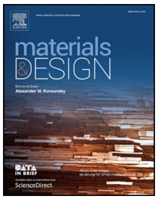
Materials and Design 91 (2016) 80–89

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes



Structural properties of Ti/Al clads manufactured by explosive welding and annealing

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ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 8 September 2015
Accepted 24 November 2015
Available online 25 November 2015

Keywords:
Explosive welding
Intermetallics
Titanium
Aluminum

ABSTRACT

The paper presents a comprehensive study on the titanium and aluminum clads manufactured by explosive welding. Particularly, the microstructure evolution of the Al/Ti interface at 825 K and various annealing time was examined. In the state directly after explosive welding, the wavy morphology of the connection was locally composed of four intermetallic phases: $TiAl_3$, $TiAl_2$, TiAl and Ti_3Al, forming small and peninsula-like morphology (vortex). The annealing process mainly caused growth of the $TiAl_3$ phase as a continuous layer. The studies of the growth kinetics showed four stages: incubation period (up to 1.5 h), the growth govern by the chemical reaction (1.5–5 h), mixed mechanism of chemical reaction and volume diffusion and finally the volume diffusion growth (36–100 h). The orientation maps revealed significant differences concerning the microstructure and texture of welded metals. Directly after explosive welding process, aluminum possessed a typical rolled texture, while in titanium intensive twinning was observed. After annealing, due to the secondary recrystallization, abnormal grain growth was observed in aluminum, while in titanium annihilation of deformation twins took place. The hardness profile made across the welded area after annealing showed the highest values between 365–750 HV in vortex regions at the Al/Ti interface.

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1. Introduction

The idea of multilayered materials came from observations of the nature. An example of multiphase complex natural composites could be found in mollusk shells. These shells are made by calcium carbonate and a series of organic binders, which create hierarchically organized structure. Due to this special construction they possess unique mechanical properties. The metallic-intermetallic laminate (MIL) composites are structural materials and they are supposed to imitate natural structures [1–3]. Various techniques can be used to obtain such materials under industrial conditions: diffusion bonding [4], hot rolling with annealing [5] and cold rolling with annealing [6]. In recent years, the explosive welding (EXW) was also shown to be an efficient method of the MIL designing [7].

EXW is becoming increasingly popular method of joining, possessing many advantages, such as high bond strength and ability to join together unweldable or difficult to weld by other methods metals. Additionally, EXW gives the opportunity to combine the materials characterized by large surfaces or materials with different thicknesses saving their properties after the shot. However, the condition of simple geometry of the joined elements, for example flat or cylindrical, must be kept. Although the explosive welding is valued for its simplicity, the level of the noise and the vibrations arising during the shot is high. Another limitation is that the metals which are joined must demonstrate enough high resistance impact and ductility [8]. In EXW the joining of elements takes place due to the high pressure, which is coming from the explosion high speed of collision (from 0.6 to 3 mm/μs). It may cause a significant plastic deformation and mixing of joined elements. Despite the heat presence generated during the explosion, there is no heat exchange between clads because of the very short time of the interaction. Moreover, there is no external heat used to assist the welding process. Therefore, it is called a cold technique [9,10].

EXW is very useful method to fabricate titanium-aluminum bimetal clads. The titanium-aluminum layered materials bounded by $TiAl_3$ phase are of great interest for materials used in harsh environments — not only for automotive or shipping, but also for aerospace industry. This is due to its unique properties such as specific strength, heat resistance and oxidation resistance. Furthermore, replacement of expensive titanium by aluminum and fabrication of $TiAl_3$ is economically advantageous [7].

Bataev et al. [7] managed to weld successfully ten plates of titanium and eleven plates of aluminum. Clads were annealed for various periods of time (from 1 h to 100 h) under an air atmosphere at 903 K. As a final product the Al–$TiAl_3$–Ti sandwiches were manufactured and examined

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http://dx.doi.org/10.1016/j.matdes.2015.11.087
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by X-ray diffraction (XRD), optical, scanning electron (SEM) and transmission electron (TEM) microscopies. Tension and impact strength tests were carried out, as well. Foadian et al. [11] reported three titanium clads created a good quality connection with three aluminum clads. The $TiAl_3$ phase was the only one being formed in the interface region. These MIL composites were annealed for various time (from 1 h to 70 h) at 903 K. The microstructure was analyzed by optical and (SEM) equipped with energy dispersive X-ray spectroscopy (EDS). Pavliukova et al. [12] joined as a result of EXW ten titanium sheets with nine aluminum sheets and annealed such assembly for 40 h at 913 K with or without external pressure of 12 MPa. Again, solely $TiAl_3$ phase was formed, which was confirmed by XRD measurements. It is the aim of the present study to explore the influence of the EXW process on the microstructure, phase composition and texture of the Al/Ti clads. The study also reveals the changes in both joined materials and their interface occurred after annealing process at 825 K, as well as to explore the mechanisms that govern the growth of the intermetallic phase due to the annealing. Finally, the microstructure changes are related with the hardness values.

2. Experimental procedure

The examined Ti/Al interconnections were manufactured in the following way: two cold rolled plates of titanium Ti Gr.2 ($140 \times 460 \times 0.8$ mm^3) – the flyer plate and aluminum A1050 ($140 \times 460 \times 4$ mm^3) – the base plate were welded in air (Fig. 1). The distance between the plates before the explosion and the detonation velocity was 1.5 mm and 1900–1950 m/s, respectively. The jetting direction was parallel to the rolling direction (RD). In the state directly after welding, the samples of dimensions 6 mm × 12 mm × 4.8 mm were cut from the central part of the clad. Selected samples were sealed in quartz ampoules and annealed at 825 K for various time and cooled with furnace. Their morphology and chemical composition changes at the Al/Ti interface were investigated for 0.5, 1, 1.5, 2, 4, 5, 11, 36, 61, 86 and 100 h with cooling breaks performed after each interval in order to investigate the microstructure and chemical composition changes across the interface.

