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Author(s)	Wahba, Mohamed; Katayama, Seiji
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Heat-Conduction Mode Joining of Dissimilar Materials

Mohamed WAHBA* and Seiji KATAYAMA**
* Central Metallurgical Research & Development Institute, Helwan 11421, Egypt
Graduate School of Engineering, Osaka University, 1–1 Yamadaoka, Osaka 565-0871, Japan
** Joining and Welding Research Institute, Osaka University, 11–1 Mihogaoka, Osaka 567-0047, Japan

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1. Introduction

The automobile industry is facing an increasing pressure to reduce the car weight due to environmental concerns as well as customers' demand of more economic vehicles. Therefore, significant efforts are being exerted to incorporate light weight materials in the construction of the car body. A critical prerequisite in this regard is the development of a robust joining technology to join the newly developed light weight materials to other structural materials.

Laser welding has occupied its place as one of the chief welding processes in the automotive industry since the invention of the welded tailor blanks [1]. The process depends on melting the materials to be welded by irradiation of a focused laser beam. Basically the power density of the laser beam is high enough to evaporate the material and form a *keyhole* therein [2]. *Keyhole* mode welding has the advantages of deep penetration and high processing speeds. However, the *keyhole* is inherently unstable. The stability of a *keyhole* is determined by the balance between the vaporization pressure, which tends to keep the *keyhole* open, and a restoring pressure of the surface tension [1]. Consequently, *keyhole* welding of dissimilar materials is quite a problematic process due to the large differences in the chemical and physical properties between the materials to be welded. An alternative mode is *heat-conduction* welding in which the power density is insufficient to cause evaporation [2]. In this mode, laser beam does not penetrate into the material and hence less perturbation is introduced to the welding process [1].

This study was performed to investigate the characteristics of joining dissimilar materials using *heat-conduction* welding mode. Magnesium alloys were selected as the base materials due to their extremely light weight [3]. Two cases were studied where magnesium alloy was welded to Zn-coated steel or joined to engineering plastics.

2. Experimental Procedures

The base materials used in this study were 3 mm thick extruded AZ31B magnesium alloy (3.28 wt% Al, 0.81 wt% Zn, 0.29 wt% Mn and balance Mg), 2 mm thick thixomolded AZ91D magnesium alloy (9.42 wt% Al, 0.7 wt% Zn, 0.26 wt% Mn and balance Mg), 1.2 mm thick SP781 Zn-coated steel (0.002 wt% C, 0.014 wt% Si, 0.159 wt% Mn, 0.0107 wt% P, 0.0048 wt% S and balance Fe) and 2 mm thick amorphous polyethylene terephthalate (PET) ($(C_{10}H_8O_4)_n$) engineering plastic.

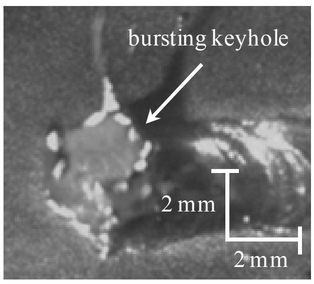
A 16 kW disc laser was used to lap-weld AZ31B alloy to SP781 steel. A laser beam was transmitted through an optical fiber of 200 μm diameter and focused on the workpiece surface by a lens of 280 mm focal length. The weld pool was shielded by Ar gas flowing at 30 L/min through a 16 mm diameter nozzle. A high speed video camera was employed to observe the molten pool and the keyhole at 8000 F/s or 1000 F/s framing rate.

Lap joining of AZ9D alloy to PET sheet was performed using a 3 kW diode laser source. A laser beam was focused on the specimen surface by a focusing lens of 100 mm focal length. The focused beam had a rectangle cross section with dimensions of 0.6 mm × 11 mm and joining was conducted in the direction perpendicular to the wide dimension. N_2 gas was used to cool down the plastic surface. It was provided through a 0.5 mm wide and 19 mm long nozzle and flowed at 35 L/min.

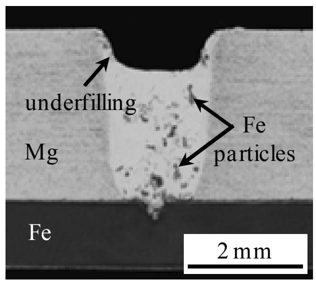
3. Results and Discussion

3.1 Welding AZ31B alloy to SP781 steel

AZ31B specimen was positioned on top of SP781 specimen and the welding parameters were set to -7mm defocusing distance, 2 kW laser power and 2-4 m/min welding speed to perform a keyhole welding mode. The process stability was observed to decrease with increasing the applied energy input. Excessive amounts of spatters were formed due to a frequent bursting of the *keyhole* that resulted in underfilled joints, as shown in Fig. 1. The process stability was improved at lower energy input, but this decreased both weld penetration into the SP781



