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Effect of processing parameters on the tensile behavior of laminated composites synthesized using titanium and aluminum foils

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ABSTRACT

Purpose: This study describe effect of processing parameters on the tensile behaviour of laminated composites synthesized using titanium and aluminium foils.

Design/methodology/approach: 50, 100 and 150 µm thick titanium and 50 µm thick aluminium foils have been used to fabricate Ti-Al_3Ti and Ti-(Al_3Ti+Al) composites. These laminated materials were synthesized in vacuum with controlled treating time and temperature. All composites were synthesized at 650°C. Treating time was a main factor determining the composition and tensile behaviour of the composites. Tensile tests were performed on the materials with different microstructures to establish their properties and fracture behaviour.

Findings: Since the examinations showed that Al_3Ti was the only intermetallic phase formed during the reaction between titanium and aluminium, the initial foil thicknesses affected only the volume fraction of the resultant Ti, Al and Al_3Ti layers. Aluminium layers reacted completely after 60 minutes resulting in microstructures with Ti residual layers alternating with the Al_3Ti layers. After 60 minutes of treating all composites had higher yield strength and higher ultimate tensile strength than composites after 20 minutes of treating produced with the same thickness of starting Ti foil. On the other hand, strain at fracture behaved conversely.

Research limitations/implications: The results of investigations indicated that tensile behaviour of the composites depended strongly on the thickness of individual Ti layers and the presence of residual Al layers at the intermetallic centrelines.

Originality/value: In the present study, the reaction synthesis was employed to fabricate laminated composites in vacuum using Ti foils with different original thicknesses and Al foils with one constant thickness.

Keywords: Titanium; Aluminium; Al3Ti; Tensile behaviour; Fracture

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PROPERTIES

1. Introduction

In late years, there has been significant interest in the design, fabrication and mechanical behaviour of a variety of laminated composites, such as metal-metal [1], metal-ceramic [2] and metal-intermetallic [3-11] systems. Especially, there is a great concern with metal-intermetallic laminated (MIL) composites, that have the potential to perform various functions, such as ballistic protection, blast mitigation, thermal management, heat exchange and vibration damping [5]. MIL composites allow for the possibility of combining the good ductility and toughness of metals with the higher elastic modulus, higher strength, and lower density of intermetallics. Lamination can significantly improve many properties including fatigue behaviour, fracture toughness, wear, corrosion and damping capacity, or provide enhanced formability or ductility for brittle intermetallics [1]. Production techniques of MIL composites may be divided into deposition or bonding. Sputter or vapour deposition techniques involve atomic scale transport of the component materials. Such nano-engineered laminated materials are typically fabricated by depositing hundreds of alternate nanoscale layers and they have received significant interest due to their extremely high strength [12]. Unfortunately, deposition techniques require sophisticated manufacturing equipment and are too slow to be practical for making large-scale components. These factors increase the cost of component production and make the application of these composites economically unattractive. On the other hand, bonding techniques (diffusion bonding, transient liquid phase bonding and reaction bonding) between metal foils have some advantages, e.g., they involve relatively simple processing and the size and the number of layers that can be produced are not limited [3]. Furthermore, the laminated structure of the composite allows for variations in the layer thickness and phase volume fractions of the components simply through the selection of initial foils thickness. A great number of laminated composites have been produced using Al and Ni [3,10,11,13], Nb [4], Fe [13] or Mg [14] foils. Among laminate composites, the Ti-intermetallic laminates have a great technological advantage and attracts special attention for various applications [5]. Previous works reveal that titanium-intermetallic composites can be produced by reaction that occurs at the interface of Ti and Nb [15], Ti and Cu [7,9] or Ti and Ni [13]. In particular, the Ti-Al system has a great practicable potentiality. The titanium aluminides Ti_3Al, TiAl and Al_3Ti offer potential for increased temperature range and enhanced high temperature strength, stiffness and oxidation resistance compared with conventional titanium alloys [16]. Specifically, the Ti-Al_3Ti laminated composites can be considered for aerospace, automotive and other structural applications because of their lower density than monolithic titanium or other Ti-based laminate systems. Furthermore, the Ti-Al_3Ti system is economically more attractive than monolithic titanium because aluminium is relatively inexpensive. This kind of laminated composites has been extensively investigated by Alman et al. [3,13], Peng et al. [17] and Vecchio et al. [5,18]. In the present study, the reaction synthesis was employed to fabricate laminated composites in vacuum using Ti foils with different original thicknesses and Al foils with one constant thickness. As a result, the laminated Ti-Al_3Ti and Ti-(Al_3Ti+Al) composites were produced. Tensile tests were performed on the materials with different microstructures to establish their properties and fracture behaviour.

