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Dissimilar material laser welding between magnesium alloy AZ31B and aluminum alloy A5052-O

Rattana Borrisutthekul, Yukio Miyashita, Yoshiharu Mutoh*

Department of Mechanical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka-shi 940-2188, Japan

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Abstract

Joining technology of lightweight dissimilar metals between magnesium and aluminum alloys is essential for realizing hybrid structure cars and other engineering applications. In the present study, the normal center-line welding of lap joint was carried out by laser welding. It was found that the intermetallic layer formed near interface between two metals significantly degraded the joining strength. FEM heat transfer analysis was carried out to find out an available method to control penetration depth and width of molten metal, which contributes to control thickness of intermetallic compound layer. Based on the results of FEM analysis, the edge-line welding of lap joint was carried out, which could easily control the thickness of intermetallic layer and successfully obtained high joining strength.

Keywords: Dissimilar metal joint; Laser welding; Lap joint; Light weight metal; Magnesium alloy; Aluminum alloy

1. Introduction

Magnesium and aluminum alloys are attractive in vehicle structure application for improving energy efficiency, which also contributes to reduction of the emission of green house affecting gases. In order to apply these alloys to vehicle structures, dissimilar joint between magnesium and aluminum alloys is required. The intermetallic compounds are found in phase diagram between Mg and Al; Al_3Mg_2, $Al_{12}Mg_{17}$ and $Al_{30}Mg_{23}$ [1]. Due to brittleness of intermetallic compound, the intermetallic compound formation has to be controlled as less as possible during joining process. According to Rathod and Kutsuna [2] and Miyashita et al. [3], in case of dissimilar joints such as steel/aluminum alloys and titanium/aluminum alloys, it is easy to realize solid/liquid state reaction only at joining interface between two metals, where only the metal with lower melting temperature is melted. However, it is difficult to apply this method to magnesium/aluminum alloys joint due to the small difference of melting point between the two metals. Therefore, another approach to control intermetallic compound formation has to be developed for joining magnesium and aluminum alloys. The controlling penetration depth of molten metal in lap joint configuration as shown in Fig. 1 might be a possible approach for reducing intermetallic compound formation. In the present study, laser welding between magnesium alloy AZ31B and aluminum A5052-O was carried out. Since the penetration depth of molten metal in lap joint will be one of important factor for controlling the thickness of intermetallic compound layer, FEM analysis for estimating shape of molten metal was also carried out. Based on the results of laser welding experiments and FEM analysis, suitable lap joint configuration as well as laser welding conditions were investigated.

2. Experimental procedure

Magnesium alloy AZ31B and aluminum alloy A5052-O of 1 mm thickness sheet were used in this study. The chemical composition specified by ASTM and mechanical properties obtained by a tensile test of these metals is shown in Tables 1 and 2, respectively. Nb–YAG laser with continuous wave was used for welding. Oxide film on

* Corresponding author. Tel.: +81 258 47 9735; fax: +81 258 47 9770.
E-mail address: mutoh@mech.nagaokaut.ac.jp (Y. Mutoh).

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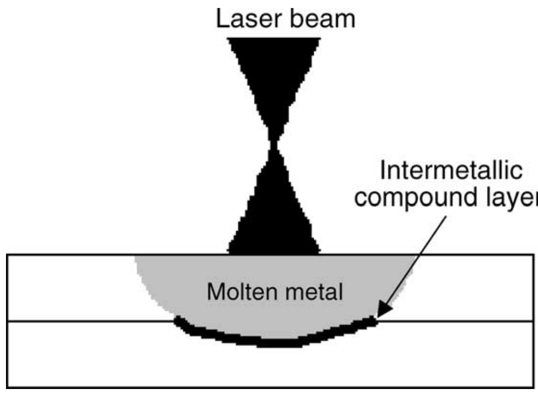


Fig. 1. Laser welding of lap joint.

the specimen surface was removed by 1500 grids emery paper before welding. Argon gas with flow rate of 40 l/min was used as a shield gas. After welding, tensile–shear tests and cross-sectional observations of welding region were carried out. Tensile–shear specimens were machined from welded lap joints, geometry of which is shown in Fig. 2.

