J Mater Sci (2007) 42:565–572
DOI 10.1007/s10853-006-1068-6

Microstructure characteristics and mechanical properties of laser weld bonding of magnesium alloy to aluminum alloy

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Received: 28 July 2005 / Accepted: 4 January 2006 / Published online: 11 November 2006

Abstract Weldability of magnesium alloy to aluminum alloy in laser weld bonded (LWB) joints was investigated. Results showed that magnesium/aluminum could be easily joined by LWB under proper technological parameters. The weld was characterized by complex vortex flow at the bottom, and there existed intermetallic compound layer between weld pool and lower sheet metal, which was composed of the brittle phases of Al_3Mg_2 and $Al_{12}Mg_{17}$, resulting in the formation of weld cracking. Adhesive in the weld was heated up and then escaped in the form of gas, which would not affect the microstructures of weld. However, Adhesive near the weld was oxidized and carbonized, leading to the formation of a failure zone. But this failure zone had little influence on load bearing capability of the joints. Besides, it was also found that the penetration of LWB joints was greater than that of laser welded joints alone. In tensile shear test and *T*-peel test, LWB samples gave both the highest shear resistance and the highest peel resistance compared to laser welded samples and adhesive bonded samples.

Introduction

The manufacturing and sale of aerospace, transportation and civil structures invariably require joining components of different materials and compositions. Because manufacturers are constantly being pressured for lower cost and reduced weight, multiple materials are being combined in many products [1–4]. As different materials are used within a given structure, there will definitely be a need to somehow join them.

Magnesium is the lightest of the structural metals with a density two-thirds that of aluminum and one-quarter that of steel [5]. The ability to join magnesium components effectively to other engineering materials would allow further design flexibility and increased application of this lightweight material [6–9], so it is urgent that light aluminum alloys and magnesium alloys are used for these components. Thus, the problem of welding for aluminum/magnesium alloys must be faced; it is known that a variety of attempts to weld aluminum/magnesium alloys have failed using arc welding [10], electron beams and laser beams, because much more intermetallic compounds form in the weld during fusion welding, which is deleterious to the mechanical properties.

LWB is referred to as a method that uses both a laser beam and adhesive to make a lap joint, as illustrated in Fig. 1. An adhesive is placed in between the sheet metals to be joined, and then laser beam penetrates through the top sheet and adhesive. The method takes advantage of the shear strength provided by the adhesive and the tensile strength offered by laser welding. The weld can be controlled so that it does not penetrate through the second sheet. It is estimated that the LWB would result in a 15–20% manufacturing cost savings. This joining method offers an attractive option for producing aircraft structures with much lower manufacturing cost [11].

The aim of this research was to evaluate the weldability of using the LWB process to join magnesium

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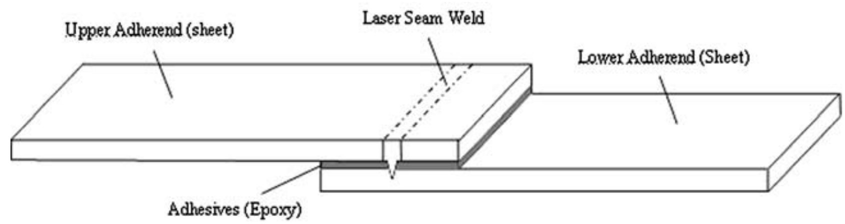

Fig. 1 Configuration of a LWB joint

alloys to aluminum alloys. LWB of dissimilar metals raises two issues that are not encountered when using single joining process. One consideration is whether two metals can be welded by laser heat source on the condition of the presence of adhesive, namely with respect to welding feasibility. The other consideration is, even though they can be welded, whether the adhesive affects microstructure characteristics of the welds and then mechanical properties of the joints, namely with respect to adhesive influence. The weldability of LWB of Al and Mg, including microstructure characteristics and mechanical properties, was examined in order to lay a foundation to the practical use of Mg/Al joints.

