Journal of Manufacturing Processes 35 (2018) 681–686

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Technical Paper

Electrically assisted pressure joining of titanium alloys

Yong-Fang Li[a,b], Hrishikesh Das[a], Sung-Tae Hong[a,*], Ju-Won Park[c], Heung Nam Han[c,*]

[a] School of Mechanical Engineering, University of Ulsan, Ulsan, South Korea
[b] School of Mechanical and Automotive Engineering, Shanghai University of Engineering Science, Shanghai, China
[c] Department of Materials Science & Engineering and RIAM, Seoul National University, Seoul, South Korea

ARTICLE INFO

Keywords:
Electrically assisted pressure joining
Titanium alloy
Joint strength
Solid-state joint

ABSTRACT

Electrically assisted pressure joining (EAPJ) of a Grade 1 titanium (Ti) alloy is experimentally investigated. In EAPJ, an electric current is directly applied to the specimen during plastic compression. Microstructural analysis shows that solid-state joints are successfully fabricated in the selected Ti alloy without melting. Shear tensile tests shows that the strength and fracture modes of the joint are strongly affected by a combination of the amount of plastic deformation (corresponding to a thickness reduction) and the electric current intensity. An optimal thickness reduction, corresponding to the maximum fracture load, exists for each value of current intensity, and decreases as current intensity increases. A higher fracture load can be obtained by adjusting the combination of the current intensity and the thickness reduction parameters.

Introduction

Due to their excellent properties such as moderately high specific strength, high fatigue life, high toughness, good formability, and excellent corrosion resistance, titanium (Ti) alloys are used in a wide range of industries, including aerospace, automotive, and biomedical [1,2]. However, to further expand the applications of Ti alloys, proper joining is an important issue. Joining processes can be divided into two major categories: fusion joining (e.g., arc welding [3] and electron beam welding [4]) and solid-state joining (e.g., friction stir welding [5,6] and pressure welding [7,8]). In general, fusion joining of Ti alloys can be challenging since Ti alloys become highly reactive in the molten state, and their mechanical properties decline due to the formation of Ti oxide and porosity in the weld bead.

Solid-state joining is an alternative to fusion joining for Ti alloys. For example, pressure joining [7,8] can result in good joint performance with low cost, high accuracy, high efficiency, and minimal damage to the surrounding parts of the material. The most widely accepted mechanism for pressure joining is the film theory [7,8]. Metal surfaces are covered with oxide layers, which prohibit metallic bonding between two contacting surfaces. During pressure joining, metals are compressed against each other and deformed, forming many micro-cracks on the surface as the surface oxides break. The virgin metals are then extruded through these micro-cracks and contact the metals on the other surface until a metallic bond is established at the interface. Thus, pressure joining establishes atom-to-atom bonds between two clean and intimately contacting metallic surfaces under pressure without the formation of a liquid phase [9].

In pressure joining, the joint strength is significantly affected by the amount of deformation and the joining temperature. Plastic deformation is generally necessary to obtain a permanent joint. Mahabunphachai et al. [10] found that threshold and optimal values of deformation exist in pressure joining. Temperature also greatly influences joint performance. Some metal alloys, such as aluminum and copper alloys [11], can be joined successfully at ambient temperature. However, others such as stainless steel, magnesium alloys, and titanium alloys can only be joined at elevated temperatures. Somekawa et al. [12] successfully joined commercial magnesium AZ31 alloys at temperatures between 623 K–723 K by selecting the appropriate pressure and time. Mahabunphachai et al. [10] found that stainless steel blanks could not be joined when the temperature was below 150 °C. It has also been reported that with increasing temperature, the threshold deformation required for joint formation decreases and the joint strength increases [13,14].

In conventional pressure joining, the workpiece temperature is usually increased in a furnace. However, this heating method inevitably heats up regions which do not need heating, and requires complex heating and control facilities. To overcome such drawbacks, electrically assisted pressure joining (EAPJ) was suggested to raise the temperature of the metals by resistance heating [15]. Researchers have successfully demonstrated this process on sheet metals and foils. For example, Ng et al. [16] successfully joined aluminum and copper sheets using an

* Corresponding authors.
E-mail addresses: sthong@ulsan.ac.kr (S.-T. Hong), hnhan@snu.ac.kr (H.N. Han).

https://doi.org/10.1016/j.jmapro.2018.09.015
Received 16 June 2018; Received in revised form 18 August 2018; Accepted 9 September 2018
1526-6125/

Table 1
The nominal chemical compositions of Grade 1 Ti alloy.

Alloying element, wt%	Ti	C	Fe	H	N	O
	At balance	≤0.1	≤0.2	≤0.015	≤0.03	≤0.18

electrically-assisted roll bonding process, and Xu et al. [17] joined stainless steel 316 L foils using EAPJ.

Unfortunately, studies on EAPJ of metal alloys are still limited and are mostly conducted on very thin foils. In the present study, lap joints of 1 mm thick Grade 1 Ti alloy sheets were fabricated by EAPJ. The suitability of EAPJ for the selected Ti alloy was evaluated along with the effects of joining parameters on the joint performance to provide guidance for process optimization.