3. Results and discussion

3.1. Center-line welding lap joint

Laser was applied on the center-line of lap part of the upper plate, as shown in Fig. 3. The laser power and focal distance used were 3 kW and +5 mm, respectively. Power density at the condition is about 370 W/mm^2. From the experimental results, it was found that welding was possible only for the case of AZ31B upper plate. Oxidation layer was found on the faying surface of AZ31B in case of A5052-O upper plate, as shown in Fig. 4. The free energy of reaction between Al surface layer and Mg molten metals, which is given in Eq. (1), has been calculated to be negative in the temperature range between 923 and 1380 K [4,5].

$$Al_2O_{3(s)} + Mg_{(l)} \rightarrow MgO_{(s)} + Al_{(l)} \qquad (1)$$

Therefore, magnesium molten metal can reduce Al_2O_3 but the aluminum molten metal cannot reduce MgO. MgO oxide layer may be remained and influence on weldability of AZ31B/A5052-O in case of A5052-O upper plate.

From the cross sectional observations, molten metal of upper plate partially penetrated in the lower plate in all welded specimens. From EDS analysis, the intermetallic compound layer between weld pool and lower plate metal was found for all welded samples. The layer was composed of Al_3Mg_2 and $Al_{12}Mg_{17}$. After tensile–shear tests, it was found that failure occurred inside intermetallic compound layer, which degraded strength of the joint. The maximum failure load and strength obtained for the center-line welding lap joint were 520 N and 20 MPa, respectively, under a welding speed of 2 m/min. This failure load is about 37% of yield load of A5052-O alloy, which is calculated from to multiply the area of cross section at the gage section of the tensile specimen (14 mm^2) by yield strength of A5052-O.

3.2. FEM analysis for development a suitable welding method

Shallow penetration depth of molten metal in the lower plate may suppress the formation of intermetallic compound. Larger welding width will contribute to higher failure load of the joint. In order to realize these conditions and to develop an effective welding method for joining of AZ31B/A5052-O, a finite element method (FEM) analysis was carried out. ABAQUS (Version 6.3) was used for the present FEM analysis. Physical properties of the materials used in the analysis are shown in Table 3 [6,7]. The laser absorption rate and the heat transfer coefficient used were experimentally obtained. K-type thermocouples were attached on the specimen for measuring temperature during laser welding. Heating and cooling history of the FEM model was calculated by varying the values of laser absorption rate and heat transfer coefficient until it becomes coincident to the experimental results. The laser absorption rate for AZ31B plate and A5052-O plate were obtained as 0.19 and 0.165, respectively. The heat transfer coefficient of AZ31B plate and A5052-O plate were 120 and 130 W/m^2/K, respectively. Two-dimensional conduction heat transfer analysis was carried out for two kinds of models. One is the center-line welding lap joint model, as shown in Fig. 5(a), and the other is the edge-line welding lap joint model, as shown in Fig. 5 (b). Fig. 6 shows examples of the results of FEM analysis. In the analysis, molten metal zone was assumed as the region where the temperature reached to the melting temperature of the material. It is found from the figure that the shape of molten zone for center-line welding lap joint is deep, while that for edge-line welding lap joint is shallow. The welding width for edge-line

Table 1
Chemical compositions of AZ31B and A5052-O specified by ASTM

Materials	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ni	Ca	Others
AZ31B	2.5–3.5	<0.10	<0.03	<0.10	>0.2	Bal.		0.5–1.5	<0.005	<0.04	<0.30
A5052-O	Bal.	<0.25	<0.40	<0.10	0.15–0.35	2.2–2.8	<0.1				<0.15

Table 2
Mechanical properties of AZ31B and A5052-O

Materials	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
AZ31B	165	257	20
A5052-O	100	213	24

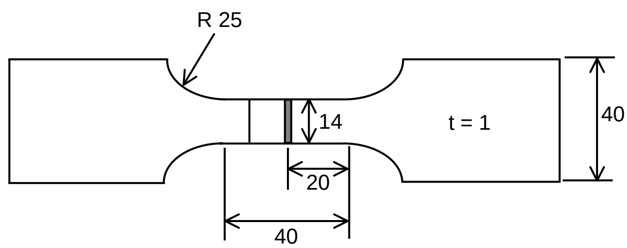


Fig. 2. Tensile–shear specimen.

welding lap joint is wider than that for center-line welding lap joint at the same weld penetration depth. Therefore, the edge-line welding lap joint will be suitable for reducing the penetration depth, which will also contribute to suppression of intermetallic compound formation and high joining strength.