Experimental

Welding and materials

For the purpose of this evaluation, samples of extruded AZ31B Mg alloy ($60 \times 20 \times 1.2$ mm) and extruded 6061Al alloy ($60 \times 20 \times 1.7$ mm) were used in this experiment. The chemical compositions of materials are shown in Table 1. Adhesive used was a one-part, heat-curing (or heat-activated) structural epoxy adhesive, which was allegedly designed specifically for use on pretreated magnesium sheet and aluminum sheet, and came as a paste that could be dispensed manually. The cure cycle was 30 min at 175 °C, with a ramp up from room temperature at no more than 5 °C per min. The welding equipment used was a LWS-500 laser welding machine.

The process flow of experiment is shown in Fig. 2. The interfaces of samples were prepared by grinding with silicon carbide paper up to 220 grit, then being degreased, dried and kept in a desiccator. The adhesive with a thickness of 0.1–0.3 mm was coated on the overlap area with a length of 15 mm. During welding, Mg alloy sheet was placed on top of Al alloy with the adhesive material in between. In present experiment, laser power was varied between 400 and 500 W, laser beam spot size was 0.8 mm, focus distance was in the range of positive 1.0–2.0 mm, and welding speed was varied between 800 and 900 mm min^{-1}. Argon gas with the purity of 99.9% was used as shielding gas of laser welding, which current was varied in the range of 8–10 L min^{-1}. The most successful welds were achieved when the appropriate technological parameters were adopted.

Mechanical testing

The tensile shear force of LWB joints was evaluated by means of an electron tension-testing machine (Css-2205) with a constant tensile rate of 3 mm min^{-1}. Meanwhile, to make comparison, those of adhesive bonded joints, laser welded joints and LWB joints under the same parameters were assessed.

Table 1 Chemical compositions of AZ31B and Al 6061, wt-%

Material	Mg	Al	Zn	Mn	Si	Fe	Cu	Ni	Ca	Cr	Others
AZ31B	Bal.	2.5–3.5	0.5–1.5	>0.2	<0.10	<0.03	<0.10	<0.005	<0.04	–	<0.30
Al 6061	0.8–1.2	Bal.	–	<0.15	0.4–0.8	<0.7	0.15–0.4	–	–	0.04–0.35	<0.15

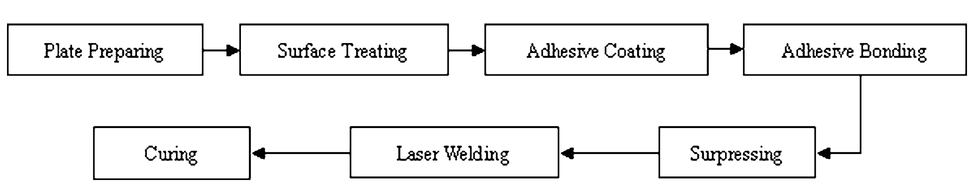

Fig. 2 Flow of LWB process

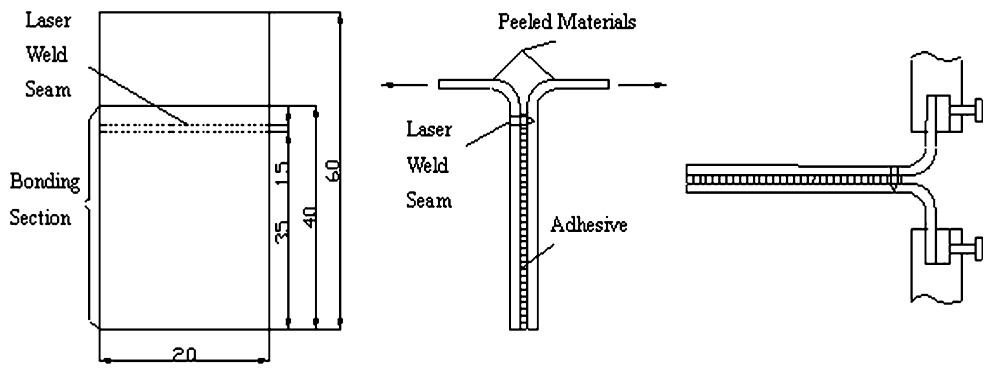

Fig. 3 Configuration of *T*-peel test

T-peel test was carried out to study the peel behavior of LWB joints, by the electron tension-testing machine with a constant peel rate of 5 mm min^{-1}, (see Fig. 3). For comparison purpose, adhesive bonded sample was also tested at the same time.

