LIQUID PHASE FABRICATION TECHNOLOGY OF LAYERED Ti/Al COMPOSITE

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In this paper, influence of technological parameters of liquid-phase producing of Ti/Al layered composite on its microstructure and mechanical properties were investigated by means of scanning electron microscopy, energy-dispersive spectroscopy, bend and tensile strength measurement. The results of microscopic studies show that the increasing of the gap between the titanium plates, holding time and melt temperature don`t affect significantly on the thickness of intermetallics that formed on Ti/Al interface. Bending test results demonstrate good adhesion and high-quality metallurgical bonding between titanium and aluminium. Tensile strength tests identify increasing of the gap from 1 to 1.5 mm having allowed manufacturing a lightweight material with acceptable mechanical properties.

Keywords: Composites, Layered composite, Infiltration, Titanium, Aluminium

1. Introduction

Layered materials with improved properties, manufactured from different metals and alloys, have known for centuries. Currently, there is a large number of composite layered systems, such as metal-metal, metal-ceramic, ceramic-ceramic, etc., which structure can improve wear resistance, fracture toughness, damping capacity and corrosion resistance [1]. Presence of interfaces in laminated materials, that prevent crack propagation, make it useable for large pressure vessels, gun tubes, protective shatterproof coatings of various technical devices etc.

Layered composites based on Al alloys, Ti alloys, Cu alloys, Ni alloys, carbon or stainless steels are becoming more widespread in industry, due to their heat and electrical conductivity, corrosion resistance and specific mechanical properties [2, 3]. Due to the combination of basic metals properties, Ti/Al layered composites are the most interesting. They exhibit low weight, high strength, stiffness, wear and corrosion resistance, and improved thermophysical properties.

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It makes Ti/Al composites attractive as a structural material, armour or coating material for work under extreme conditions for automotive, aerospace and defense industries [2, 4, 5].

Especially prevalent ones are solid-phase methods of Ti/Al layered composite materials manufacturing, such as spark-plasma sintering [6], explosive welding [7-10], cold and hot rolling [11-15], etc. These methods remain multi-staged, time-consuming and long-term processes [6-11] with some disadvantages. For instance, hot roll bonding is considered to be complex and expensive because it is performed isothermally followed by pack rolling to reduce the deformation resistance and improving stress states [16]. Explosive welding has another problem – a number of defects, including large area fractures, violent bending deformation and serious surface burns, would easily occur in the ultrathin multilayer laminates [16].

In recent years, liquid-phase methods of metal composites formation, where metal frame is infiltrated with another metal melt, have been developed. Such methods, in turn, are profitable and technologically simpler [17, 18]. Liquid-phase technologies provide good metallurgical bonding between metals and develop composite materials with complex structure and high mechanical properties [17, 19].

Producing process of layered Ti/Al composite material, which is simplified in comparison with existing solid-phase methods, submitted in the present work. Influence of the gap between the titanium plates, holding time and melt temperature on the microstructure and mechanical properties of the produced composite was studied. Presented approach permits the producing of lightened layered composite with acceptable mechanical properties. Described technological process can be scaled and used in industrial production.

2. Experimental procedures

Commercial pure aluminium casting ingots (99% purity) and titanium plates (99% purity) with dimensions of 30×30×0.5 mm were used as the starting materials.

The surface of titanium plates was mechanically polished with 80-grit SiC papers before application and then cleaned with alcohol. To achieve good adhesion between titanium plates and aluminium melt, flux based on the KF-AlF_3 eutectic system was used. Titanium plates were coated with an aqueous solution of flux and dried until water totally evaporated. Two titanium flux coated plates assembled into a package, immersed, infiltrated and held in molten aluminium (Fig. 1). Titanium plates package infiltration conditions (the width of the gap between the titanium plates and the melt temperature) are given in Table 1. To explore the effect of melt temperature on the Ti/Al interaction packages held in the melt for 900 s. Then, obtained samples were air cooled to room temperature.