3.3. Edge-line welding lap joint

Laser welding experiments for the edge-line welding lap joint were carried out base on the FEM analysis, as shown in Fig. 7. The copper block was used for intimate contact of two plate. In case of the A5052-O upper plate, the laser power and focal distance were 3 kW and +3 mm, respectively. The lapping width and the edge angle of specimen were 4 mm and 30°, respectively. In case of AZ31B upper plate, the laser power and focal distance were 2 kW and +6 mm, respectively. The lapping width and edge angle of specimen were 8 mm and 90°, respectively. From the experimental results, it was found that the welded joint could be obtained for both of upper plate materials. This may results from that the magnesium vapor can easily move out in the edge-line welding compared to center-line welding.

Fig. 8 shows the cross-sectional observations of edge-line welding lap joint at high and low welding speeds.

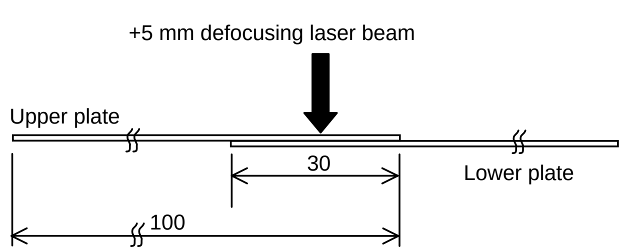


Fig. 3. Center-line welding lap joint.

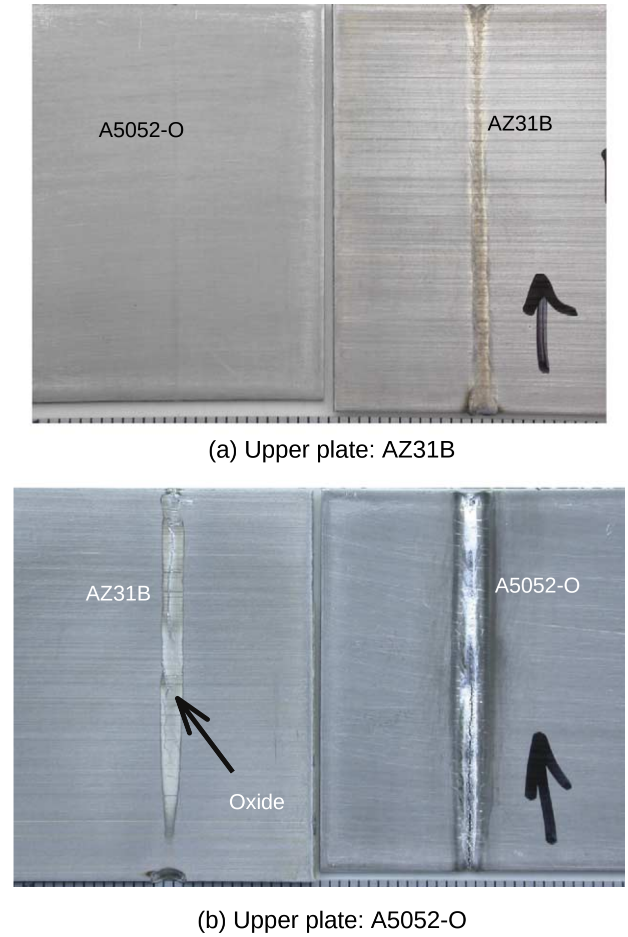


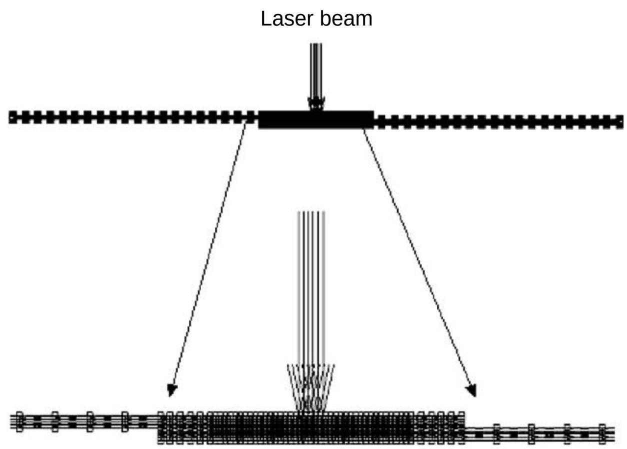
Fig. 4. Outward appearances of faying surfaces obtained by center-line welding lap joints. (a) Upper plate, AZ31B; (b) upper plate, A5052-O.