Metallography and microanalysis

Samples were analyzed by optical microscopy and electron probe microanalysis, after preparation by grinding on successively finer grit papers and then polishing using a 3 μm diamond paste. After final polishing using suspension, samples were carefully flushed with alcohol. Due to nature of dissimilar metal weld, Mg alloys of optical microscopy samples were etched in a hydrofluoric acid solution and Al alloys in a sodium hydroxide solution. Samples examined by electron probe microanalysis were studied in the unetched condition.

Results and discussion

Analysis of microstructures of joints

Figure 4 shows an optical macrograph of a transverse section from one of the trial welds. It could be seen that the weld had good formation without defects and still maintained characteristics of laser welding Mg/Al [12]. Molten metal of upper sheet partially penetrated in the lower sheet in all welded samples. The penetration depth of the weld pool within the lower sheet was 0.5 mm or so. Based on XRD analysis, the intermetallic compound layer between weld pool and lower sheet metal was found for all welded samples, as shown in Fig. 5. The layer was composed of Al_3Mg_2 and $Al_{12}Mg_{17}$ (see Fig. 6), coinciding with observation in joints of laser welding Mg/Al [12]. After tensile shear tests, it was found that failure occurred inside intermetallic compound layer, which degraded strength of the joints. The mixing of the two metals could be clearly seen, as shown in Figs. 7 and 8. The magnesium and aluminum at the bottom penetrated each other in the form of a vortex, not being uniformly blended. These should be attributed to the material undergoing a helical motion when the laser beam stirred weld. This illustrated complex chaotic dynamic patterns characteristic of fluid mixing. Since the difference in physical

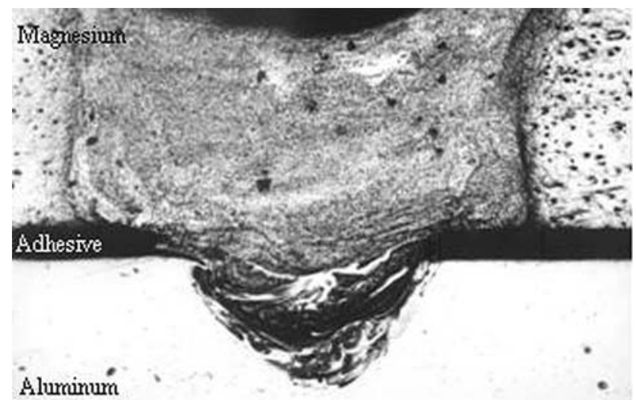

Fig. 4 Transverse sectional observation of LWB MgAl (×40)

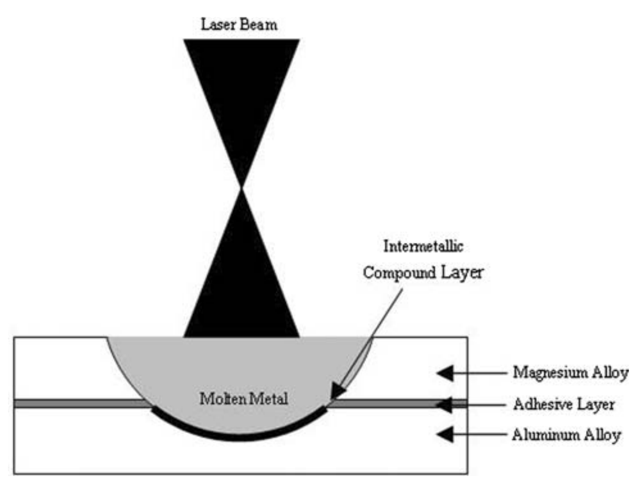

Fig. 5 Configuration of transverse sectional observation of LWB Mg/Al

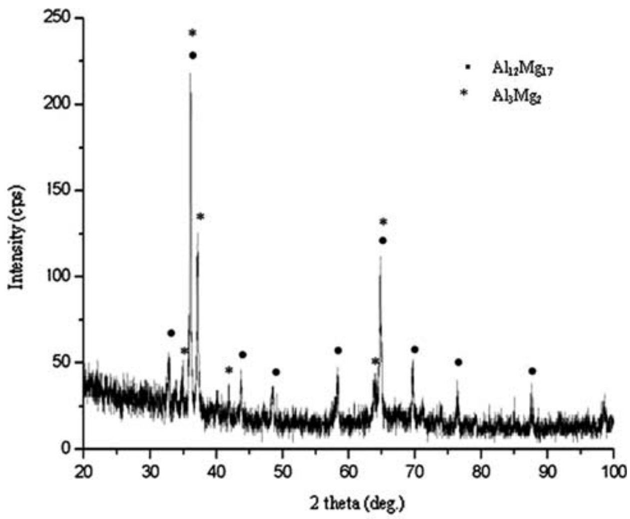

Fig. 6 XRD patterns from the LWB welds

Fig. 7 Complex vortex flow at the bottom of the weld (×200)