Experimental set-up

Grade 1 Ti alloy sheets with a thickness of 1 mm were used for the experiment. The nominal chemical compositions of the alloy are listed in Table 1. Joining specimens with a length of 120 mm and a width of 10 mm were fabricated by laser cutting along the rolling direction of the as-received Grade 1 Ti sheets, as shown in Fig. 1. Prior to the experiment, the specimens were degreased with acetone to remove oil from the surface. For EAPJ, a custom-made fixture was designed (Fig. 2) and installed in a universal testing machine (DTU-900MH, Daekyoung, South Korea). Upper and lower dies with small tips of carbon steel with a hardness of HRC > 60 were used as electrodes. The end face of the tip was semicircular with a radius of 2 mm, as shown in the inset of Fig. 2.

During the joining process, a preload of 100 N was applied to the specimens by the universal testing machine to ensure good contact between the dies (electrodes) and the specimens and to avoid sparks between them. Then, axial compression with a constant displacement rate of 12 mm/min and a continuous electric current with a duration of 10 sec were applied to the specimens simultaneously, as listed in Table 2 and schematically described in Fig. 3. As listed in Table 2, each magnitude of electric current (current intensity) corresponded to four or six different maximum displacements. To verify the repeatability of these results, at least three specimens were tested for each parameter set.

The load history during EAPJ was measured by a load cell and recorded as a function of displacement using a PC-based data acquisition system. Resistance heating for joining was induced by an electric current generator (Vadal SP-1000U, Hyosung, South Korea) with a programmable controller. Also, a set of insulators made of bakelite was inserted between the dies and the machine to isolate the electricity from the testing equipment. A fusion welding process, resistance spot welding (RSW) with a spot size of 6 mm, was also conducted on the same specimen configuration in a control group (Fig. 1). An infrared thermal imaging camera (FLIR-T621, FILR, Sweden) was employed to monitor the temperature of the specimens during joining.

Microstructural analysis was conducted on the cross section of the joint perpendicular to the width. The cross section was first etched with Kroll's reagent and examined by optical microscopy (OM) to confirm that the joint contained no macroscopic defects. The microstructure of the joint was further observed using a field emission gun scanning electron microscope (FE-SEM, SU70, Hitachi, Japan) equipped with an electron backscatter diffraction system (EBSD, EDAX/TSL, Hikari, USA). The grain boundaries were defined as a misorientation angle of 15°. Vickers hardness measurements (300 gf, 10 sec) were also carried out on the cross section perpendicular to the width using a Vickers indenter (HM-100, Mitutoyo, Japan). The mechanical properties of the joints were evaluated by lap shear tensile tests (Fig. 4) with a displacement rate of 1 mm/min. To align the direction of force along the center of the joint, a spacer was placed on each sheet.

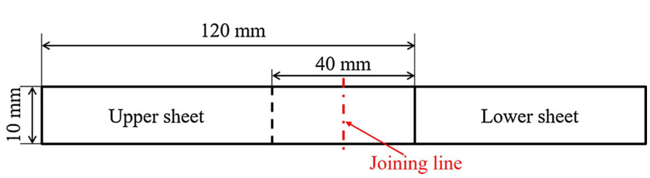

Fig. 1. Configuration of joints and dimensions of specimens.

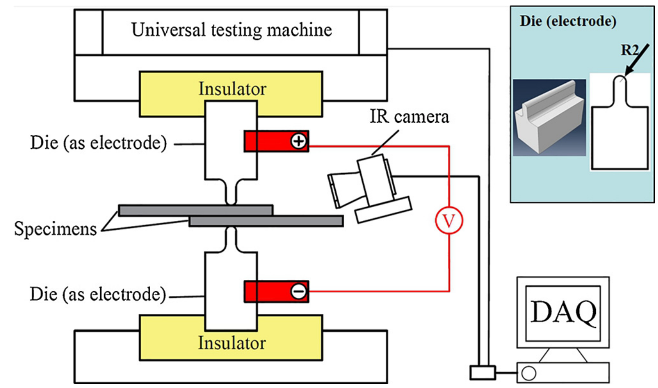

Fig. 2. Schematic of the experimental set-up.

Table 2
Parameters of EAPJ experiment.

Current intensity (kA)	Maximum displacement (mm)	Thickness reduction (R_t) (%)
1.2	1.3	43.0
	1.4	48.5
	1.5	51.8
	1.7	62.7
	1.9	68.5
	2.0	71.0
1.4	0.9	43.2
	1.0	47.0
	1.1	50.5
	1.3	57.7
	1.5	67.2
	1.6	72.5
1.6	0.7	39.7
	0.9	53.2
	1.1	62.3
	1.3	69.0

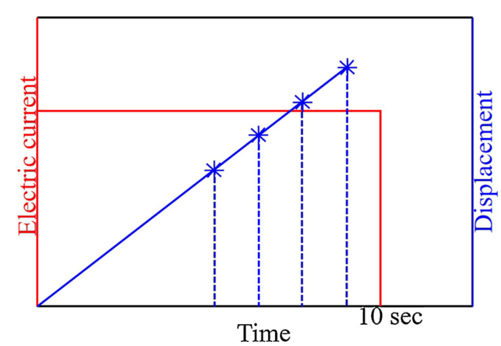

Fig. 3. Schematic of electric current and displacement during EAPJ.

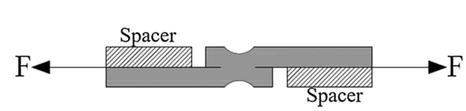

Fig. 4. Schematic of lap shear tensile test.