(a) High speed video observation photo of molten pool at 8000 F/s



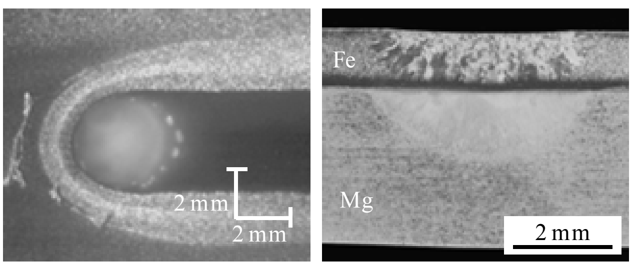
(b) Cross-sectional macrostructure of welded joint

Fig. 1 High-speed video observation photo showing welding phenomenon during *keyhole* mode welding, and cross section of lap-welded joint between AZ31B alloy and SP781 steel.

specimen and the consequent joint strength. This behavior might be attributed to the formation of a *keyhole* in the SP781 specimen at high energy input and the consequent evolution of Fe plume that disturbs the *keyhole* stability of the above molten Mg. The excessive spatter formation at high energy input required a recurrent replacement of the cover glass of the laser welding head. This rendered the welding process unfeasible in addition to the resulting underfilled joint.

To avoid the negative influence of the *keyhole* instability on the welding process, welding parameters were set to obtain a *heat-conduction* mode. One important advantage of a heat-conduction mode in this case is to allow Zn to interact with Mg to overcome the metallurgical problem of welding two elements with no mutual solid-solubility such as Mg and Fe [4]. SP781 specimen was lapped on top of AZ31B specimen and the applied welding parameters were +20 mm defocusing distance, 3 kW laser power and 0.5 m/min welding speed. The welding process was very stable. Fig. 2 shows a snapshot from the high speed video observations, indicating the unbroken liquid metal of the molten pool, and a cross-sectional macrostructure of the resulting joint. Low aspect ratio fusion zones, characteristic of *heat-conduction* mode, were formed in both specimens. The width of the joined interface was approximately 4.5 mm. The strength of a 25 mm wide specimen of such a joint exceeded 6000 N in tensile shear testing and fracture occurred in the fusion zone of the AZ31B alloy. This very high joint strength suggests that a metallurgical bonding has been developed between the two specimens.

In order to elucidate the joining mechanism the microstructure of the interface was investigated with transmission electron microscopy (TEM). Fig. 3(a) shows bright filed images of the joining zone. A lamellar structure consisting of 48.8 wt% Mg, 3.6 wt% Al and 47.6 wt% Zn was observed in the upper part of the fusion zone of AZ31B alloy (the right hand side of the image in Fig. 3 (a)). The chemical compositions of this phase indicate that it is an Mg-Zn eutectic solidification product. The area between the Mg-Zn eutectic and the steel surface was composed of a Mg substrate depleted of Al (0.22 wt%) and enriched with Zn (6.3 wt%) and Fe-Al or Fe-Zn-Al particles. The width of

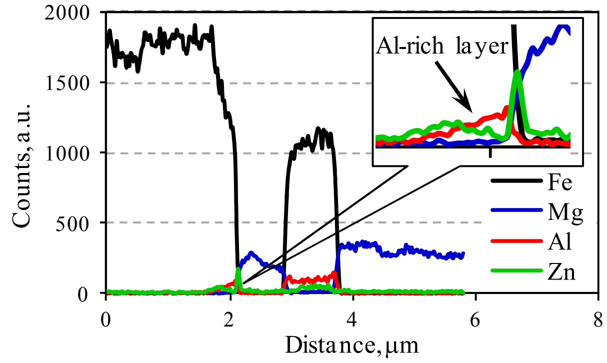


(a) High speed video observation photo of molten pool at 1000 F/s

(b) Cross-sectional macrostructure of welded joint

Fig. 2 Welding phenomenon during *heat-conduction* mode welding, and cross section of lap-welded joint between Zn-coated SP781 steel and AZ31B alloy.

(a) Bright field TEM image of interface



(b) EDS line scan

Fig. 3 Interfacial microstructure and EDS chemical analysis of *heat-conduction* mode welded joint between Zn-coated SP781 steel and AZ31B alloy

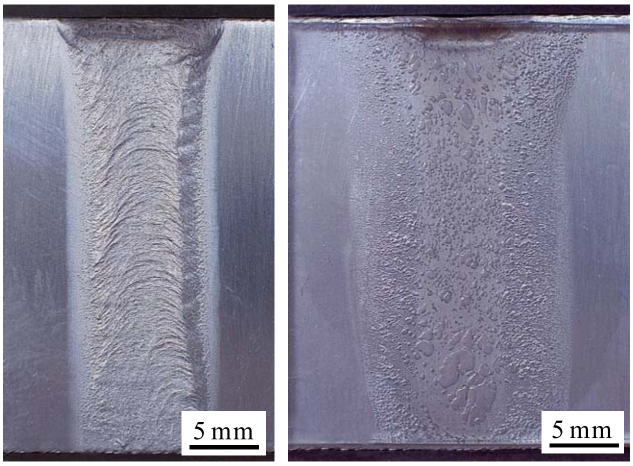
this area corresponds to the thickness of the original Zn coating layer on the steel surface. Fig. 3 (b) shows EDS line scan analytical results measured at the red line in Fig. 3 (a). It can be observed that the steel surface was enriched with Al to a depth of approximately 450 nm.