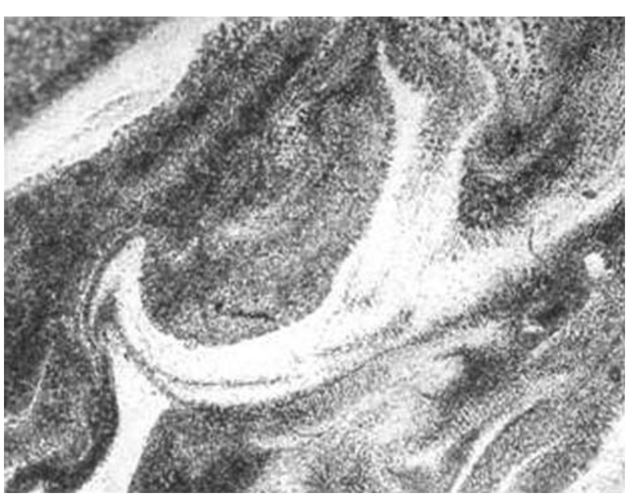

Fig. 8 Complex vortex flow at the bottom of the weld (×500)

and chemical properties of these dissimilar metals might produce different mixing regions, the complex dynamic process provided a mechanism for flow among mixing regimes, which made it possible that the metals could be joined.

Elemental distribution of the joints

Figure 9a shows secondary electron figure of transverse section of a joint and Fig. 9b, 9c and 9d show face scans of element Mg, Al and C, respectively. Seen from Fig. 9b, the Mg content within weld was slightly lower than that of base metal, Mg content on the top of weld was higher than that at the bottom, while the Al content in the weld distributed evenly (see Fig. 9c). It was well known that adhesive was composed of C, O and some other organic elements [13]. To study its influence on the joint, the element C was analyzed in Fig. 9d. Element C was not be found in the weld, so the microstructures were not affected by adhesive.

While Mg/Al was laser welded, base metals were heated rapidly then transferred heat to adhesive layer. Since the adhesive was made up of organic compounds, its heat-durability was poor and heat resisting temperature was low. Under laser high energy density and high heating-up temperature (the highest temperature in which could reach ten thousand degree Centigrade), adhesive was heated up rapidly and decomposed, escaping in the form of gas. At the same time, owing to their viscoelasticity, the adhesive heated in and near the weld flowed far away from the heat source. So there was no adhesive in the weld because of the above two reasons.

Figure 10 shows line scans of element C and O in the middle of adhesive layer. Seen from it, there was still no adhesive element in the weld. Meanwhile, the C content near the weld was lower than that far from the weld, while the O content was opposite. By reason of short working time and high temperature caused by laser, on the one hand, the adhesive near the weld was burnt incompletely (i.e. partial oxidation), on the other hand, it was carbonized and dehydrated, escaping water molecules and remaining black substances, which made the area near the weld disabled. Obviously, the adhesive near the weld suffered from dual actions of carbonization and oxidation, but oxidation played major position. That was why the O content near the weld was higher than that far from the weld. Since the laser was a heat source with high energy density and short holding time, the failure zone of adhesive layer was about 0.3 mm distance to the weld edge. Though loaded area of adhesive layer was

