THE FORMATION OF $TiAl_3$ DURING HEAT TREATMENT IN EXPLOSIVELY WELDED Ti-Al MULTILAYERS

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Abstract: *Metallic-intermetallic laminate (MIL) composites are promising materials for structural applications especially in the aerospace industry. One of the interesting laminate composites is the Ti-$TiAl_3$ multilayer. In this work, commercially pure sheets of aluminum and titanium with almost equal thickness of around 0.5 mm were explosively joined. The achieved multilayers were annealed at 630 ℃ in different times so that an intermetallic layer was formed at the Ti/Al interface. The resulting microstructure was studied by optical and scanning electron microscopy and Energy Dispersive Spectroscopy (EDS). $TiAl_3$ was the only intermetallic phase that was observed in all annealing times. The kinetics of the formation of $TiAl_3$ was investigated and compared to previous research studies performed on Ti-Al multilayers which were fabricated using methods other than explosive welding.*

Keywords: *Intermetallic; Laminate Composites; $TiAl_3$; Intermetallic Formation Kinetics.*

1. INTRODUCTION

Materials that maintain their mechanical properties at high temperatures are in demand for high-temperature structural applications in which high values of strength-to-weight and stiffness-to-weight ratios are essential [1]. Intermetallics such as Ti_3Al and Ni_3Al maintain their strength and even develop reasonable ductility at elevated temperatures. According to a simple definition, intermetallics are compounds of metals whose crystal structures are different from those of the constituent metals, and thus develop properties different from the constituting metals [2,3]. Titanium aluminide intermetallic compounds offer an attractive combination of low density and good oxidation and ignition resistance with unique mechanical properties such as high strength and elastic stiffness as well as excellent high temperature retention. Thus, these compounds belong to the few classes of emerging materials that have the potential to be used in demanding high-temperature structural applications whenever specific strength and stiffness are of major concern [4]. Five main intermetallics, i.e. Ti_3Al, TiAl, Ti_2Al_5, $TiAl_2$ and $TiAl_3$ can be seen in the Ti-Al phase diagram [5].

Among the titanium trialuminide based composites, the multilayer "metallic-intermetallic laminate" (MIL) composites should be emphasized. This composite possesses a unique set of mechanical properties. An important advantage of the multilayer composites is the possibility of combining the properties of both the hard and refractory intermetallics and the ductile matrix [6]. Metallic-Intermetallic composites have many application such as damping elements or blast energy absorber [6]. Reactive foil sintering is one way for producing these composites; however, the necessity to apply high pressures to prevent oxidation during sintering of the foils makes this process expensive for the production of this group of materials.

Explosive welding or bonding followed by annealing can be utilized as a non-expensive method to produce these types of materials. Explosive welding is the process of forming a bond by explosively impacting two metallic plates onto each other under controlled conditions. The explosive welding process yields excellent bonding of similar or dissimilar metals with different hardness, melting points, thermal-expansion characteristics and electrode potentials. Furthermore, the process can be applied to a broad range of thicknesses and area dimensions due to the ability to distribute the high energy of explosion over the entire welding area [7]. Applications of explosive welding are therefore numerous, from the production of "sandwich" plates for coinage to the more sophisticated use of titanium-to-stainless-steel transition joints in spacecraft [7]. The high strength and fracture toughness of explosively welded materials are due to the particular structural state of the welds formed by the dynamic interaction of work pieces [8-12].

Unlike the pressure-applying methods such as reactive foil sintering, explosive welding provides a very good contact between layers before heat treatment of layers without the need to apply high pressures. The kinetics of intermetallic formation in Ti-Al multilayers have been studied by several investigators [13-15]; however, there is a lack of information about kinetics of the formation of intermetallics during the heat treatment of explosively welded Al-Ti multilayers. Therefore, the present work is undertaken to study the kinetics of the formation of intermetallics during annealing of explosively welded Al-Ti multilayers.

