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Cladding of titanium and magnesium alloy plates using energy-controlled underwater three layer explosive welding

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ABSTRACT

Titanium and magnesium alloy AZ31 plates were explosively welded using the underwater shock wave technique. A thin AZ31 interlayer was utilized as a proposed method to reduce kinetic energy loss and the formation of excessive molten zone at the interface. Through the experiments, the effects of initial inclined angle of the explosive, water distance and annealing of the AZ31 plates were investigated. Different experimental conditions allowed confirmation of the excessive molten zone, moderately welded zone and separation zone. Characterization of the welded interface suggests that bonding quality in the welded region showed planar interface without a molten zone. The effects of various welding parameters are discussed to evaluate moderate conditions of explosive welding. Welding conditions are discussed based on a weldability window estimated by numerically simulated dynamic bending angle at collision and horizontal collision point velocity, which may provide the kinetic energy lost by collision.

1. Introduction

Two-layer cladding of magnesium and titanium using conventional explosive welding techniques has been investigated by Ghaderi (2008) but encountered numerous unacceptable problems such as cracks, molten pockets, and an excessive molten zone, all of which result in a poor welded interface. Also, Manikandan et al. (2006) investigated explosive welding techniques for titanium and stainless steel, whose incompatibility makes them very difficult to bond conventionally, suggesting impressive success in metallurgical combinations by controlling energetic conditions. These experiments included insertion of a thin middle plate between the two plates. Recently, Hokamoto et al. (2009) proposed underwater explosive welding, which may offer a significant alternative to decrease kinetic energy loss using a thin plate as flyer plate. Conventional explosive welding techniques are normally performed in air, meaning that a higher energy is conducted to the flyer plate, normally several mm in thickness, and these results in higher kinetic energy dissipated by collision.

In respect to the welding of titanium and magnesium, Aonuma and Nakata (2012) attempted to clad magnesium and titanium by such solid state welding techniques as friction stir welding. However, numerous impermissible characters were observed, resulting in a poor welded interface. Habib et al. (2014), who attempted the cladding titanium and magnesium alloy using an underwater explosive welding technique, indicated that direct welding of titanium with magnesium alloy was difficult due to a thick molten zone. Habib et al. (2014) have also found that the use of an intermediate plate was effective in improving welding conditions by suppressing formation of this molten zone, a cause of poor quality bonding, but the molten zone was not easily avoided in the entire length of the sample. In addition, separation occurred under a low pressure region. This suggests that weldable conditions are quite limited and should be chosen very carefully but not detailed discussion based on the welding conditions has been made in the former paper.

The present investigation attempted a series of underwater explosive welding experiments of titanium and magnesium alloy AZ31 with the insertion of a thin AZ31 intermediate plate, and the experimental results were compared with those numerically simulated results, drawing a weldability window for the combinations. Based on the numerical simulation, the effects of dynamic bending angle at collision which is related to vertical velocity and the amount of kinetic energy loss by collision of titanium with AZ31 are clarified. Since the kinetic energy loss related with the lower limit of welding in the weldability window is the most important parameters to suggest its weldability, the experimental results are discussed based on the energetic consideration.

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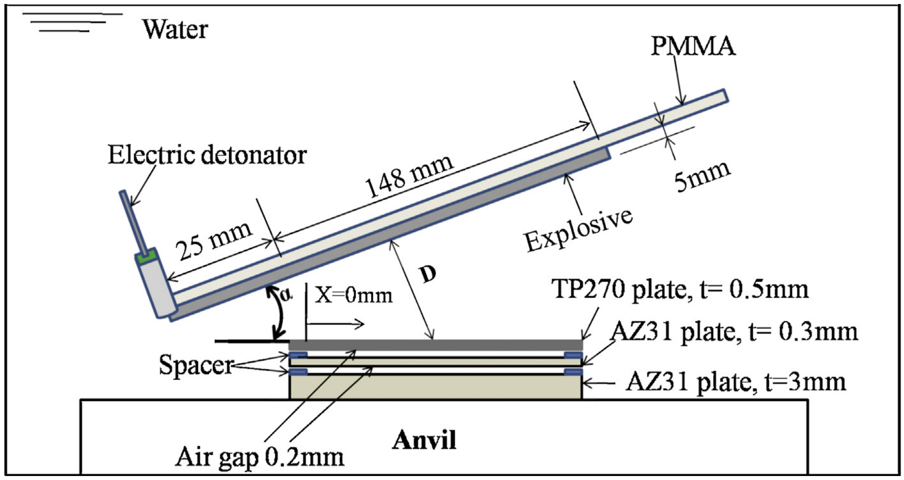

Fig. 1. Experimental setup for three layers explosive welding, using of underwater shock wave technique.