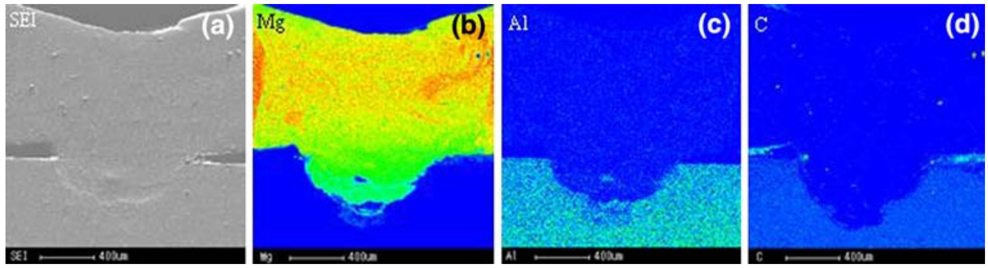

Fig. 9 Elemental face scans: (**a**) secondary electron, (**b**) face scan of element Mg, (**c**) face scan of element Al, (**d**) face scan of element C

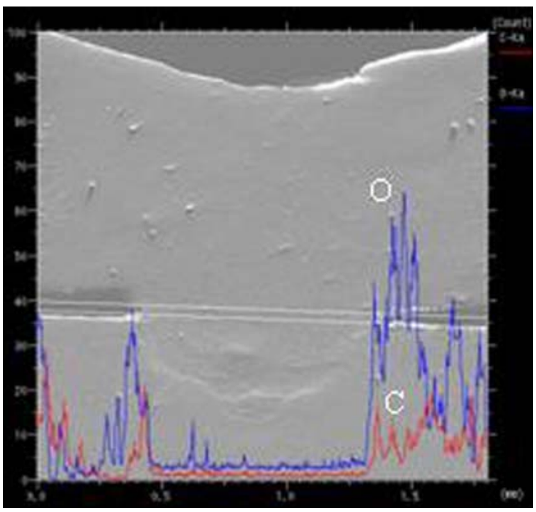

Fig. 10 Line scans of element C and O

deceased, in fact it had little influence on load bearing capability of the joints.

The influence of adhesive on weld penetration depth

Of all welded samples, a phenomenon was observed. The penetration depth of weld pool into lower sheet of LWB samples (averagely 0.5 mm or so) was much greater than that of laser welded samples (averagely 0.3 mm or so), (see Fig. 11). In other words, the introduction of adhesive could increase penetration depth of laser welds. The reasons were maybe as follows:

First of all, the density of free electrons in the solid-state Al was high, they were easy to act on with laser photons, and most energy was reflected out, so the absorptivity of Al sheet to laser was terribly low, less than 3% [14]. Besides, thermal conductivity of Al sheet was good and the laser energy absorbed was dissipated quickly. So it was very difficult to obtain deep penetration welds. Absorptivity of adhesive surface to laser was greater than that of Al sheet. When the weld metal was melted, the laser penetrated the upper sheet, and more laser energy was absorbed to destroy adhesive under the laser beam and melt lower Al sheet. During welding, adhesive layer was like a surface coated, which increased the initial absorptivity to laser and changed weld penetration depth.

Next, adhesive gas would expand quickly along the downward direction (along the orientation of laser transmission) before it escaped from the weld. Laser beam and adhesive gas pressed and impinged the lower sheet, which leaded to increase weld penetration depth.

Third, based on the theory ''Marangoni convection'' established in AGTAW, Heiple, Roper and Olsen [15, 16] and Takeuchi et al [17] proposed that the surface ctive elements such as O, S, Se, Te, and Bi could change the temperature coefficient of surface tension from negative to positive and further converted the fluid flow direction of weld pool. In that case, a relatively deeper and narrower weld was produced. In this study, weld pool was filled with element O before solidification, the mechanism of the adhesive increasing penetration was similar with that of activated fluxes, but both were different, surface active elements

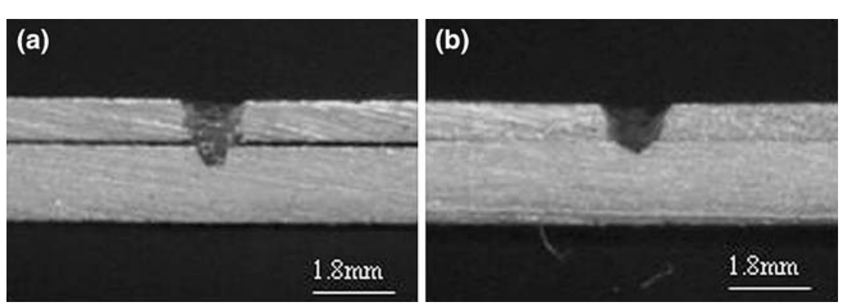

Fig. 11 Comparison with penetration depths of two types of joints: (**a**) a LWB Mg/Al joint, (**b**) a laser welding Mg/Al joint

within activated fluxes still were in the weld after welding, while element O of adhesive was not existing in the weld in this experiment.