2. EXPERIMENTAL

2. 1. Materials and Explosive Welding

Six alternative sheets of aluminum and CP-titanium were explosively welded together. The initial thickness of aluminum and titanium sheets was almost 0.5 mm. The chemical composition of initial materials is presented in Table 1. As shown in 0 1, parallel set-up for explosive welding was used. Ammonium nitrate mixed with TNT and fuel oil was used as explosive. The welding assembly was placed on a wooden plate placed on a sand bed.

Table 1. Chemical composition of initial materials for explosive welding.

Material	Composition wt. %			
Ti Plates	Ti=99.93	Al=0.03	C=0.04	
Al Plates	Al=99.55	Fe=0.32	Mg=0.03	Ti=0.05

2. 2. Microstructural Studies

The cross section of samples were ground and polished to 0.3 μm finish. Microstructural investigation and analysis of the samples were conducted using an optical and scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS).

2. 3. Heat Treatment

After studying the interface of initial as-welded samples, the multilayer samples were annealed between 1 and 70 hours at 630℃ in

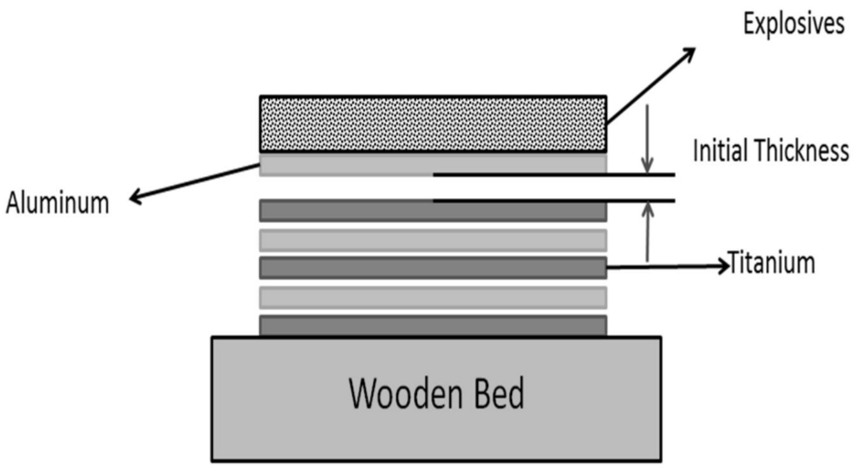

Fig. 1. Schematic presentation of parallel setup used for Ti-Al multilayer explosive welding.

ambient atmosphere using a resistance furnace. Intermetallic thickness was measured using optical and scanning electron micrograph images. Since the intermetallic phase could be readily distinguished, no etchant was used.

3. RESULTS AND DISCUSSION

3. 1. Structural Studies of Ti-Al Composite After Explosive Welding

Scanning electron micrograph of the initial multilayer sample (after explosive welding and rolling) is shown in Fig. 2(a). As can be seen in this figure, there is a smooth interface between aluminum and titanium layers, and no vortex zones are formed. The vortex zones are microvolumes which are sometimes formed by explosive welding and can have different shapes, depending upon the welding conditions and the properties of the joined materials [8]. In the specimens prepared for the study no vortex was detected between layers. However, intermetallics were formed at different locations of the interfaces (Fig. 2b)), although the formation was not uniform. EDS analysis of these intermetallics is shown in Fig. 2(c). These analyses show that the initial intermetallic was $TiAl_3$. The formation of $TiAl_3$ is favorable from both thermodynamic and kinetic points of view. Based on the optical images of sample (Fig. 3), average thickness of the intermetallic formed before heat treatment was 9.54 ± 2.84μm.