From comparison of the cross sectional observations between center-line and edge-line welding lap joints, it was found that shallow penetration depth could be obtained in the edge-line welding lap joint. The intermetallic compound phase (IMP) was still observed even for the edge-line welding lap joint. The layer was composed of Al_3Mg_2 and $Al_{12}Mg_{17}$. The penetration depth of the molten metal into the lower plate becomes shallower with increasing welding speed. It was also found that the intermetallic compound formation becomes less when the penetration depth become smaller.

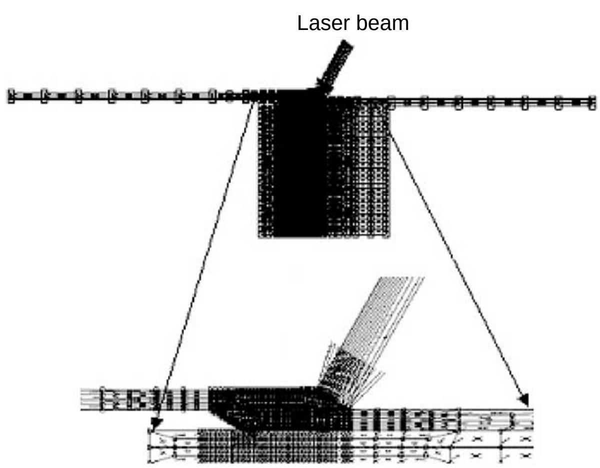
Fig. 9 shows the relationship between failure load and welding speed. It can be seen from the figure that failure load increased up to 5 m/min with increasing welding speed

Table 3
Physical properties of AZ31B and A5052-O

Materials	Density (kg/m^3)	Thermal conductivity (W/(m K))	Heat capacity (J/(kg K))
AZ31B	1780	75	1050
A5052-O	2680	138	900



(a) Center-line welding lap joint



(b) Edge-line welding lap joint

Fig. 5. FEM models. (a) Center-line welding lap joint; (b) edge-line welding lap joint.

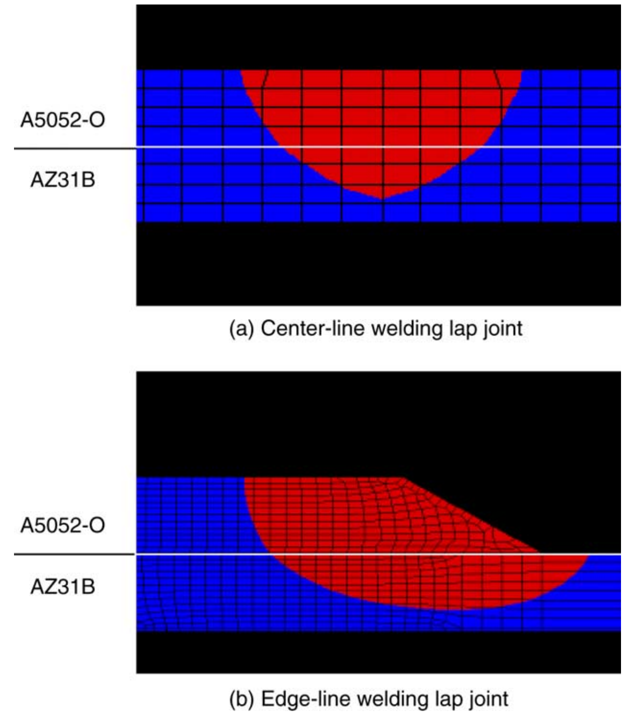


Fig. 6. The shapes of weld pool for center-line and edge-line welding at the same penetration depth. (a) Center-line welding lap joint; (b) edge-line welding lap joint.

and then it decreased with increasing welding speed. Even though the intermetallic compound formation was less, the joints were failed at the intermetallic layer in the tensile–shear test, as shown in Fig. 10. Two kinds of fracture morphology were found in the fracture surface. The dominant fracture morphology was composed of Al_3Mg_2 and $Al_{12}Mg_{17}$ intermetallic phase. Another fracture morphology formed with the mixing phase between solid solution phase and intermetallic phase was slightly observed. Fig. 11 indicated the relationship between penetration depth, thickness of intermetallic layer and welding speed. It can be seen from the figure that higher welding speed results in shallower penetration depth of molten metal into lower plate and simultaneously thinner intermetallic compound layer. In this region of welding speed lower than 5 m/min, thickness of intermetallic layer will be a dominant parameter to control the strength of joint. Consequently higher failure load will be obtained at higher welding speed. In the welding speed region higher than 5 m/min, as shown in Fig. 9, failure load decreased with decreasing welding speed. In this region thickness of intermetallic compound layer was thin enough and welding width, which decreased with increasing welding speed as seen from Fig. 8, might become a dominant parameter to control failure load.