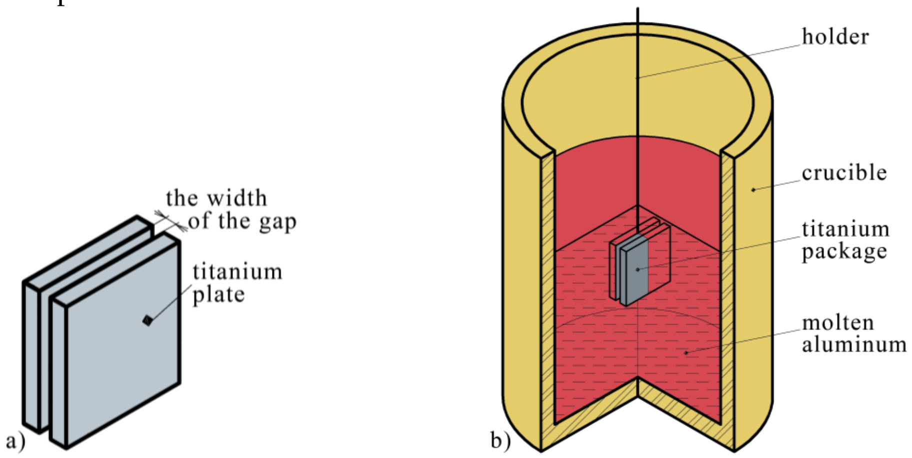


Fig. 1. Schematic illustration of titanium plates package (a) and layered Ti/Al composite material production process (b)

Table 1

Titanium plates package infiltration conditions

Infiltration conditions	№ of the titanium plates package								
	1	2	3	4	5	6	7	8	9
Melt temperature t, °C	700			750			800		
The width of the gap between the titanium plates S, mm	0.5	1	1.5	0.5	1	1.5	0.5	1	1.5

To investigate the effect of the holding time of the titanium package in the aluminium melt, the width of the gap between the plates and the holding temperature were fixed. The holding time varied from 15 to 900 s (Table 2).

Table 2

The holding time of the titanium plates package in the melt

t, °C	S, mm	Holding time τ, s						
750	1	15	30	45	60	300	600	900

Microstructural observations of the composite were performed with scanning electron microscopy (SEM) (SEM-106 I) equipped with energy dispersive spectrometer (EDS).

3-point bending tests were performed on a CERAMTEST universal testing machine with a loading rate of 2 mm/min according to GOST 14019-2003 (equivalent to ISO 7438-85). Schematic representation of a specimen for bending tests, made from fabricated composites, is given in Fig. 2. Tensile tests were accomplished on a UTM-100 universal testing machine with a loading rate of 3 mm/min according to GOST 1497-84 (equivalent to ISO 6892-84). Schematic representation of a specimen for tensile tests, made from fabricated composites, is given in Fig. 3. The reported data for all mechanical tests were average values of three tested specimens.

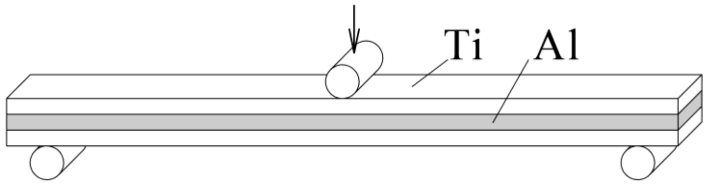


Fig. 2. Schematic representation of a specimen for bending tests

Fig. 3. Schematic representation of a specimen for tensile tests

3. Results and discussion

As illustrated in Fig. 4, a transition layer at the Ti/Al interface has been formed as a result of infiltration and holding the packages for 900 s. The uniform transition layer has been formed for each sample and voids or micro-cracks at the interface are not observed. Flux on the titanium surface facilitated for qualitative and even infiltration of aluminium melt between titanium plates and good bonding between metals. As can be seen, neither melt temperature rising nor gap changing between titanium plates significantly influence the transition layer thickness, which, on average, is in the range of 1.9-2.6 μm.

The results of EDS analysis, performed to determine chemical compositions of 1-9 points, are presented in Fig. 5. It was found, that the light grey, grey and dark grey phases on the images correspond to titanium, titanium aluminides and aluminium, respectively. The presence of $TiAl_3$, $TiAl_2$ and TiAl phases was found for all investigated samples in the grey transition layer.

