Materials Characterization 145 (2018) 402–412

Contents lists available at ScienceDirect

Materials Characterization

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

Effect of niobium interlayer in dissimilar friction stir welding of aluminum to titanium

Amlan Kar[a,*], Sounak K. Choudhury[b], Satyam Suwas[a], Satish V. Kailas[a]

[a] Indian Institute of Science, Bengaluru 560012, India
[b] Indian Institute of Technology, Kanpur 208016, India

ARTICLE INFO

Keywords:
Friction stir welding
Interlayer
X-ray computed tomography
Intermetallics
Dynamic recrystallization
Mechanical properties

ABSTRACT

The most important issue associated with dissimilar welding is the formation of detrimental intermetallics and consequent reduction in mechanical properties of the weld. It was expected that addition of an interlayer would modify the pattern of the intermetallic formation. The present investigation deals with Friction Stir Welding of aluminum (Al) to titanium (Ti) in presence of niobium (Nb) interlayer. X-ray Computed Tomography results highlighted that fine particles of both Ti and Nb are homogeneously distributed. Large Ti particles are substantially fragmented whereas large Nb particles remain as flakes. Microstructural features of the nugget zone indicated a complex mixing of materials. Jointing had been perceived through elemental diffusion at the interfaces of Al/Ti and Ti/Nb. However, Nb restricted the reaction between Al and Ti, and acted as an efficient interlayer to retard the formation of brittle Al_3Ti intermetallic phase. Mechanisms of microstructural evolution in Al side of the weld have been identified as Dynamic Recovery, Dynamic Recrystallization and particle stimulated nucleation. Significant improvement in the tensile ductility had been observed due to the presence of finer particles. The presence of Nb in the weld nugget influences the microstructural evolution and tensile properties of the weld by reducing the formation of intermetallics.

1. Introduction

Aluminum (Al) and Titanium (Ti) are crucial structural materials in aerospace and automobile industries. Aluminum has a high strength-to-weight ratio, high formability, and low cost. Titanium possesses good strength, high temperature stability, excellent corrosion resistance and very good toughness. Due to complementary properties in many structural parts, these two materials are widely used. However, welding of Al to Ti materials is a challenge due to their difference in melting point, thermal conductivity, limited solid solubility and formation of brittle intermetallic phases. Joining of aluminum and titanium has been carried out using reaction synthesis [1], diffusion bonding [2], friction welding [3,4] and laser welding [5] and ultrasonic welding [6,7] with the objective to minimize the formation of intermetallic phases and increase the mechanical properties of the weld [8]. Earlier reports suggested that Al_3Ti is the primary intermetallic compound evolved in the weld during welding of Al to Ti [3,9–13]. Sujata et al. [14] studied the kinetics of formation of $TiAl_3$ during the reaction synthesis of solid Ti and liquid Al. Their experimental and theoretical studies have shown that $TiAl_3$ is the only possible phase formed at liquid Al/solid Ti interfaces due to thermodynamic and kinetic considerations involved in reaction and diffusion [13]. A similar result was obtained by Fronczek et al. [4] during their studies on growth kinetics of $TiAl_3$ phase in annealed Al/Ti/Al explosively welded clads. The authors also showed that the location of the interface played a crucial role when the kinetics studies were concerned. It is now understood that process parameters and property of interfaces influence the reaction and the formation of final phases at the interface, and the mechanical property of the bond depends on the interface characteristics. Fuji et al. [3] studied friction welding of pure Al and pure Ti and concluded that the growth of intermetallic phase depends on time and temperature during post annealing. It was further observed that strength and ductility of weld varied with the thickness of intermetallic phase [3]. The thickness of intermetallic layer in laser welding has been reported as small as 500 nm [15] which is much less than the critical thickness (5 μm) of the intermetallic layer obtained in friction welding [16]. Therefore, controlling the intermetallic phase formation at the interfaces is a prerequisite condition for satisfactory bond formation in dissimilar welding.

Friction stir welding is considered as one of the most suitable solid state welding processes due to its versatility in application and ability to restrict the development of continuous and thick layer of intermetallics

* Corresponding author.
E-mail address: amlankar@iisc.ac.in (A. Kar).

https://doi.org/10.1016/j.matchar.2018.09.007
Received 19 May 2018; Received in revised form 28 August 2018; Accepted 5 September 2018
Available online 06 September 2018
1044-5803/

at the interface [17]. It also provides a solution to the welding of incompatible similar [18,19] and dissimilar [20] materials having differences in their physical properties. There have been several studies on friction stir welding of Al/Ti [9,11,17,21–23] investigating microstructural evolution and effect of welding parameters on weld property. Key process parameters influencing the welding property were tool rotational speed, welding speed, plunge depth and tool-offset position. The position of the tool with respect to the faying interface between aluminum and titanium controls elemental mixing in weld nugget [22]. This is the most important process parameter in dissimilar friction stir welding. It takes into account the differences in the physical property of working materials and avoids tool wear as well.

Recent studies have shown that Niobium (Nb) has a strengthening effect on Ti at both room temperature and at elevated temperature without sacrificing the ductility. The addition of 5 atomic percent (5 at.%) of Nb increases the strength of TiAl alloy at a temperature up to 500 °C. However, Nb content beyond 10 at.% has shown less significant effect on mechanical properties of the TiAl alloys [24]. Effect of Nb disappears at temperature above 600 °C. The temperature of friction stir welding is expected to be well below the critical temperature of 600 °C [23]. Zhang et al. [25] showed that annealing of multilayered Al/Nb/Ti sheet at 600 °C followed by cold rolling led to almost complete reaction of the Al with Ti and Nb to produce $TiAl_3$ or $NbAl_3$, respectively. The formation of intermetallic compound other than $TiAl_3$ can be useful in the reduction of brittleness and enhancement of mechanical properties of the weld. Addition of niobium can improve the ductility of intermetallic phases formed in Al-Ti weld by stabilizing the high temperature phase [26,27]. Therefore, Nb can be used as one of the prospective interlayer materials to enhance the mechanical properties of Al-Ti friction stir welds.