Strength of the joint was calculated by using failure load and welding area. The maximum tensile–shear strength obtained was 48 MPa. The joining strength obtained was higher than that for center-line welding lap joint. The maximum strength of frictional welded joint between A1050 and AZ31B has been reported as 90 MPa [8]. The maximum strength of diffusion bonded joint has been also reported as 80 MPa [9]. Stress state of the joint between the present study and the previous reports indicated above is

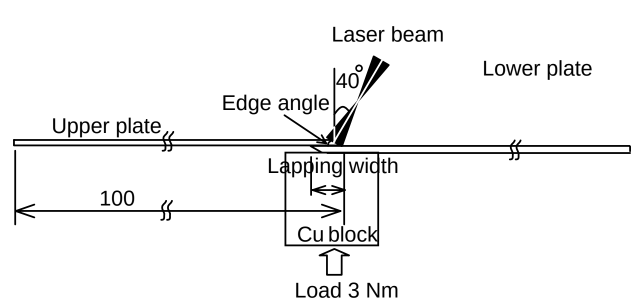


Fig. 7. Configuration of edge-line welding lap joint.

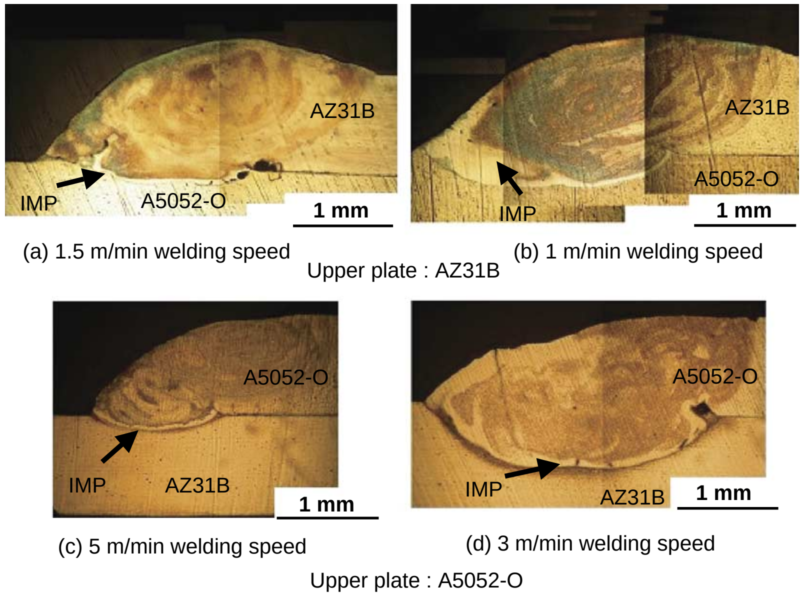


Fig. 8. Cross-sectional observations of edge-line welding lap joint.

different, namely the present study is in shear mode and the previous reports are in tensile mode. Based on the difference of loading mode, it can be assumed that shear strength is equivalent to $1/\sqrt{3}$ of tensile strength for the same material. Therefore, it can be concluded that the strength of the present joint obtained by laser welding is comparable to those of the joints produced by solid state bonding techniques.