2. Experimental procedure

In the work, 50, 100 and 150 μm thick foils of titanium (99.14 at. % Ti, 0.35 at. % Fe, 0.24 at. % Al, 0.21 at. % O, 0.04 at. % N, 0.02 at. % C) and 50 μm thick foil of aluminium (99.53 at. % Al, 0.21 at. % Fe, 0.16 at. % Si, 0.05 at. % Zn, 0.03 at. % Cu, 0.02 at. % Ti) were used to produce laminated titanium-intermetallic composites with controlled treating time, temperature and pressure. Titanium and aluminium foils were cut into 50 mm x 10 mm rectangular pieces. No special surface preparation treatment was applied to the foils prior to processing. Any contamination on the surface of foils was removed with cotton swabs in a bath of 5 pct HF in water. After that foils were rinsed in water and then in ethanol. After drying rapidly, they were stacked into laminates in an alternating sequence. To obtain 5 mm thick laminates, there were used 51, 34 or 26 pieces of Ti dependently on the thickness of the Ti foils. A pressure of 5 MPa was employed at room temperature in a specially constructed vacuum furnace to ensure good contact between the metals. The temperature was increased from 20 to 600°C at a heating rate of 0.25°C/s. The samples were heated in vacuum of 0.01 Pa at 600°C for 2 h under applied 5 MPa pressure to allow diffusion bonding of the layers. After that, the foils were heated to 650°C and held at this temperature for 20 or 60 minutes. The pressure was reduced to 1 MPa during this processing sequence with the purpose of eliminating possible expulsion of liquid phases. The temperature was then decreased slowly (cooling rate of 0.16°C/s) to 600°C and the pressure of 5 MPa was applied again. The thermal aging cycle at 600°C was employed for 2 hours to remove any residual porosity that might have formed as a result of solidification of the transient liquid phase. Finally, the samples were furnace-cooled to room temperature. The laminated composites prepared from 50, 100 and 150 μm thick Ti foils are denoted later as samples Ti50, Ti100 and Ti150, respectively. After fabrication, the samples were polished using standard metallographic techniques. Microstructural observations were performed using a JEOL JMS 5400 scanning electron microscope and a Carl Zeiss NEOPHOT 2 optical microscope. The chemical composition of the phases was determined by an energy dispersive spectroscopy utilizing a ISIS 300 Oxford Instruments. An X-ray diffraction using a D/max RAPID2 diffractiometer was employed to identify the intermetallic phases. Before the samples were examined with the optical microscope they had been etched using an aqueous HF solution (2%) to reveal any titanium grain boundaries and the structure of the intermetallic layers. Samples with dimensions of 50 mm x 8 mm x 4 mm, made from fabricated composites, were subjected to tension test on an INSTRON screw machine at a constant crosshead speed of 0.1 mm/min. Fracture surfaces of specimens were examined by macroscopic observations and scanning electron microscopy to evaluate deformation mechanisms.

3. Results and discussion

3.1. Microstructural characterization

After fabrication, the composition of the phases in the composites was determined. The examinations showed that only Al_3Ti phase was formed in the samples irrespectively of treating time. The XRD results confirmed that the composites treated at 650°C for 20 minutes consisted of alternating Ti, Al_3Ti and Al layers. No unreacted Al was detected in any of the composites processed at 650°C for 60 minutes, so the composites consisted of Ti and Al_3Ti layers. The laminated materials were well-bonded and nearly fully dense. The thickness of the Al_3Ti layers formed during processing was independent of the starting thickness ratio of the Ti and Al foils, what indicated that only certain quantity of titanium was consumed by the aluminium during the synthesis reaction. Microstructural investigations indicated also that the central zones of the formed Al_3Ti layers contained many Al_2O_3 inclusions. They are thought to originate from surface oxide films on the Al foils, which after breakdown were pushed aside towards the liquid Al side by the growing continuous Al_3Ti layers. A migration of oxide films from the surfaces of the Al foils to the middle of the formed intermetallic layers was previously observed during formation of another aluminides belonging to the binary Ni-Al [10,11] and Mg-Al [14] systems. Any oxides accumulated at the centreline of intermetallics can be a weak point in the microstructure because cracks are usually developed at the defect points.

