High speed welding of aluminium alloy sheets using laser assisted alternating current pulsed metal inert gas process

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Alternating current pulsed metal inert gas welding is an appropriate process for joining aluminium alloy sheets because of its great gap tolerance and low heat input, which assists in avoiding burn through. However, when welding speed is higher than 2 m min^{-1} the low heat input is no longer an advantage since lack of penetration becomes a problem. Irradiation of the vicinity of the arc using a laser beam can solve this problem, and adjustment of the laser power can control the penetration. As a result, thin aluminium alloy sheets can be joined at a high speed of 4 m min^{-1} with sufficient gap tolerance. Moreover, investigation of the effect of laser beam diameter on the resulting weld for thin sheets indicates that a defocused laser beam having a diameter of several millimetres can further improve the ability to bridge joint gaps and tolerance of deviations in torch aim. Consequently, a high power diode laser having a relatively thick beam waist is suitable for this application. STWJ/335

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INTRODUCTION

Aluminium alloys have attracted considerable attention as a substitute for steel to reduce the weight of vehicles. New types of car and motorcycle produced from aluminium alloys are under rapid development and some products are already on the market.[1] To promote the popularisation of aluminium alloy cars, welding processes exhibiting good quality and high productivity for mass production are essential. Direct current (dc) pulsed metal inert gas (MIG) welding and laser welding are the major processes currently in use. A hybrid welding process,[2] which combines a dc pulsed MIG arc and a laser beam to produce one molten pool, and ac pulsed MIG welding[3] have also recently been put to practical use. However, it is difficult for any of these processes to satisfy the increasing demand from the automobile industry for welding quality and productivity. The desired welding speed is over 2 m min^{-1}, which is beyond the ability of individual dc pulsed MIG welding or individual ac pulsed MIG welding. Although the speed of laser beam welding or hybrid welding using a laser beam and dc pulsed MIG arc is sufficiently high to meet the productivity demand, burn through and failure in bridging the joint gap are the main quality problems because most of the aluminium alloys used for cars, and especially for car bodies, are thin materials. Therefore, development of a new welding process is a task of very high priority.

Laser assisted ac pulsed MIG welding is proposed by the present authors to join thin aluminium alloys at high welding speed and with good quality. It is expected that control of heat input by adjusting the electrode negative (EN) ratio of ac pulsed MIG arc current[4] can solve the burn through problem. Moreover, since a feature of the ac pulsed MIG welding process is high joint gap tolerance, it is anticipated that the low gap tolerance of laser beam welding can be improved when an ac pulsed MIG arc is combined with the laser beam. Furthermore, combining a laser beam with an ac pulsed MIG arc can solve such problems as lack of penetration and bead irregularity, which are unavoidable when ac pulsed MIG welding is performed at high travel speed. Accordingly, the productivity of laser assisted ac pulsed MIG welding is expected to be high. One of the objectives of the present work is to investigate these promising features of laser assisted ac pulsed MIG welding.

Another objective of the present work is to investigate the effect of laser beam diameter in laser assisted ac pulsed MIG welding. A laser beam having a thin waist, such as a YAG or CO_2 laser, is generally used for welding and cutting because the energy density is high and the absorption factor is large. The drawbacks are low energy conversion efficiency and large capital investment. In contrast, although the beam waist of a high power diode laser is relatively thick, the energy conversion efficiency is high and the price of high power diode laser systems has been decreasing rapidly. If a laser beam having a relatively large diameter proves to be capable of the same or superior welding results in comparison with a thin waist laser beam in welding thin aluminium alloys using the laser assisted ac pulsed MIG process, the application range of high power diode lasers can be broadened.

Considering the above points, the present work discusses the advantages of the laser assisted ac pulsed MIG welding process in welding thin aluminium alloys. Effects of laser beam diameter and laser power on bead shape, ability to bridge joint gaps, and tolerance of torch aim deviations are investigated. Good results are obtained using a defocused YAG laser and the applicability of high power diode lasers is confirmed.

LASER ASSISTED AC PULSED MIG WELDING SYSTEM

A new hybrid welding system has been developed by integrating a laser generator and laser torch into an ac pulsed MIG welding robot system, as shown in Fig. 1.