The objective of the present investigation is to understand the effect of niobium (Nb) as an interlayer on microstructural evolution, phase formation and mechanical properties of the weld in friction stir welding of Al with Ti. Since changing of tool offset with respect to faying interface allows Nb to get mixed in different proportions with Al and Ti, an optimum tool offset of 1.6 mm has been selected based on the earlier research works. Detailed characterization corresponding to the weld has been performed to understand the mechanisms of microstructural evolution, weld formation, phase evolution, and mechanical properties of the weld. Improvement in mechanical properties of the weld in comparison to as-received Al is correlated with ternary mechanical mixing (Al, Ti and Nb), reduction in the formation of brittle intermetallic compounds in presence of Nb addition and variation in microstructural evolution across the weld nugget.

2. Experimental Procedure

2.1. Materials and Processing

In the present study, 4 mm thick sheet of commercially pure Aluminum (Al) and commercially pure Titanium (Ti, Grade 2) were used to obtain friction stir welds (FSW). Niobium (Nb) interlayer was placed in between Al and Ti plates, clamped on the machine bed as shown in Fig. 1. The thickness of Nb interlayer was kept as 200 μm. The chemical composition of the starting materials is given in Table 1.

Friction stir welding experiments were conducted on a custom-built machine (of IISc Bangalore, India and ETA Technologies (Pvt.) Ltd., Bangalore, India) in which the tool was mounted in a horizontal position, and the specimen was held vertically. A custom-build tool, made of tungsten carbide-cobalt alloy (WC-8% Co) was used for the experiment. Tool rotational speed, traverse speed and tool-offset on Al side from the faying interface as illustrated in Fig. 1 were 900 rpm, 90 mm/min and 1.6 mm, respectively. These parameters were used based on the machine capability, recommendation from the earlier research works and results obtained from exploratory experiments. Welding was carried out by offsetting the tool axis to specific distances on the aluminum side from the faying interface to avoid pin wear and overheating of the aluminum alloy due to less interaction of tool with titanium.

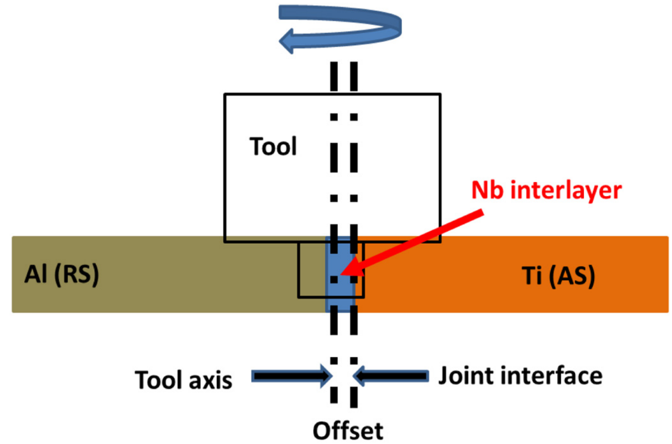

Fig. 1. A schematic image showing the positions of Al, Ti and Nb. Nb interlayer with 200 μm thickness was placed between Al and Ti plates. The tool was at a specific offset into Ti side of the weld.

2.2. Characterization of the Welds

2.2.1. Tomographic Analysis

X-ray Computed Tomography (XCT) measurements were taken using the Zeiss Versa 520 system for three-dimensional (3D) non-destructive visualization and quantification of each element present within the weld nugget. The resolution of the scan was determined by the magnification factor of the object, which resulted from the relative positions of the source/detector geometry. During the scan, an additional optical magnification of 4× was used to cover the field of view that was achieved by the relative positions of the movable X-ray source and the detector. The sample was placed such that the weld zone was positioned within this field of view and the axis of X-ray path. The combined effect of all these parameters yielded a resolution of 6–10 μm depending on the sample dimensions.

2.2.2. Microstructural and Structural Characterization

To observe the microstructure of the weld, specimens were sectioned by Electro-Discharge Machining (EDM) perpendicular to the welding direction. A transverse cross section of the samples was polished by a standard metallographic method. The fine polished samples were chemically etched by Kroll's reagent for titanium and Keller's reagent for aluminum. The microstructure and chemical composition of the weld interface were examined by an optical microscopy (OM) and a scanning electron microscope (SEM) equipped with an energy-dispersive spectrometer (EDS) (Quanta 200, FEI). Fine features of the microstructure were further investigated using electron backscatter diffraction (EBSD) method. The sample for this investigation was prepared by electro-polishing using Struer's Lactropol-5 automatic electro-polisher with the standard A2 for Al. EBSD scan was analyzed using TSL orientation imaging microscopy (OIM) software. The formation of phases at the weld nugget was examined by Bruker X-ray diffractometer (XRD) with CuKα radiation.

2.2.3. Mechanical Characterization

Vickers hardness was measured across the weld cross section using a micro-hardness tester (Model: Zwick/Roell ZHV) with a diamond pyramid indenter of 136° included angle (between opposite faces of the pyramid) with a load of 200 g and dwell time of 10 s. Hardness was measured across the stir zone maintaining a distance of 1.0 mm between the indents, which was more than five times the diagonal of the