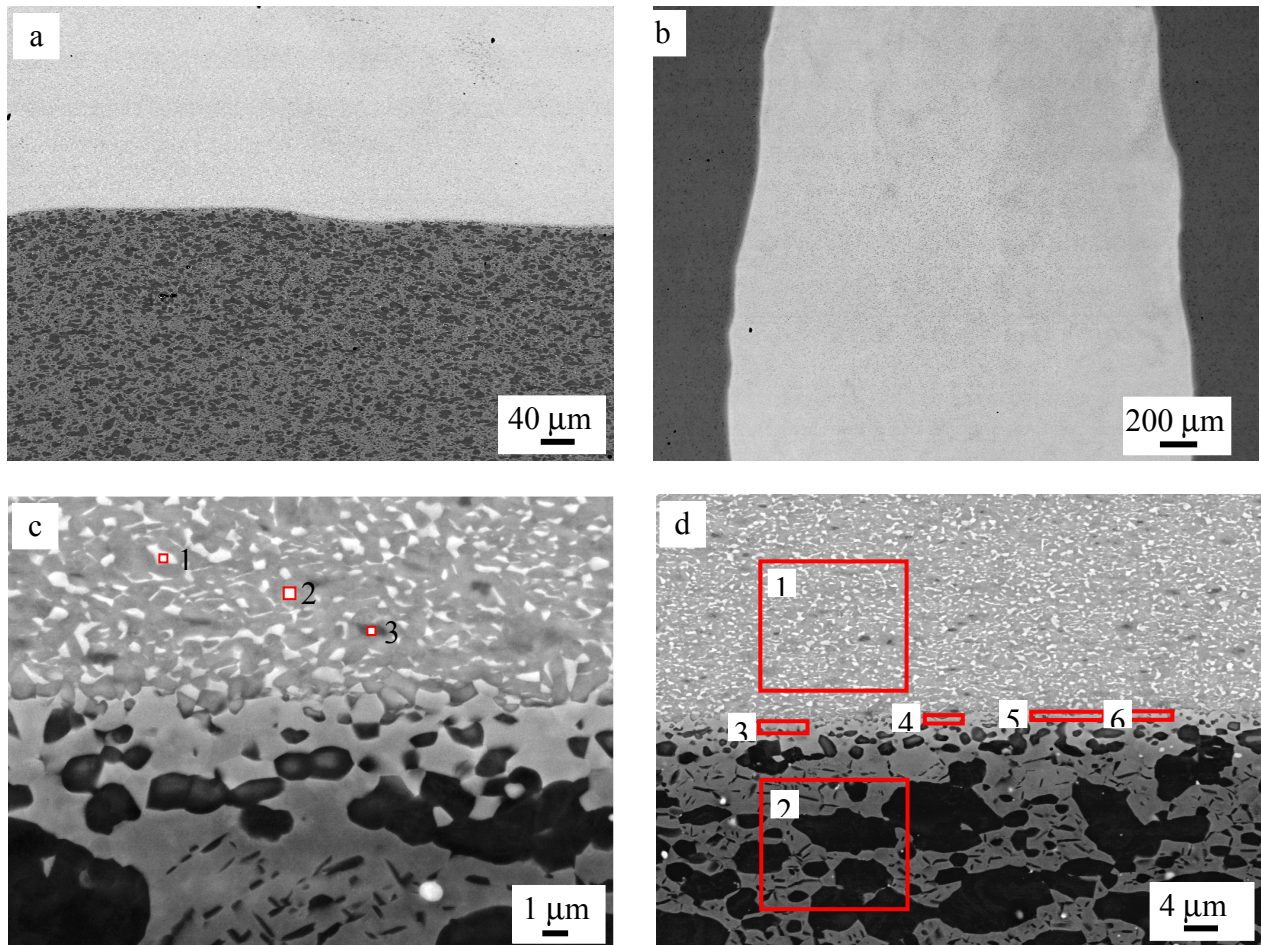


Fig. 1 BSE images of the bonding zone in the composite material Ti-alloy/O-alloy: a, c, d – top layer is the O-alloy, b – intermediate layer is the O-alloy. (c, d) The areas are marked from which EDX analysis was made.

Table 1 Results of EDX analysis of the O-alloy (in at. %)

Areas in Fig. 1c	Al	Si	Ti	V	Zr	Nb	Phase
1	21.9 6	0.17	49.8 7	2.45	0.43	25.1 2	β (B2)
2	25.9 1	0.13	53.2 2	1.01	0.09	19.6 4	O
3	25.7 3	0.28	56.3 2	0.69	0.30	17.2	O

EDX analysis of the intermetallic layer showed that the β (B2) phase was rich in niobium and vanadium whereas in the O phase the content of these elements was significantly lower (Fig. 1c, Table 2). Note that niobium and vanadium are known to be the β -stabilizing elements. The alloy compositions corresponded approximately to the nominal compositions and the bonding zone had an intermediate composition (Fig. 1d, Table 2). One can see that in the bonding zone the grey O phase of the intermetallic layer was bonded with the grey β phase of the titanium alloy which was slightly brighter. A brighter contrast of the β phase in the titanium alloy should be ascribed to the presence of heavy elements molybdenum and tungsten.