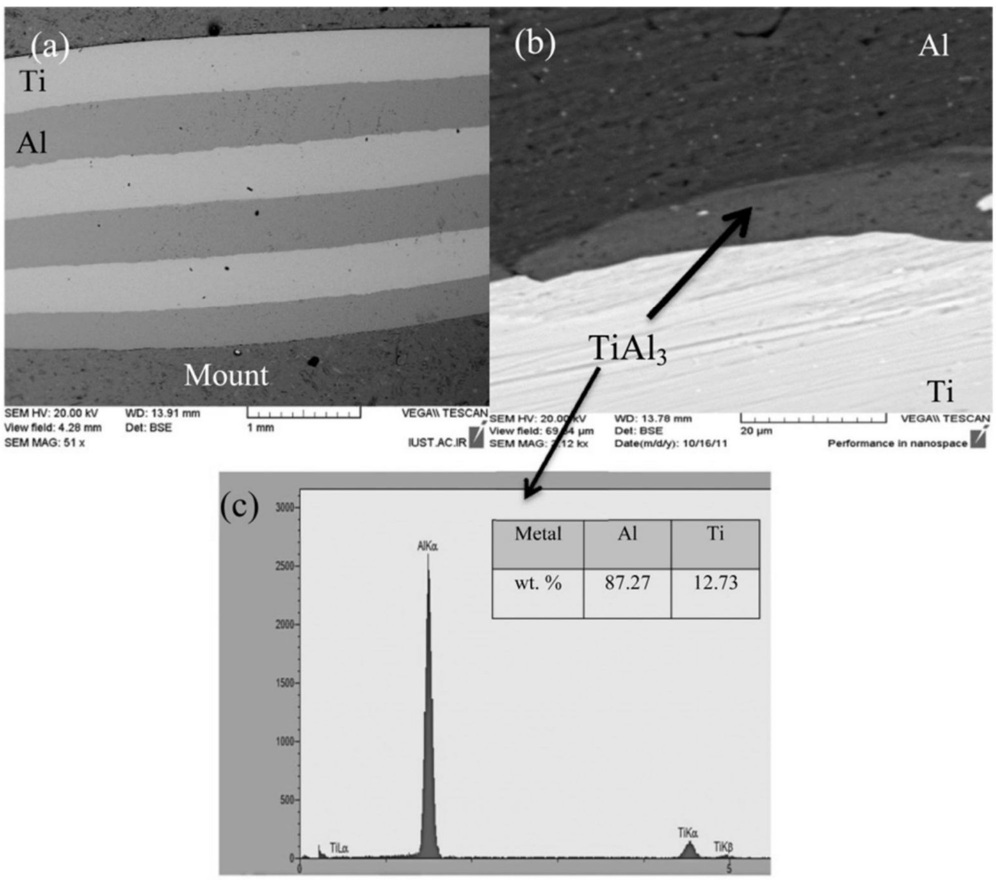

Fig. 2. SEM micrographs of as-welded sample, (a) the Ti/Al multilayer, (b) the intermetallics formed at the interface (c) EDS analysis of the intermetallic phase.

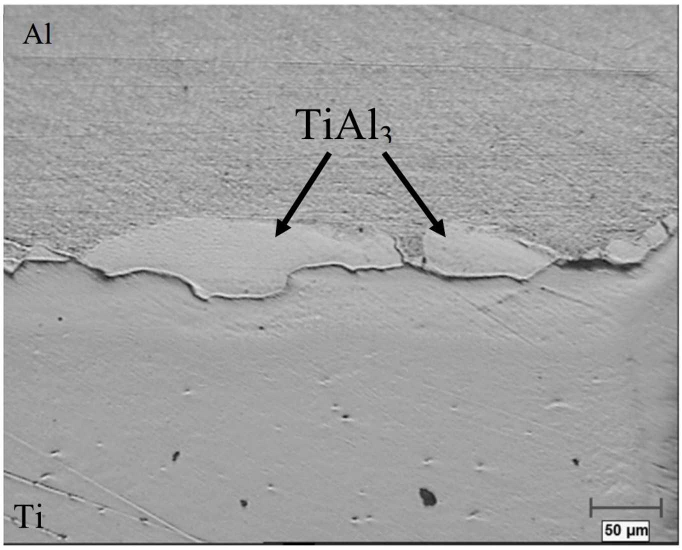

Fig. 3. Optical micrograph showing the non-uniform formation of $TiAl_3$ at Ti/Al interface in the as-welded sample.