Ti is considered to be the diffusing species above the melting point of Al. Firstly, solid Ti dissolves in liquid Al, and supersaturation of the liquid aluminium phase with titanium leads to the formation of the $TiAl_3$ phase. According to Gibbs, free energies of formation [20], first phase that can be formed in Ti/Al system is $TiAl_3$. Furthermore, it is the most stable phase in the system. The formation of the $TiAl_3$ phase is accompanied by other intermetallic phases formation due to the reaction between $TiAl_3$ and titanium and growth of $TiAl_3$ according to the reaction between $TiAl_3$ and liquid aluminium. $TiAl_3$ phase forms and remains in Ti/Al system until aluminium exists in it. With the depletion of aluminium, other intermetallics can be formed [21, 22]. It can be assumed that the limited volume of aluminium at the titanium-aluminium interface led to the depletion of the aluminium phase and the formation of $TiAl_2$ and TiAl phases.

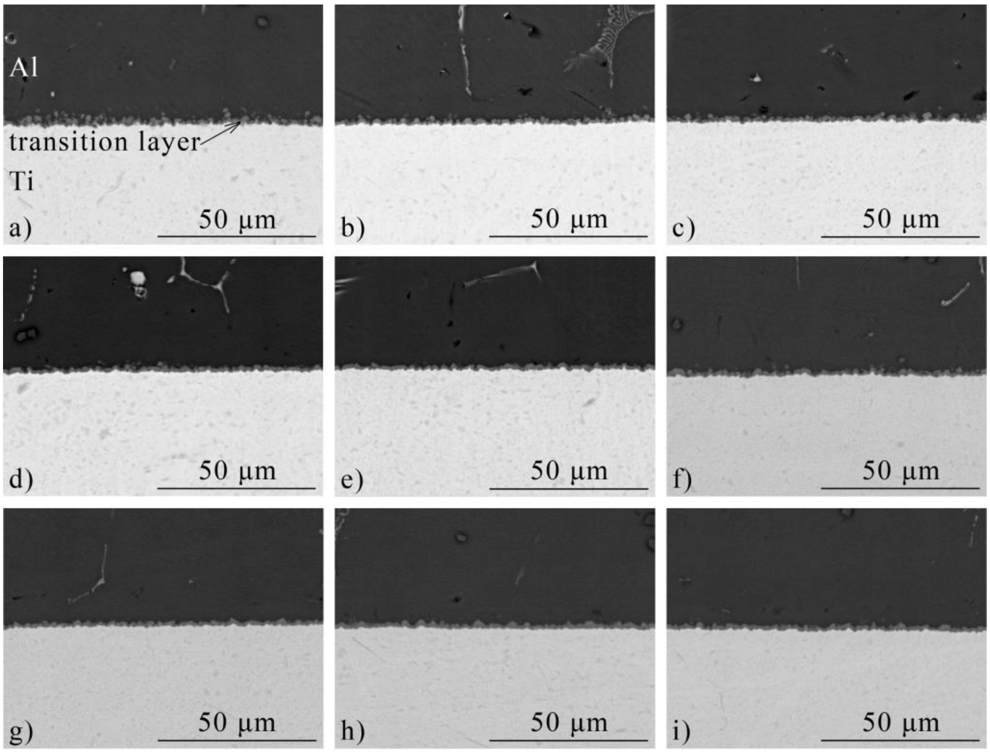
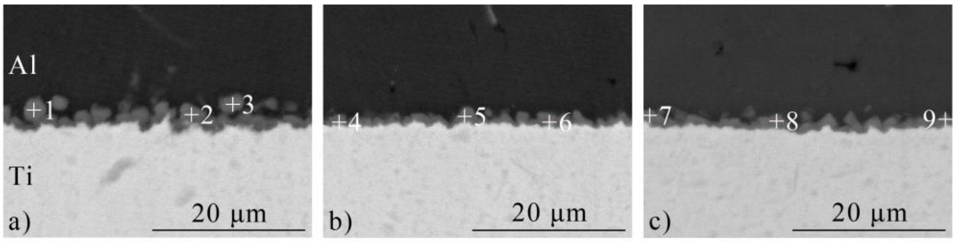