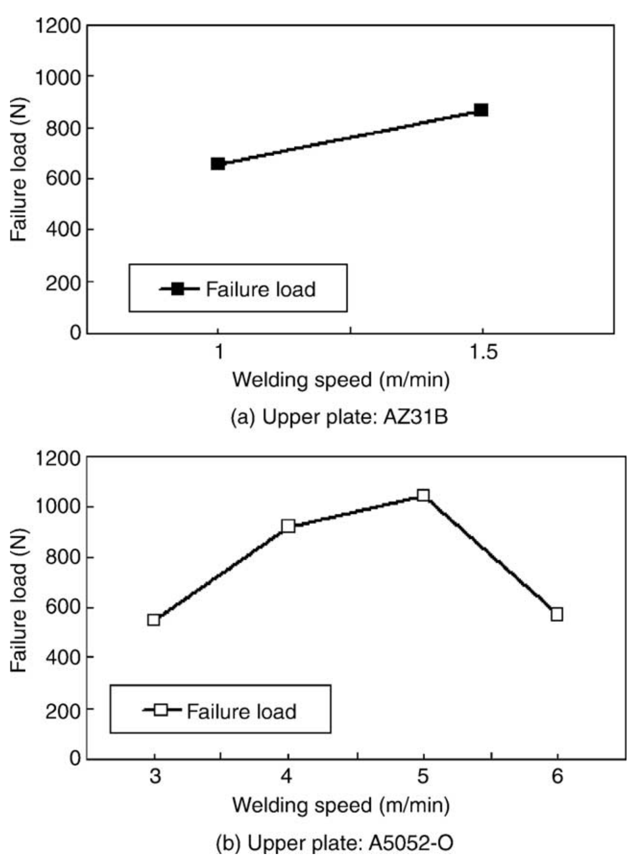


Fig. 9. Relationship between failure load and welding speed for edge-line welding lap joints.

4. Conclusions

It was difficult to obtain enough quality of welding strength in normal center-line welding lap joint between magnesium and aluminum alloy plates due to intermetallic compound layer formation. A possible method to suppress the intermetallic compound formation was investigated based on FEM analysis. It was found that the edge-line welding lap joint could realize the shallow penetration depth of molten metal into lower plate, which would be effective for reducing the reaction between two metals and then the formation of intermetallic compound. According to the results of FEM analysis, edge-line welding was carried out

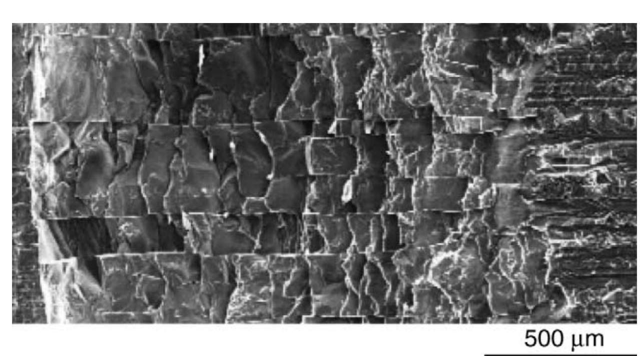


Fig. 10. Fracture surface of the joint at AZ31B (laser power, 3 kW; welding speed, 5 m/min; upper plate, A5052-O).

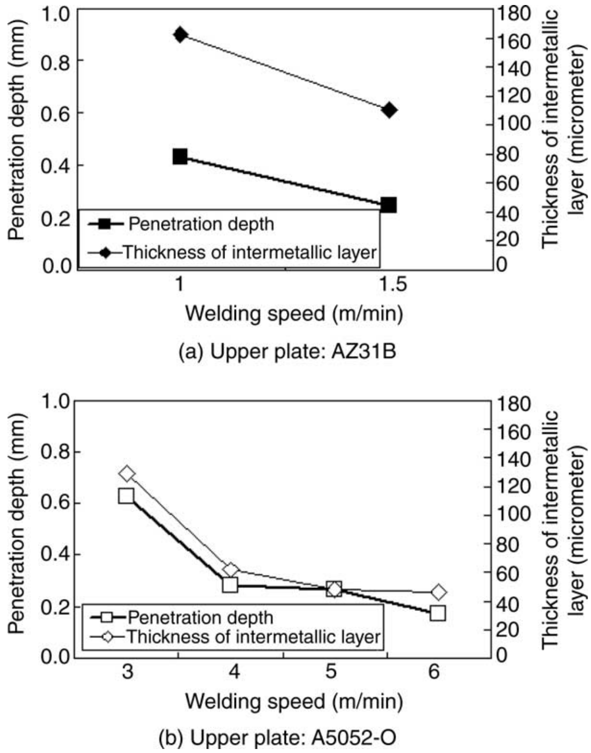


Fig. 11. Relationship between penetration depth, thickness of intermetallic layer and welding speed for edge-line welding of lap joints.

under various laser welding conditions. From the experimental results, it was found that shallow penetration depth into lower plate, thin intermetallic layer and then higher joining strength could be obtained in the edge-line welding lap joint.

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