3. 2. Microstructural Studies of Annealed Samples

During annealing at 630 °C, the intermetallic layer grows at the interface between titanium and aluminum. $TiAl_3$ is the only intermetallic formed independent of the annealing time. Aluminum, titanium and $TiAl_3$ thickness variations during heat treatment were measured. Intermetallic thickness variation vs. time is shown in Fig. 4. As can be seen in this figure, the intermetallic growth takes place through two different mechanisms. The first part of the growth (until 10 hours), shows a linear behavior between thickness and time, this stage is reaction-controlled [16]. After 10 hours of annealing, on the other hand, a parabolic relationship between thickness and time can be seen, which is indicative of diffusion controlled behavior.

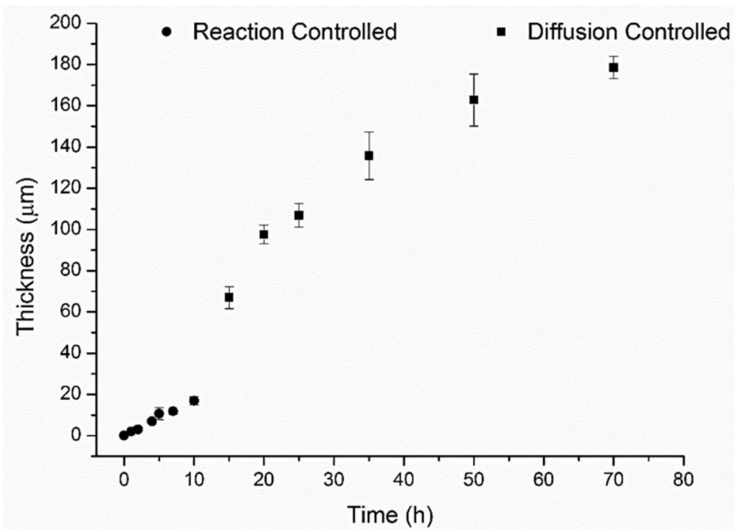

Fig. 4. Dependence of the average thickness of intermetallic layer on the annealing time

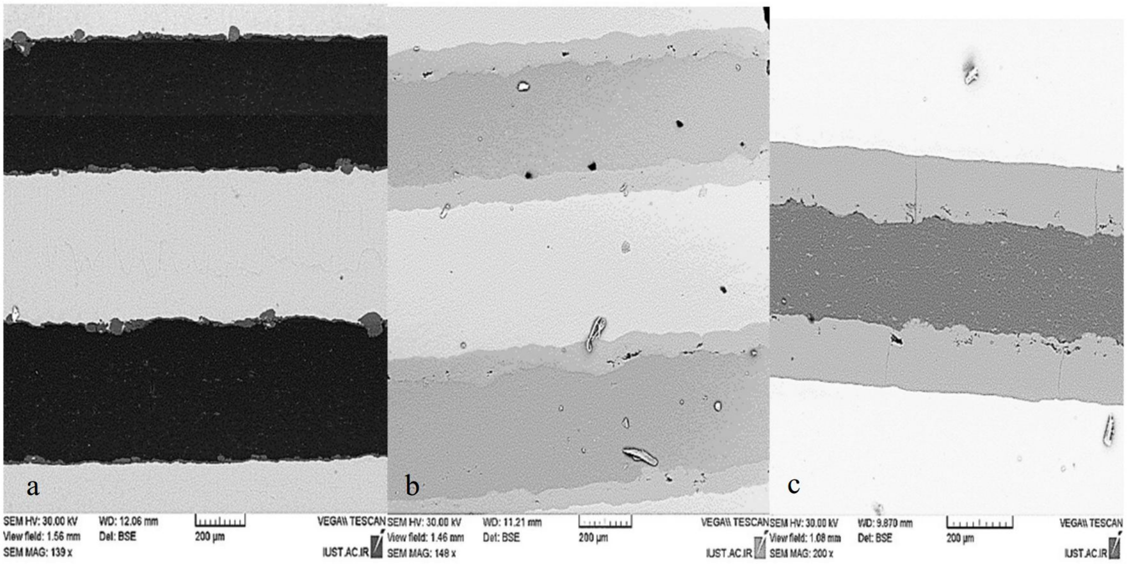

Fig. 5. Aluminum and titanium layers thickness decrease during anealling of layers at 630 for (a) 5h, (b) 15h and (c) 35h.