2. Experimental procedure

A flyer plate of pure titanium (JIS TP270) was positioned at a stand-off distance (SOD) fixed at 0.2 mm above the magnesium alloy (AZ31) intermediate and base plates, as illustrated in Fig. 1. The length of the sample welded was 70 mm. Hokamoto et al. (2004) reported that the explosive-driven water pressure was sufficiently high as to accelerate the flyer plate under a small SOD to result in a metallurgically sound bonding at the interface. The SOD between those plates was fixed at 0.2 mm by inserting 0.2 mm-thick aluminum plate as spacer between the plates, while the flyer plate had a thickness of 0.5 mm, the intermediate plate 0.3 mm, and the base plate (AZ31) 3 mm. The initial inclination angle α of the explosive was varied at 20° or 30° to control the collision angle β and the horizontal collision point velocity V_c as reported by Manikandan et al. (2011). For optimum welding conditions, the collision point velocity toward horizontal direction V_c must be below the sonic velocity of the cladding plates, thus, the inclination set-up angle of the explosive is an essential as noted by Hokamoto et al. (2004). Water distance between the explosive and the center of the sample D was set at 35 mm and 45 mm, moderate conditions for welding based on our experience. The authors conducted experiments with D set at 25 mm and 55 mm for as received AZ31 middle plate but were unsuccessful. The experimental conditions are summarized in Table 1.

In the experiments, a layer of explosive with thickness of 5 mm was bonded to a PMMA plate and positioned above the flyer plate. The explosive trade name SEP, a plastic bond explosive with the compositions of 65 wt% PETN (pentaerythritol tetranitrate) and 35 wt% paraffin (density 1310 kg/m^3, detonation velocity 6970 m/s, Kayaku Japan Corporation), was used for the experiments. A steel anvil was positioned below the sample as to adjust and to ensure the sample flatness.

3. Experimental results

3.1. Microstructure of welded interface

Fig. 2 shows the microstructure of the welded interface of sample No. 1, where horizontal distances from the detonation side at X = 5 mm, 30 mm and 60 mm, α at 20°, D = 35 mm, and an intermediate plate with a thickness of 0.3 mm as received (work hardened) was used. It is observed that the interface shows a small area with molten zone less than 10 μm-thick along the interface via a micrograph with distance X = 5 mm. Such molten zone was limited to this region and was invisible via micrographs at X = 30 mm and 60 mm. It is related to the pressure applied to the flyer plate. A collision velocity relatively high in the vertical direction is expected when the explosive is close to the sample. The interface revealed a planar structure due to the difference of the properties of the welded interface as previously mentioned by Hokamoto et al. (1999), but the bonding strength is considered sufficient because the interface does not separate during cutting and polishing.

Sample No. 2, the water distance D = 45 mm, resulted in no molten zone through the welded interface as shown in Fig. 3. This result indicates that sound welding condition exists to distance X = 50 mm. Separation was observed more than the distance X = 50 mm due to the low applied pressure to the sample.

Fig. 4 shows the microstructure of sample No. 3, where α = 30° and D = 35 mm. From the distance at X = 5 mm to 30 mm, uniformly well-welded interface was observed, and separation began from the distance X = 45 mm.

So as to clarify the effect of heat treatment of the AZ31 plate, AZ31 plate were annealed at 260 °C for 1.5 h (5.4 ks) and used for underwater explosive welding. Fig. 5 shows a micrograph of the results, displaying large amount of excessive molten zone under the use of 0.3 mm AZ31 annealed interlayer. Such an excessive molten zone as found in X = 5 mm and 30 mm (Fig. 5) increased as

Table 1
Experimental conditions.

Experiment no.	Inclination angle (α)	Water distance (D/mm)	Spacer/SOD (mm)	Middle plate thickness (mm)
1	20°	35	0.2	0.3 (as received; work hardened)
2		45		
3	30°	35		
4	20°	35		0.3 (annealed)
5		45		