Table 2 Results of EDX analysis in the bonding zone (in at. %)

Areas in Fig. 1d	Al	Si	Ti	V	Zr	Nb	Mo	Sn	W	Area
1	22.20	0.14	49.62	1.19	0.13	26.73	-	-	-	O-alloy
2	12.21	0.54	86.21	-	2.14	0.52	1.95	0.91	0.21	Ti-alloy
3	15.28	-	63.38	0.88	1.02	18.85	0.44	0.04	0.11	Bonding zone
4	15.68	0.06	64.21	0.84	1.01	17.46	0.52	0.11	0.12	Bonding zone
5	16.39	0.04	63.41	0.85	1.00	17.88	0.27	-	0.16	Bonding zone
6	15.62	0.08	63.64	0.99	0.89	18.59	0.33	0.08	0.08	Bonding zone

Microstructure analysis showed that the bonding zone does not contain pores. The shear strength tests of the two-layer composite material revealed that the shear strength of the laminated composite material was by 22.4% higher than that of the O alloy ($\sigma_{sh}=580$ MPa) and by 22.5% lower than that of the titanium alloy ($\sigma_{sh}=870$ MPa). This fact testifies to a high quality of diffusion bonding of components in the laminated composite material.

Table 3 represents the results of the room temperature tensile tests of samples cut out of the laminated composite materials. The samples had different fraction volumes of the titanium/intermetallic constituents because of inhomogeneous flow of the layers that resulted in a wavy boundary between layers (Fig. 1a,b). The fraction of the titanium constituent for each tested sample is given in Table 3. For comparison, the tensile mechanical properties obtained for samples of the titanium and O-alloy in a fine-grained condition after annealing at $T=950^{\circ}\text{C}$ ($\tau=1$ h) and furnace cooling are also given. One can see that ultimate tensile strength of the laminated composite material is comparable with that of the O alloy and correspondingly higher than that of the Ti alloy. One can see that the ultimate tensile strength increased with decreasing the volume fraction of the titanium alloy. The elongation value of the laminated composite material was found to be slightly above than that of the O alloy and slightly below than that of the titanium alloy. Elongation increased from 3-4% to 10% with increasing the volume fraction of the titanium alloy from 44 to 62 vol. %. Fracture was always initiated from the surfaces between the intermetallic and titanium layers, and brittle failure occurred in the intermetallic layer but ductile failure of the titanium constituent impeded premature failure of the composite sample. It should be expected that the fracture toughness of such composite material will be appreciably higher than that of the pure O-alloy.

Table 3 Room temperature tensile mechanical properties of the laminated composite materials

Mechanical characteristics	Laminated composite material					Ti-alloy	O-alloy
	Two-layered		Three-layered				
	The volume fraction of the Ti-alloy (V_{Ti}), %						
	48	53	55	62	44		
σ_B , MPa	1250	1225	1210	1160	1235	1100	1205
δ , %	3	4	7	10	4	14	4

Table 4 represents the results of mechanical tensile tests at elevated temperatures. One can see that ultimate tensile strength of the composite material was by 25% higher than that of the titanium alloy but elongation was lower than that of the titanium alloy. Note that the obtained high-temperature properties of the laminated composite material are comparable with those of different O alloys [14].

Table 4 Tensile mechanical properties of the laminated composite materials at elevated temperatures

Test temperature, °C	Mechanical characteristics	Laminated composite material		Ti-alloy
		Two-layered (V _{Ti} ≈ 55%)	Three-layered (V _{Ti} ≈ 50%)	
500	σ_{UTS} , MPa	1050	–	835
	δ , %	8	–	22
600	σ_{UTS} , MPa	835	875	680
	δ , %	12	21	30
700	σ_{UTS} , MPa	610	645	510
	δ , %	18	26	65

Fig. 2 represents the beginning of failure in the three-layered composite material tested at T=700°C. As at room temperature, fracture was initiated in the middle intermetallic layer and then was restrained by external titanium layers. This suggests that the titanium layers increased the fracture toughness in comparison with that of the O alloy. It should be noted that higher values of ultimate tensile strength of the composite material in comparison with those of the titanium alloy probably indicate that such composite material might be applied at higher temperatures than the titanium alloy.

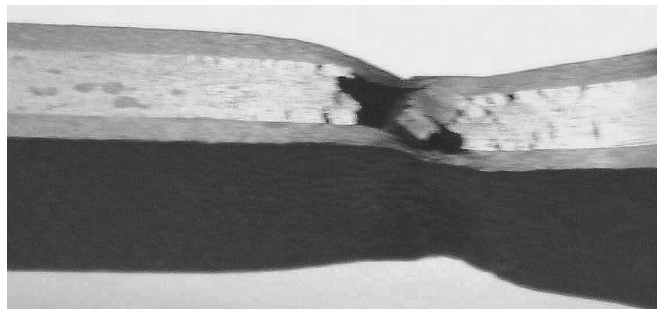


Fig. 2 Three-layered (Ti+O+Ti-alloy) composite sample tensile tested at 700°C. The test was interrupted before failure.

The performed experiments have demonstrated the feasibility of fabrication of the laminated composite materials using diffusion bonding and hot-pack rolling. Preliminary tensile mechanical tests showed that the properties of the obtained composite materials are superior in a wide temperature range to those of the titanium alloy used as the composite material constituent. In the case of component manufacturing that may give, at the minimum, a gain in the specific weight.

4 CONCLUSION

Laminated composite materials consisting of an orthorhombic Ti₂AlNb based alloy and an (α + β) titanium alloy have been successfully fabricated at a laboratory scale using a two-step process involving diffusion bonding and hot-pack rolling. SEM examination and shear strength tests revealed that high-quality bonding was reached between the intermetallic and titanium alloy constituents. Preliminary assessment of the tensile mechanical properties of the obtained two- and three-layered composite materials showed that, on the whole, they were superior to those of the titanium alloy and insignificantly inferior to the orthorhombic alloy. It

was found that failure was initiated within the intermetallic layer whereas the titanium alloy layers prevented premature failure. The composite constituent materials and their volume fractions need further optimization to achieve improved mechanical properties.

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