Fig. 4. SEM images of the Ti/Al interfaces formed at 700 °C (a-c), 750 °C (d-f) and 800 °C (g-i) with the gap of 0.5 mm (a, d, g), 1 mm (b, e, h) and 1.5 mm (c, f, i)



Element content, at %	Point no.								
	1	2	3	4	5	6	7	8	9
Al	77.72	76.38	82.58	64.03	66.54	66.12	72.22	68.66	74.91
Ti	20.28	21.23	15.46	33.99	31.77	32.12	25.91	29.43	25.09
Si	2.01	2.38	1.96	1.98	1.69	1.76	1.87	1.91	-

Fig. 5. EDS analysis of the grain phases on the Ti/Al interface of specimens produced at 700 °C (a), 750 °C (b) and 800 °C (c) with the gap of 0.5 mm between plates

Presumably, with a larger volume of aluminium melt in contact with solid titanium, $TiAl_3$ would be the only intermetallic phase.

In samples with fixed width of the gap and melt temperature, similar to the previous case, the formation of the transitional intermetallic layer is observed (Fig. 6). Increasing of titanium package holding time from 15 to 900 s leads to a slight increase of transition layer thickness from 2.3-2.8 to 3.5-3.7 μm, respectively. Besides, an insignificant enlargement of intermetallic grains at the Ti/Al interface is also observed. The transition layer consists of titanium aluminides, which is also confirmed by EDS analysis.

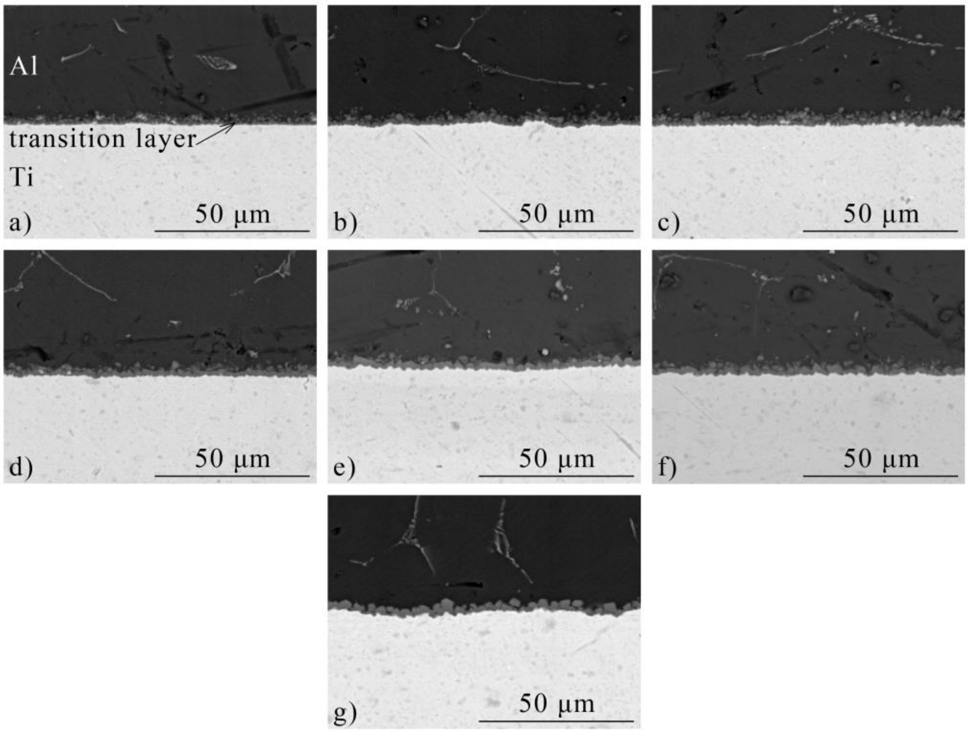


Fig. 6. SEM images of the Ti/Al interfaces formed during holding time of: 15 s (a), 30 s (b), 45 s (c), 60 s (d), 300 s (d), 600 s (e), 900 s (e)

