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Joint properties of friction welded joint between pure magnesium and pure aluminium with post-weld heat treatment

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ABSTRACT

The present paper described the investigation of the joint properties of friction welded joint between pure magnesium (CP-Mg) and pure aluminium (CP-Al) with post-weld heat treatment (PWHT). The joint in as-welded condition fractured from the adjacent region of the weld interface, although that had the same strength as the tensile strength of the CP-Al base metal. This joint had the intermediate layer (interlayer) consisting of intermetallic compound (IMC) on the weld interface, and its thickness was below approximately 1 μm. Most of joints subjected to PWHT autogenously fractured at IMC interlayer and that mainly occurred between Mg_2Al_3 and $Mg_{17}Al_{12}$ although those layers had a little each other at the fractured surfaces. The IMC interlayer grew to CP-Mg and CP-Al sides, and its thickness increased with increasing heating temperature and/or heating time. The main reasons for the autogenous fracture from the adjacent region of the weld interface of the joint were considered the growth of IMC interlayer of the joint during PWHT process. Furthermore, that fracture of the joint was thought the generating of the thermal stresses in the radial and/or circumferential directions during the cooling stage of PWHT process.

1. Introduction

Dissimilar metal joints (referred to as dissimilar joints) have some advantages such as high functionality characteristics for the industrial usage. Since an expansion in the use of dissimilar joints is expected and widely used in various component parts, easy welding method for dissimilar joints is strongly required. On the other hand, the dissimilar joints have several severe problems. In particular, one problem will occur when the dissimilar joints are operated at elevated temperature environment, and/or after post-weld heat treatment (referred to as PWHT). In addition, the intermediate layer (interlayer) consisting of a brittle intermetallic compound (IMC) will generate at the joint interface of both dissimilar metals, so that IMC interlayer will give fatal damage to equipments [1]. Some researchers had reported the mechanical and metallurgical properties of dissimilar joint, which was made with various welding method subjected to PWHT such as friction welding [2–4], friction stir welding [5–7], explosion welding [8], laser welding [9–11], electron beam welding [12,13], and arc welding [14–16]. However, even the PWHT condition of dissimilar joint made by friction welding method that has less generating IMC interlayer at the weld interface, has not been fully clarified. In particular, it is one of the main reasons for the concerned point that the joint will be fractured from the weld interface after PWHT [17,18]. To utilize of dissimilar joint for industrial usage, it is very essential to clarify the joint strength and fractured portion of that under various PWHT conditions, because it is considered that the joint will be used into high temperature conditions. Moreover, if the characteristics of dissimilar joint subjected to PWHT will be clarified, it will be also useful under extreme conditions such as aerospace industry.

In previous works, some of the authors were investigated as basic research that the effect of friction welding conditions on the mechanical (mainly tensile strength) and metallurgical properties of the joint with various PWHT conditions in addition to as-welded condition up to now for dissimilar joints made by friction welding method as following combinations: pure titanium (Ti) and austenitic stainless steel [19], pure Ti and pure aluminium (Al) [20], pure Ti and Al alloys [21], pure Ti and pure nickel (Ni) [22], Al alloys and low carbon steel (LCS) [23], pure Al and LCS [24], brass and LCS [25], and pure Al and pure Ni [26,27]. From those reports, even though the friction welding process can minimize the generation of IMC interlayer between dissimilar metals, it was estimated that IMC interlayer will be affected to PWHT condition for the joint fracture. In particular, it is very useful to clarify the fractured portion of dissimilar joint and that reason to design of the joint. However, the fractured portion of dissimilar joint differs, since mechanical properties such as the tensile strength and thermal properties such as the thermal conductivity are different in their combinations. Hence, to

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clarify the cause of the fractured portion of dissimilar joint subjected to PWHT is strongly required for design of the joint made by friction welding method, because the guideline of that joint for using into high temperature condition will be obtained.

According to the back ground described above, the authors have been carrying out research to clarify the fracture mechanism of dissimilar joint made by friction welding method subjected to PWHT. In this report, the authors chose in the present work the combination of between pure magnesium (Mg) and pure Al, because an expansion in the use of those materials are expected in various component parts, and the joint of those combination will be expected to be used in the transport industry. Furthermore, this dissimilar joint in as-welded condition for those material combinations had IMC interlayer at the weld interface which will be described later. Hence, the authors investigate the fracture of the friction welded joint between pure Mg and pure Al, under various PWHT conditions, and also will clarify the composition of IMC interlayer and its growth mechanism, because it will be considered that the interlayer will grow during PWHT process. In addition, the authors will present about how the fracture will occur at the adjacent region of the weld interface of friction welded joint between pure Mg and pure Al during the cooling stage of PWHT process.

2. Experimental procedure

2.1. Materials and friction welding condition

Commercially pure Mg (referred to as CP-Mg) and commercially pure Al (referred to as CP-Al) of 16 mm diameter round bars were used throughout in the experiments in this study. CP-Mg bar had the chemical compositions of 0.006Al–0.01Mn–0.01Si–0.004Fe–Mg in balance (mass%), and that was supplied with an ultimate tensile strength of 219 MPa and an elongation of 8.0%, respectively. CP-Al bar had the chemical compositions of 0.25Si–0.40Fe–0.05Cu–0.05Mn–0.05 Mg–0.05Zn–0.03Ti–Al in balance (mass%), and that was supplied with an ultimate tensile strength of 82 MPa, a 0.2% yield strength of 44 MPa, and an elongation of 42.5%, respectively. Both round bars were used for the experiments in this study as received condition. Those materials were machined to 70 mm length, i.e. the diameter of the weld faying (contacting) surface was 16 mm. Then, all weld faying surfaces were polished with a buff before joining in order to minimize the effect of its surface roughness on the joint properties [21].