In order to perform the microstructure observation and chemical analysis in SEM the cross-sections of the samples were polished using abrasive papers (1000, 2000 and 4000) and diamond polishing pastes (6 μm, 3 μm, 1 μm and 0.25 μm) mixed with alumina.

The surface observations were carried out using scanning electron microscopes: FEI Quanta 3D FEG equipped with Trident energy-dispersive X-ray spectrometer produced by EDAX and PHILIPS XL30 equipped with LINK ISIS EDS system (Oxford Instrument). The standard and standardless analyses were done at accelerating voltages of 12 kV and working distance of 10.0 mm. 'Casino' Monte Carlo Simulation program revealed that the accelerating voltages of 12 kV induced a material volume of about 1 μm^3.

Additionally, the microstructures of clads directly after the explosion and after annealing for 100 h were analyzed using FEI Quanta 3D FEG equipped with the TSL EBSD system. To obtain a proper surface quality, specified parameters of the electrolytic etching were used. A slight modification of the procedure described in [13] was applied to shorten the process of electropolishing with the following materials and parameters: electrolyte Struers A3, voltage of 33 V, electrolyte temperature of 283 K, specimen temperature of 77 K, polishing time 4 × 5 s. The EBSD measurement parameters were set to: the tilt angle of 70°, the voltage of 20 kV, the working distance of 10.0 mm and mappings step size of 0.27 μm. The microstructures of the samples were examined in a direction perpendicular to the plane of observation. The inverse pole figure (IPF) color codding with respect to transverse direction (TD) allowed for determination of orientation of the individual grains. The TSL program was used to generate the pole figures.

To obtain information from the bulk, diffraction of high-energy synchrotron radiation (87.1 keV, $\lambda = 0.014235$ nm) using beam line P07 at DESY in Hamburg, Germany, was used. The high penetration depth of synchrotron radiation allows investigations in transmission geometry, resulting in a representative large sample volumes. The diffraction information was collected using an area detector, located at a distance of 1050 mm from the sample and the beam size 0.8×0.8 mm^2. In order to perform the synchrotron analysis the sample of dimensions $5 \times 4.8 \times 4.8$ mm^3 was cut from the central part of the clad. All faces were polished using abrasive papers up to P4000. To enclose the largest volume fraction of the intermetallic phases the sample was irradiated along the Al/Ti interface. Moreover, to ensure that the whole volume of Al/Ti interface is in the beam the sample was continuously rotated around the ω axis by $-90° < x < 90°$ (perpendicular to the Al/Ti interface) [14]. In such a way all orientations enclose in a $0.8 \times 0.8 \times 5$ mm^3 sample volume were recorded in one single image.

For x-ray diffraction and EBSD measurements the following crystal structures were used: $TiAl_3$ — tetragonal crystal structure with space group I4/mmm and lattice parameters: $a = b = 3.8537$ Å, $c = 8.5839$ Å, $\alpha = \beta = \gamma = 90°$ [15]; $TiAl_2$ — tetragonal crystal structure with space group I41/amd and lattice parameters: $a = b = 3.9700$ Å, $c = 24.3090$ Å, $\alpha = \beta = \gamma = 90°$ [16]; TiAl — tetragonal crystal structure with space group P4/mmm and lattice parameters: $a = b = 2.832$ Å, $c = 4.07$ Å, $\alpha = \beta = \gamma = 90°$ [17]; Ti_3Al — hexagonal crystal structure with space group P63/mmc and lattice parameters: $a = b = 5.780$ Å, $c = 4.647$ Å, $\alpha = \beta = 90°$, $\gamma = 120°$ [18].

The hardness measurements were carried out on polished samples without annealing and after 100 h of annealing using microhardness tester CSM Instruments at the room temperature. The measurements were made with a Vickers indenter and a maximum applied load of 0.09807 N with a dwell time of 15 s. The obtained results were the average of 3 to 5 indentations.

To improve the statistics of intermetallic thickness determination a specialized computer program was used for measuring the width of the intermetallic layers. The program examines the width in 600 points over a particular area and implements the average width and standard deviation. All measurements were carried out in representative areas of the sample.

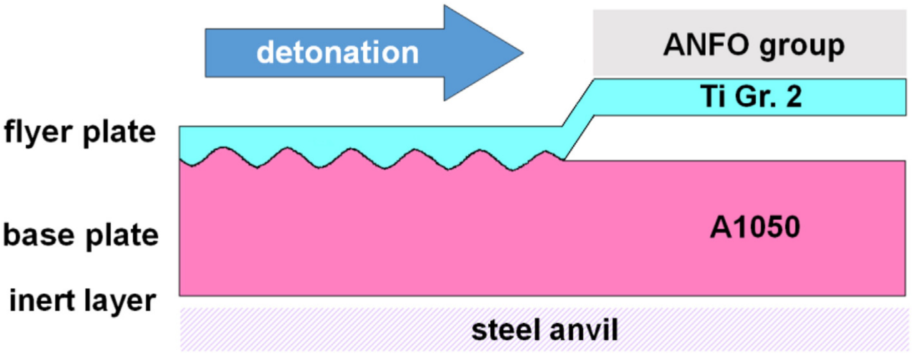

Fig. 1. Experimental setup of explosive welding process.

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