Result analysis of tensile shear test

Tensile shear test results for the three types of joints are illustrated in Fig. 12. As shown, the LWB samples gave the highest shear resistance.

In a laser welded joint, the inner surfaces of two sheets were not bonded except for the weld seam, and the intermetallic compound layer was found at the bottom of weld, which was the main cause of generating fracture under low shear force. Meanwhile, a natural notch occurred at the junction between the sheets, which resulted in serious stress concentration at the weld seam edge. Observing the sample in the test process, the failure began in the intermetallic compound layer at the weld edge.

The bonded area in adhesive bonded joints was very large, and the stresses distributed uniformly relatively to laser welded joints, whilst the stress concentration was very small. Therefore, the shear properties of adhesive bonded joints were superior. For an adhesive bonded joint, fracture was initiated at overlap joint edges, in which existed stress concentration and some defects such as cavities and adhesive-free zones [18–20].

In LWB joints, the introduction of adhesive layer resulted in not only strengthening joining but also balancing the stresses in dissimilar material joints. Meanwhile, the weld seam was just like a metallic bridge through adhesive layer between two sheets, which could prevent crack from propagating along the interface of adhesive layer and adherends. So it could be thought that the two components of LWB samples, i.e., the adhesive layer and the weld seam, had a cooperative contribution to the mechanical properties of LWB joints. A similar failure mode with that of adhesive bonded samples was noted for LWB joints at the first-fracture phase, while after the adhesive layer became fracturing, the shear behavior of LWB samples was the same as that of laser welded samples.

Result analysis of *T*-peel test

Besides shear resistance, the ability of resisting peel was also one of the important criterions of assessing the service performances of the overlap joints. Generally speaking, working stress and rupture stress were considered as acting on the line in the peel test, while acting on the plane in the shear test. For thin metal adherends, *T*-peel test was usually adopted. In such a test, the load was entirely delivered to joint, so the *T*-peel strength measured was much lower than that of other types of peel tests. Figure 13 shows the *T*-peel force of LWB joints and adhesive bonded joints. Seen from this comparison, the average initial peel force of LWB samples increased by 70% relatively to adhesive bonded samples. The adhesive bonding that was strengthened by laser welding could prevent thin sheets from being peeled out.

A load-displacement curve obtained for an adhesive bonded joint is shown in Fig. 14a. At the preliminary stage of the test, the load increased linearly with the increase of displacement, and then the slope coefficient of the curve began to decrease with the load rising continually, which indicated that the joint behaved the characteristics of plastic deformation. After the value was the maximum, the stresses redistributed. The curve rose continually to another peak value, and then the peel load was almost invariable until the adhesive bonded sample was split completely.

Figure 14b shows the load-displacement curve for a LWB joint. It was observed that in the first stage when the