To characterize flexural properties of the material, a 3-point bending test was performed. Stress-strain curves of bending test are shown in Fig.7, a. Samples with the gap of 0.5, 1 and 1.5 mm held for 300 s at 700 °C and 900 s at 750 °C were used for the tests. It was found that the separation of titanium plates from the aluminium part does not occur, and layered samples haven't been destroyed during loading. The maximum bending stresses reached the average values of 689, 521 and 428 MPa (Table 3) for samples with the gap of 0.5, 1 and 1.5 mm, respectively, held for 900 s at 750 °C. There are no splintering and delamination on the Ti/Al interface for all samples, reflecting the good adhesion and high-quality metallurgical bonding between metals. With decreasing of samples bending angle to 130-120 °, cracks at the interface, with a maximum size up to 20 μm, were formed (Fig. 7 b, c). As a result, cracks that have emerged did not lead to delamination and destruction of the test sample. Based on the result, it can be assumed that minimum thickness of the transitional intermetallic layer has positive effect on mechanical behaviour of the material interface. As it is known, crack initiation occurs in the fragile intermetallic layer [7]. Accordingly, the thickening of the intermetallic layer can lead to more active crack initiation on the interface and destruction of the layered material under loading.

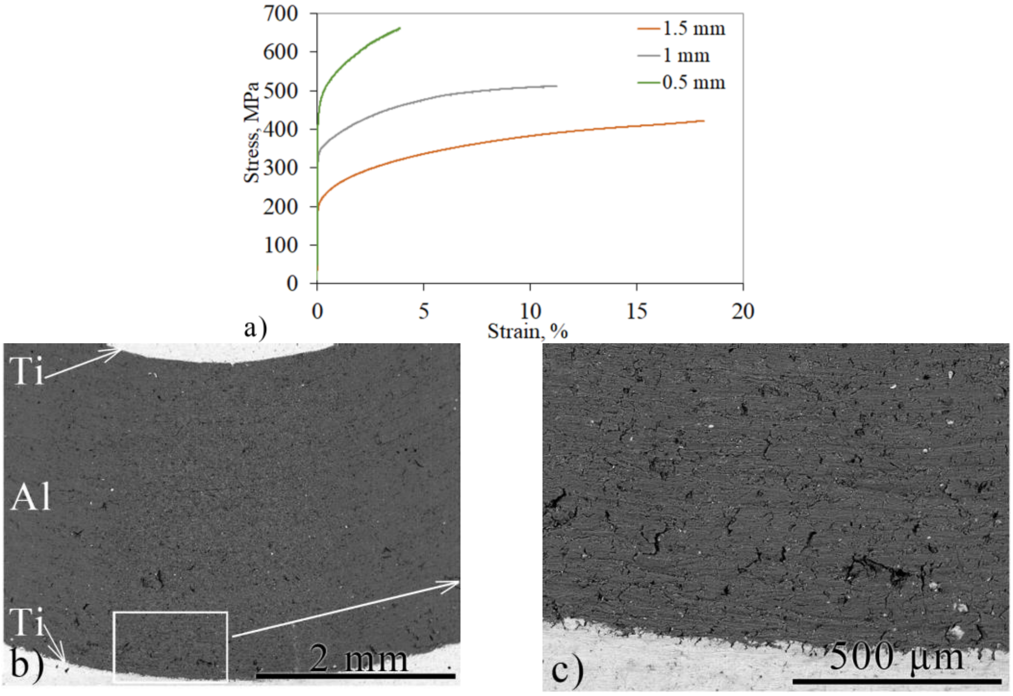


Fig. 7. The bending test results: stress-strain curves of bending test for samples holding at 750 °C with different width of the gap between the titanium plates (a), the morphology of the Ti/Al interface at a bending angle in the range of 130-120 ° (b, c)

Table 3

Maximum bending stress of Ti/Al layered composites

t, °C	S, mm	Maximum bending stress, MPa	σ, standard deviation
700	0.5	658	2.828
	1	528	9.899
	1.5	412	21.920
750	0.5	689	7.778
	1	521	13.435
	1.5	428	9.192

The tensile strength was determined on samples held for 300 s at 700 and 750 °C. Results of the test are presented in Table 4 and Fig. 8.