A continuous (direct) drive friction welding machine was employed for joining. During friction welding operations, the friction welding condition was set to the following combinations: a friction speed of 25 s^{-1} (1500 rpm), a range of friction pressures from 10 to 50 MPa, a range of friction times from 0.5 to 2.5 s, a forge pressure of 90 MPa, and a forge time of more than 6.0 s. All joint tensile test specimens were machined to 12.5 mm diameters and 60 mm in parallel length. Then, the joint tensile test was carried out in as-welded condition (hereafter the joint with this condition called as the AW joint) at room temperature. In addition, analysis via SEM-EDS was carried out to analyse the chemical composition at the adjacent region of the weld interface for the joint in as-welded condition.

2.2. Fracture test of joint and PWHT condition

The fracture test of joint subjected to PWHT was carried out as follows. The specimen for the fracture test was machined to 8 mm in diameter in parallel length as shown in Fig. 1, and it was machined to AW joint. Fig. 2 shows the fracture test equipment with a vacuum furnace that carried out with PWHT in order to progress with IMC interlayer growth. The joint (the specimen for the fracture test) was set on the spacer that was put into a vacuum furnace, CP-Mg side of its joint was set to like as a cantilever. Furthermore, two kinds of thermocouples were attached to CP-Mg and CP-Al sides respectively, for the fracture test. One thermocouple was used for measuring temperature of the joint, and another was for measuring occurrence of fracture for it during this process. The former thermocouple was connected to the large diameter part of the joint (CP-Mg side), and the latter one was connected to the 8 mm diameter part of that (CP-Al side). When the joint fractured from the adjacent region of the weld interface during PWHT, the latter thermocouple indicated its temperature and timing with a breaking of measuring current. Fig. 3 shows the pressure and temperature cycle diagrams of PWHT. The heating temperatures were at 423 to 673 K (150 to 400 °C) and the heating times were from 43.2 to 86.4 ks (12 to 24 h), and those were set under the vacuum environment of approximately 0.1 Pa (7.5×10^{-4} Torr), which was shown in Fig. 3. Then, when PWHT to the joint was finished with a setting heating time, it was cooled to room temperature by furnace cooling, i.e. the heating was stopped. Thereafter, this joint (hereafter the joint with this condition called as the PWHT joint) was taken out from the furnace. The details of this experimental method were the same of those in a previous report [26]. After fracture test, analysis via SEM-EDS was carried out to analyse the chemical composition at the cross-section of PWHT joint. In this case, some samples for SEM observation of the cross-sections of PWHT joints were mounted into resin for ease of handling, and those were analysed. Furthermore, the fractured surfaces of PWHT joints were also analysed using X-ray diffraction analysis.

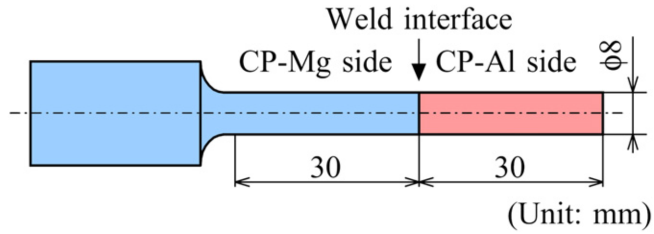

Fig. 1. Dimension of joint for fracture test during PWHT.

2.3. In situ observation of IMC interlayer of joint

To clarify the characteristics of the IMC interlayer of the joint, the continuous *in situ* observation during PWHT process was carried out. The specimen (AW joint) was used with the shape wherein the adjacent region of the weld interface of the joint was processed with 3 mm in diameter and 3 mm in thickness by wire electric discharge machining. Then, the continuous *in situ* observation during PWHT process was carried out at a heating temperature of 573 (300 °C) and/or 673 K, and it was heat treated in a vacuum environment. A high temperature microscope was used for the observation of the IMC interlayer growth at the weld interface, which was recorded continuously using digital video. The detailed method of this *in situ* observation has been described in previous reports [20,24].

3. Results

3.1. Properties of as-welded joint

To clarify the characteristics of AW joint, the tensile and metallurgical properties of that was investigated. Fig. 4 shows an example of the joint appearance at a friction time of 50 MPa and a friction time of 1.0 s. The flash (burr or collar) of CP-Mg and CP-Al was exhausted from the weld interface. That is, the appearance of AW joint was displayed as completely joined, although the quantities of the flash differed at the joint with other friction welding conditions. Fig. 5 shows the relationship between the friction time and the joint efficiency of AW joint. The joint efficiency was defined as the ratio of joint tensile strength to the ultimate tensile strength of the CP-Al base metal. Fig. 6 shows an example of the appearance of the joint tensile tested specimen for AW joint. When the joint was made with a friction pressure of 10 MPa as showed by the open rhombus symbols in Fig. 5, the joint