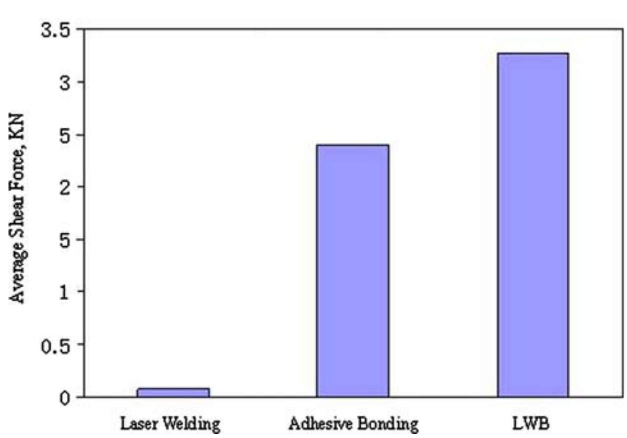

Fig. 12 Results of tensile shear test

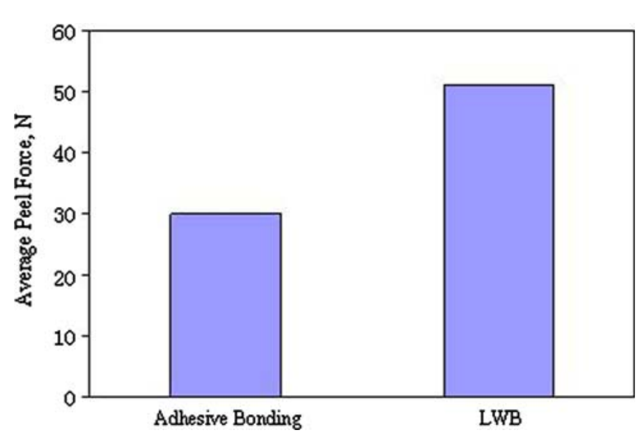

Fig. 13 Results of *T*-peel test

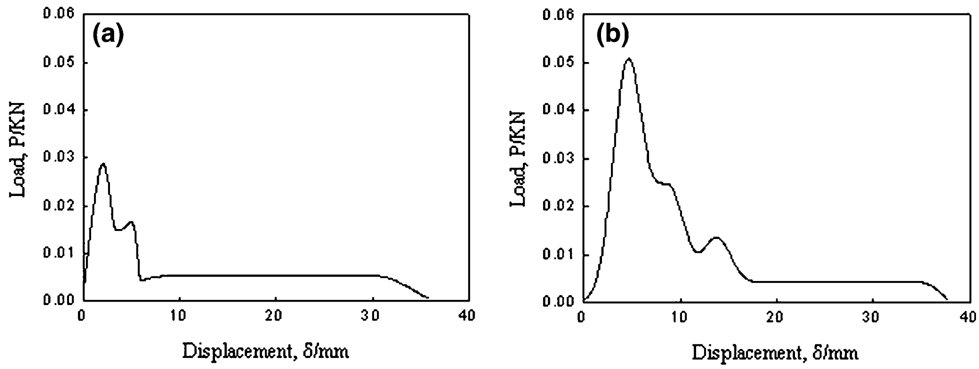

Fig. 14 Load-displacement curves of *T*-peel test for two types: (**a**) an adhesive bonding Mg/Al joint, (**b**) a LWB Mg/Al joint

load fell gradually, the weld seam had already been peeled open. The results obtained had shown that a mixing curve with peeling characteristics reflected two components of adhesive layer and weld seam. The first peak value corresponded to the peel load under which the weld seam failed, and the second was the maximum force developed only when the adhesive layer bore peel load.

Conclusions

1. Magnesium/aluminum could be easily joined by LWB under the proper technological parameters, and the weld was characterized by complex vortex flow at the bottom. The results of XRD indicated that the intermetallic compound layer between weld pool and lower sheet metal was found. The layer was composed of the brittle phases of Al_3Mg_2 and $Al_{12}Mg_{17}$, which were the cause of the weld cracking.
2. The adhesive in the weld was heated up rapidly and decomposed, escaping in the form of gas. While the adhesive near the weld was oxidized and carbonized, there existing a failure zone with about 0.3 mm distance to the weld edge, so the failure zone had little influence on load bearing capability of joints.
3. In comparison with laser welding alone, the introduction of adhesive in LWB joints could increase weld penetration depth. Mechanisms of action were maybe as follows: (1) Existence of adhesive increased the initial absorptivity of Al sheet to laser. (2) The gas produced by adhesive pressed and impinged lower sheet along the direction of laser transmission. (3) Element O in the adhesive layer modified interfacial force of weld pool and affected flow direction of weld pool.
4. In tensile shear test, the shear force of LWB joints was much greater than that of laser welded joints and adhesive bonded joints. At the first-fracture phase, the failure mode of LWB samples was similar with that of adhesive bonded samples. After the adhesive layer became fracturing, the shear behavior of LWB samples was the same as that of laser welded samples.
5. In *T*-peel test, compared to adhesive bonded joints, the peel force of LWB joints was greater, and the adhesive bonding that was strengthened by laser welding could prevent thin sheets from being peeled out.

Acknowledgments The authors gratefully acknowledge the sponsorship from Supported by Program for New Century Excellent Talents in University under project NCET-04-0271.

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