The original tensile strength of starting titanium and aluminium were 400-450 and 60 MPa, respectively. Samples with the gap of 0.5 mm have higher tensile strength than other samples, regardless of the holding temperature, and reaches up to 306 and 283 MPa for 700 and 750 °C, respectively.

Table 4

Tensile strength of Ti/Al layered composites

t, °C	S, mm	Tensile strength, MPa	σ, standard deviation
700	0.5	306	7.071
	1	209	0.707
	1.5	192	1.414
750	0.5	283	2.828
	1	212	2.121
	1.5	206	0.682

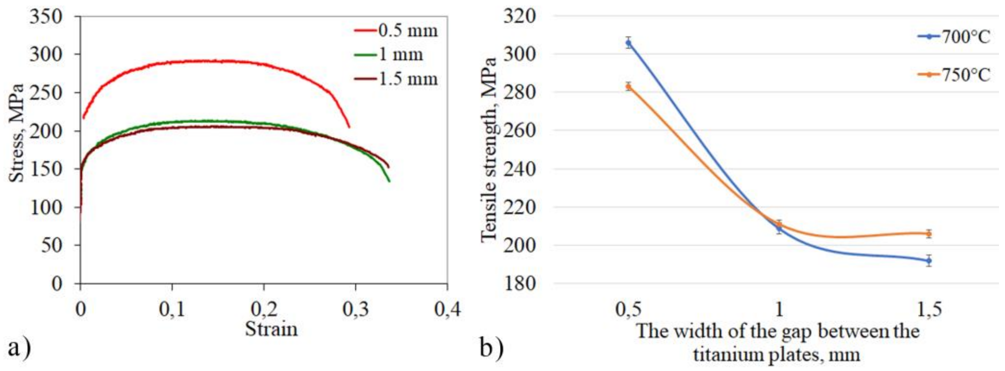


Fig. 8. The tensile test results: stress-strain curves of tensile test for samples holding at 750 °C with different width of the gap between the titanium plates (a), curves of the tensile strength of the composite versus the gap between titanium plates (b)

It resulted from the ratio of titanium to aluminium layers thickness – two parts of titanium and one of aluminium. Increasing of aluminium thickness in the samples (gap – 1 mm, the ratio of titanium to aluminium thickness – 1 to 1) resulted in a decrease of strength to 209 and 212 MPa for 700 and 750 ° C, respectively. Further increase of aluminium thickness in the samples (gap – 1.5 mm, the ratio of titanium to aluminium thickness – 1 to 1.5) brought to a slight decrease of strength to 192 and 206 MPa for 700 and 750 °C, respectively. Since the tensile strength for samples with the gap of 1 and 1.5 mm slightly differ with aluminium thickness increasing, lightened layered composite that don`t lose its mechanical properties can be produced. Moreover, presence of interfaces would positively affect on crack propagation in composite, and high hardness and strength at the surface in combination with high toughness and ductility in the core can ensure the effective operation of the composite as a material for shatterproof protection systems.

4. Conclusions

The presented work introduces a simplified liquid-phase technology for layered Ti/Al composite materials production consisted in infiltration of titanium plate's package with molten aluminium. In produced materials, electron microscopy analysis highlighted the presence of a transition intermetallic layer, that thickness doesn`t change significantly with increasing of melt temperature and holding time. In the result of bending and tensile test it was found, that flaking of titanium plates from aluminium layer doesn`t occur, and Ti/Al layered composite has acceptable mechanical properties, along with reducing its weight.

Produced composite material can be an effective material for shatterproof protection systems. Further work will focus on manufacturing of multilayer Ti/Al materials (five and more layers) and studying of treatment methods for improving it mechanical properties.

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