By passing of time and growth of intermetallic layer, the thicknesses of aluminum and titanium layers were reduced. The decrease in thickness can be seen in Fig. 5. As shown in this figure, the thickness of aluminum decreases more rapidly than titanium. Aluminum and titanium thickness reduction as a function of heat treatment time is shown in Fig. 6. By heat treatment at longer times, aluminum will totally be consumed and Ti-$TiAl_3$ multilayers will form. Ti-$TiAl_3$ is a laminate composite with a very good compressive strength and low density and high Young's modulus [17].

The experimental results for measurement of $TiAl_3$ thickness which was already demonstrated in Fig. 4, is re-plotted as a function of time in logarithmic scale in Fig. 7. To express the intermetallic thickness variation (x) as a function

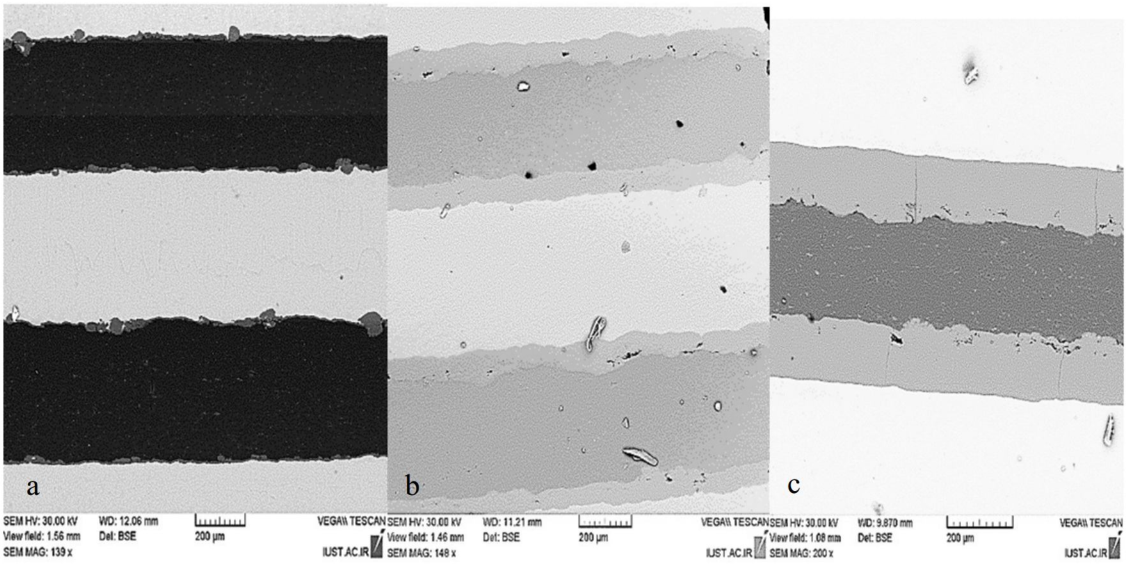

Fig. 6. Aluminum and titanium thickness reduction as a function of annealing time.

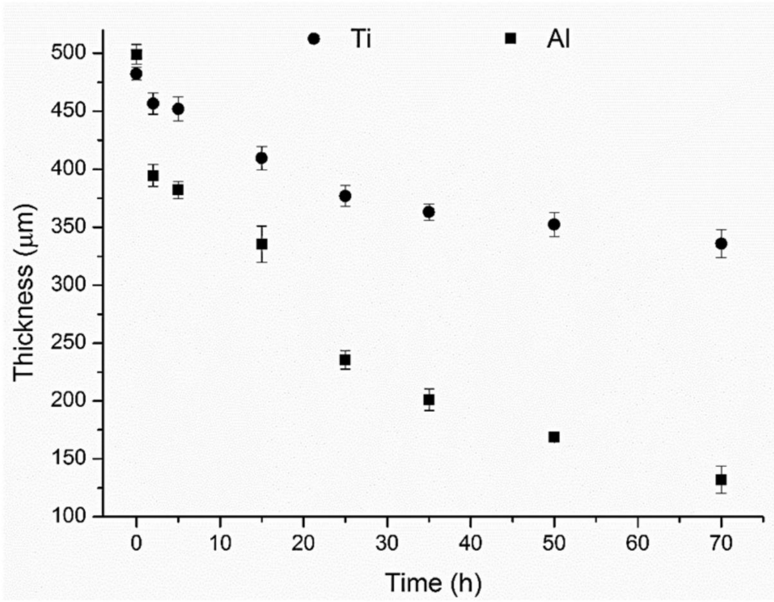

Fig. 6. Aluminum and titanium thickness reduction as a function of annealing time.