This analysis implies that the Zn-coating layer was melted and interacted with Mg. The formation of Mg-Zn eutectic could dissolve the oxide layer on the Mg surface The AZ31B alloy melt was then allowed to come into an intimate contact with a non-oxidized steel surface. The Al was rejected from the AZ31B alloy melt and reacted with Fe. These reactions were promoted by the less dynamic nature of the *heat-conduction* mode and could not be achieved with *keyhole* welding mode.

3.2 Joining AZ91D alloy to PET

In the second case, joining of AZ91D magnesium alloy to PET plastic was investigated. The very different atomic structure of plastics poses great challenge in joining them to metals. Therefore, joining methods that mainly depend on mechanical forces have been applied [5]. These methods include adhesive bonding and mechanical joining using screws or rivets. However, each of these techniques has its own drawbacks including severe quality control or non-flexible design. Accordingly, the potential of joining metals to plastics using direct irradiation of a laser beam in the *heat-conduction* mode is introduced.

An inherently low power density diode laser beam was



(a) AZ91D surface appearance (b) PET surface appearance

Fig. 4 Surface appearances of *heat-conduction* welded joint betweenAZ91D and PET.

employed to lap join AZ91D magnesium alloy to PET sheet. AZ91D specimen was lapped on top of PET specimen. The optimized joining parameters were 1500 W laser power and 17 mm/s joining speed. Fig. 4 shows typical surface appearances of the joined area of both AZ91D and PET specimens. The surface appearance of AZ91D specimen was like a bead-on-plate weld. The top surface of the PET specimen was smooth while many small bubbles were formed inside the plastic adjacent to the interface. The applied joining parameters produced a joint with an average width of 14 mm. The strength of such a joint exceeded the strength of the base plastic. A 30 mm wide specimen of this joint failed in tensile shear testing at loads exceeding 2600 N by base plastic elongation.

Fig. 5 shows a cross section of the interface between AZ91D alloy and PET in the joining zone. As can be seen the PET specimen was tightly bonded to the AZ91D alloy. Also some bubbles could be observed at the interface inside the PET specimen. It is believed that the heat generated from laser-material interaction on the AZ91D side raises the temperature at the interface to melt and partly decompose a narrow surface region of the PET specimen. Decomposition gas bubbles are then formed inside the plastic at the interface. The high pressure caused by generation and rapid expansion of these bubbles makes the activated plastic surface come into intimate contact with the heated metal surface, and consequently physical (Van der Waals), chemical and mechanical (Anchor effect) bonding between metal and plastic are achieved [6]. Therefore, the formation of gas bubbles in a discrete morphology, as seen in Fig. 5, secures a large areas of bonded interface and hence a high joint strength.

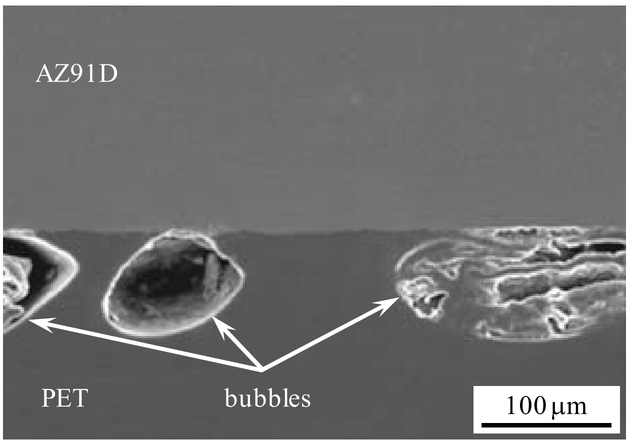


Fig. 5 SEM photo near AZ91D-PET joint interface showing the existence of bubbles in PET and tight bonding between alloy and plastic.

4. Conclusions

Heat-conduction mode was applied in laser welding of dissimilar materials. It was demonstrated that the problems stemming from the large differences in the physical and chemical properties between the materials to be joined could be avoided. The maintenance of the liquid metal unbroken in the molten pool and the less dynamic nature of the *heat-conduction* mode, allowed metallurgical reactions to take place between AZ31B magnesium alloy and SP781 Zn-coated steel and develop strong bonding. *Heat-conduction* mode joining of two different types of materials such as metals and plastics was feasible providing the process with advantageous characteristics in the design and the production stages over the conventional joining methods.

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