3.2. Tensile testing

Fig. 1 shows the typical tensile stress-strain curves for the as-processed Ti100/20 and Ti100/60 laminated materials. Table 1 summarizes the tensile properties of all synthesized composites. With an increase of the treating time at 650°C, the Al_3Ti layers grow, leading to an increase in volume fraction of the intermetallics. As a result, the yield strength and the tensile strength of all investigated composites increased and the total strain at fracture decreased. The tensile behaviour of the Ti-(Al_3Ti+Al) and Ti-Al_3Ti composites was majorly dependent on the laminates microstructure, particularly, on the volume fraction of the layers. The failure mechanism in the course of straining of both types of the composites was carefully investigated. At the early stage of plastic straining the Ti and Al grains were deformed by slip. No traces of plastic deformation were noticed in the intermetallic layers. Unfortunately, during deformation the crystal structures mismatch between the base metals (HCP crystal structure for Ti and FCC for Al) and Al_3Ti layers crystallizing in the tetragonal DO_{22} unit cell [17] makes almost impossible slip-bands slide through a metal/intermetallic interfaces.

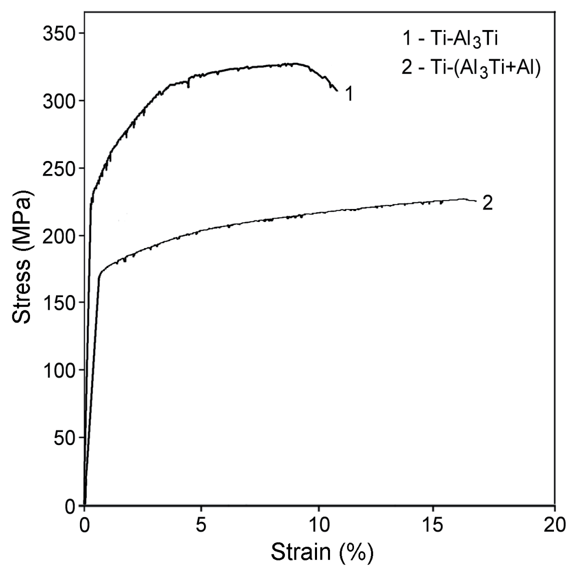

Fig. 1. Tensile curves for the Ti-Al_3Ti and Ti-(Al_3Ti+Al) composites

Table 1.
Summary of tensile properties of Ti-Al_3Ti and Ti-(Al_3Ti+Al) laminate composites

Treating time at 650°C, min	Sample designation	Volume fraction, %			Tensile properties		
		Ti	Al	Al_3Ti	σ_{YS}, MPa	σ_{UTS}, MPa	Strain at fracture, %
20	Ti50/20	44.4	28.3	27.3	155	216	16.4
	Ti100/20	63.8	18.2	18.0	167	224	16.8
	Ti150/20	73.1	13.8	13.1	172	230	17.3
60	Ti50/60	24.0	0	76.0	234	454	3.2
	Ti100/60	54.5	0	45.5	231	388	8.2
	Ti150/60	67.7	0	32.3	228	350	10.8