of annealing time (t), Eq. (1) can be assumed. Since there is a delay before the formation of intermetallic layer as well as the activation of the second mechanism, an initial time (t0) was accounted for in Eq. (1), which changes it to the form of Eq. (2):

$$x=kt^n \quad (1)$$

$$x=k\,(t-t_0)^n \quad (2)$$

where n is the growth exponent and k is the

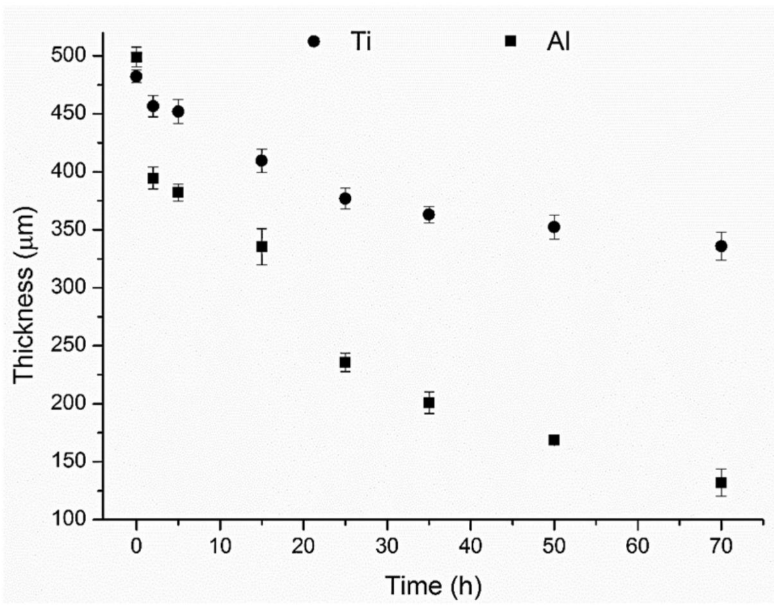

Fig. 7. Plot of thickness vs. time as fitted to Eq. (2) for both diffusion-controlled and chemical-controlled mechanisms.

growth rate constant. For first and second stages, theoretically, n should be 1 and 0.5, respectively. Using Eq. (2) and fitting it separately for two different steps in Fig. 7, "n" and "k" were calculated separately for both mechanisms. It can be seen that for reaction controlled mechanism, n and k are 0.96 and 1.86 μm/sn, respectively, while for diffusion controlled mechanism n and k are 0.31 and 50.96 μm/sn, respectively. Thus, the kinetic of the intermetallic formation at 630 ℃ can be expressed in the form of Eqs. (3) and (4):

For reaction controlled mechanism:

$$x = 1.86 \times t^{n} \quad (3)$$

For diffusion controlled mechanism:

$$x = 50.96 \times (t-t_0)^{0.31} \quad (4)$$

CONCLUSION

MIL composites can be produced in several ways, e.g. reactive foil sintering, but most of these methods need quite expensive equipment. Combination of explosive welding and annealing is an inexpensive and effective way to produce these kind of composites. In this work, 6 alternative layers of Al and Ti were explosively welded together and then annealed at 630 ℃ from 1 to 70 hours to produce intermetallic layer. In the as-welded sample, intermetallic were already formed nonuniformly. EDS analysis showed that $TiAl_3$ is the only intermetallic compound formed in the interface. The thicknesses of intermetallic, aluminum and titanium layers were measured. It was shown that aluminum is consumed faster than titanium. Growth exponent of $TiAl_3$ in explosively welded titanium and aluminum at the annealing temperature of 630 ℃ is about 1.3.

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