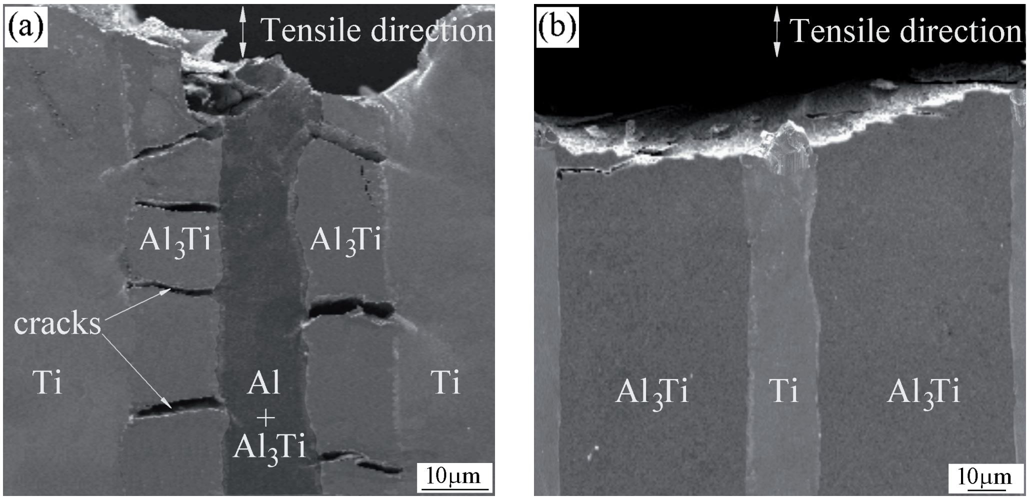

Fig. 2. A cross-section of a fractured Ti-(Al_3Ti+Al) tensile specimen showing the metals layers bridging many cracks in the aluminide layers (a), and a view of the fracture surface of the Ti50/60 tensile specimen showing brittle fracture of the composite (b)

Therefore, formation of cracks in the Al_3Ti layers was the characteristic feature of the prolonged deformation. The observed serrations in the stress-strain curves in Fig. 1 correspond to the formation of multiple cracks in the intermetallic layers. The cracks developed at defect points within the brittle Al_3Ti layers and then propagated across them. The perpendicular cleavage cracks were blunted by the titanium and aluminium layers when the cracks reached the Ti/Al_3Ti or Al/Al_3Ti interfaces. The energy absorption capability of the metals layers allowed numerous cracks to develop within each intermetallic layer before failure (Fig. 2a). With permanent increase of the crack number in the Al_3Ti layers the titanium and aluminium layers gradually underwent the total external load. As a result the plastic flow that took place in the metals layers was restricted to the small regions between opposite cracks in the neighbouring Al_3Ti layers. When the number and distribution of cracks in the intermetallic layers reached a critical limit, the final failure occurred by shearing fracture of the metals layers. It is obvious that strain hardening of the tensile specimens (Fig. 1) was produced due to plastic deformation of the titanium and aluminium layers. The only exception to the deformation model was the Ti50/60 composite having the thinnest titanium layers (only 17.6 μm). Since there was not sufficient material with the metal layers to absorb the cracks release energy, only one single crack propagated. As a result the Ti50/60 composite failed in a brittle manner (Fig. 2b). The obtained data are consistent with the results previously reported by Alman et al. [3,13] and Vecchio et al. [5,18]. The authors demonstrated that fracture mechanism and failure energy in metal-intermetallic laminated composites were controlled by varying the intermetallic-to-metal volume ratio. Their considerable body of work was also devoted to the mechanical behaviour aspects and fracture behaviour of the Ti-aluminide laminated composites, but their composites were fabricated using much thicker titanium foils than in the present investigations.

The fracture behaviour of the Ti-(Al_3Ti+Al) and Ti-Al_3Ti laminated composites was typical of ductile-phase-toughened matrix composites. The failure characteristic described for the Ti-(Al_3Ti+Al) and Ti-Al_3Ti composites is strictly consistent with previous studies of cracking and damage mechanisms in Ti-Ti_2Ni [13], Ti-(TiCu+Ti_2Cu) [7], Nb-Nb_3Al [4], Ni-Ni_2Al_3 [3,13], Fe-intermetallics [8] and Cu-intermetallics [6] laminated composites. The damage mechanisms of the unlike laminated composites during tensile testing are alike because different intermetallics formed from different constituent metals behave very similar. They are ordinarily brittle at room temperature due to the limited mobility of dislocations, have insufficient number of slip or twinning systems, and very low surface energy resulting in little or no plastic deformation at crack tips.

4. Conclusions

The laminated Ti-(Al_3Ti+Al) and Ti-Al_3Ti composites have been successfully produced by interlayer reaction process using Ti and Al foils. Microstructural examinations show that the Al_3Ti phase is the only phase formed during the reaction between Ti and Al at 650^{o}C independently on the treating time. The microstructural characterization indicates that after 20 minutes not all aluminium is consumed and therefore the formed composites consist of alternating layers of Ti, Al and Al_3Ti. After 60 minutes aluminium is completely consumed resulting in micro-structures with Ti residual layers alternating with the Al_3Ti layers. The central areas of the intermetallic layers contain many Al_2O_3 inclusions which originate from surface oxide films on the Al foils. The mechanical response and fracture behaviour of both types of composites were examined by tensile test. After 60 minutes of treating at 650^{o}C all investigated composites have higher yield strength, higher ultimate tensile strength than composites after 20 minutes of treating produced with the same thickness of starting Ti foil. On the other hand, strain at fracture of the composites behave conversely. It happens because an amount of residual aluminium at the intermetallic centrelines increases ductility of the laminated composites. The results also show that tensile properties of the composites depend strongly on the thickness of individual Ti layers.

References

[1] J. Wadsworth, D.R. Lesuer, Ancient and modern laminated composites – from the Great Pyramid of Gizeh to Y2K, Materials Characterization 45 (2000) 289-313.

[2] Y.L. Shen, S. Suresh, Steady-state creep of metal-ceramic multilayered materials, Acta Materialia 44 (1996) 1337-1348.

[3] D.E. Alman, C.P. Dogan, J.A. Hawk, J.C. Rawers, Processing, structure and properties of metal-intermetallic layered composites, Materials Science and Engineering A 192-193 (1995) 624-632.

[4] D.R. Bloyer, K.T. Venkateswara Rao, R.O. Ritchie, Laminated Nb/Nb_3Al composites: effect of layer thickness on fatigue and fracture behavior, Materials Science and Engineering A 239-240 (1997) 393-398.

[5] K.S. Vecchio, Synthetic multifunctional metallic-intermetallic laminate composites, JOM 57/3 (2005) 25-31.

[6] M. Konieczny, A. Dziadoń, Strain behaviour of copper-intermetallic layered composite, Materials Science and Engineering A 460-461 (2007) 238-242.

[7] M. Konieczny, Processing and microstructural characterisation of laminated Ti-intermetallic composites synthesised using Ti and Cu foils, Materials Letters 62/17-18 (2008) 2600-2602.

[8] M. Konieczny, R. Mola, Fabrication, microstructure and properties of laminated iron - intermetallic composites, Steel Research International 79/11 (2008) 499-505.

[9] M. Konieczny, Mechanical properties and deformation behaviour of laminated titanium-intermetallic composites synthesised using Ti and Cu foils, Metallic Materials 48/1 (2010) 47-53.

[10] M. Konieczny, R. Mola, P. Thomas, M. Kopciał, Processing, microstructure and properties of laminated Ni-intermetallic composites synthesised using Ni sheets and Al foils, Archives of Metallurgy and Materials 56/3 (2011) 693-702.

[11] M. Konieczny, Microstructural characterisation and mechanical response of laminated Ni-intermetallic composites synthesised using Ni sheets and Al foils, Materials Characterization 70 (2012) 117-124.

[12] S. Tixier-Boni, H. Van Swygenhoven, Hardness enhancement of sputtered Ni_3Al/Ni multilayers, Thin Solid Films 342/1-2 (1999) 188-193.

[13] D.E. Alman, J.A. Hawk, A.V. Petty, J.C. Rawers, Processing intermetallic composites by self-propagating high temperature synthesis, JOM 46/3 (1994) 31-35.

[14] A. Dziadoń, R. Mola, L. Błaż, Formation of layered Mg/eutectic composite using diffusional process at the Al-Mg interface, Archives of Metallurgy and Materials 56/3 (2011) 677-684.

[15] N.P. Rudnitskii, Studies on the strength and plasticity of Ti-Nb-based laminated composites in a temperature range of 290-1700 K, Strength of Materials 34/6 (2002) 612-616.

[16] C.M. Ward-Close, R. Minor, P.J. Doorbar, Intermetallic-matrix composites – a review, Intermetallics 4/3 (1996) 217-229.

[17] L.M. Peng, H. Li, J.H. Wang, Processing and mechanical behaviour of laminated titanium-titanium tri-aluminide (Ti-Al_3Ti) composites, Materials Science and Engineering A 406/1-2 (2005) 309-318.

[18] D.J. Harach, K.S. Vecchio, Microstructure evolution in metal-intermetallic laminate (MIL) composites synthesized by reactive foil sintering in air, Metallurgical and Materials Transactions A 32/6 (2001) 1493-1505.