The laser and MIG torches are fixed together to form a hybrid torch. The hybrid torch is attached to the wrist of

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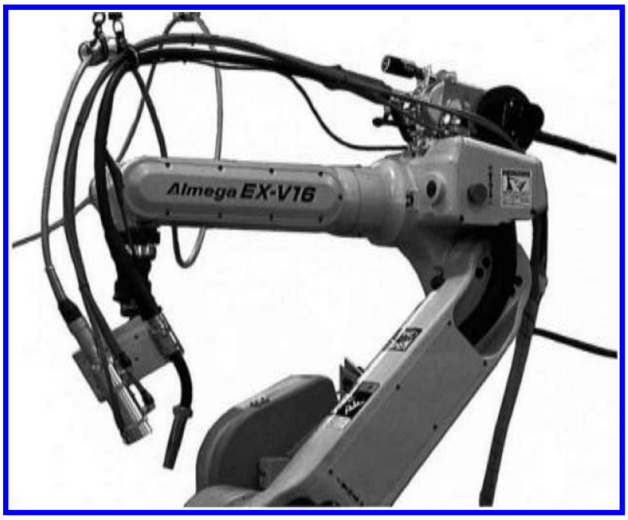
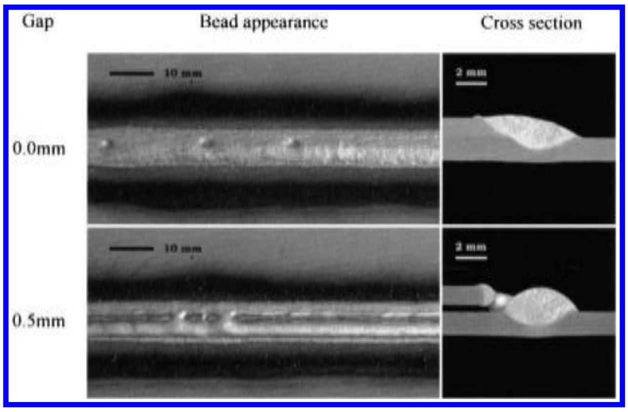


1 Laser assisted alternating current (ac) pulsed metal inert gas (MIG) welding system



2 Effect of joint gap on bead appearance and cross-section (optical) for direct current (dc) pulsed MIG arc welding at speed of 4 m min^{-1} (wire feedrate 13 m min^{-1}, welding current 215 A, and arc voltage 19·8 V)

a manipulator by a special bracket. Preliminary experiments showed that the angle of the laser torch had no obvious effect on the welding result. Therefore, there is some flexibility in setting the angle between the laser and MIG torches. The angle between the laser and MIG torches in the present work is 45°, to produce a hybrid torch that is as compact as possible and to ensure that there is no interference between the laser beam and MIG nozzle. The position of the laser torch is adjusted to keep the centre of the laser beam waist 2 mm away from the MIG wire tip at a wire extension of 15 mm. It is very important to keep the MIG torch at a push angle of about 15° during welding of aluminium alloy to ensure effective gas shielding and a stable arc. Accordingly, the laser beam of the hybrid torch always runs ahead of the MIG arc at a drag angle of 30°. The work angle for the thin sheet lap joint was set at 80°. The welding arc and its vicinity are protected from air by argon gas flowing out from the MIG torch nozzle.

The optical system inside the laser torch is cooled by water and is protected from welding fume and spatter by an air curtain formed at the tip of the laser torch using compressed air. Laser power is transferred to the laser torch via an optical fibre having a diameter of 1 mm. The total transfer rate of the fibre and lenses is about 77%. A high power diode laser having wavelengths of 940 and 810 nm is used for the welding system and the diameter of the laser beam waist is about 5 mm.

A digitally controlled inverter type ac/dc pulsed MIG welding power source supplies ac pulsed or dc pulsed electric power to the MIG arc. Welding conditions and ac or dc pulsed current waveform parameters can be set by key operations on a teaching pendant. Standard current waveform parameters linked with wire feedrate setting or welding current setting at an intermediate EN ratio of 20% are also displayed on the teaching pendant as a convenient reference for operators to optimise current waveform parameters for their specific application. The EN ratio can be simply adjusted via the EN duration. All welding sequences are controlled and synchronised by a robot controller.

PERFORMANCE OF WELDING PROCESSES IN JOINING SHEETS AT HIGH SPEED

The main quality problems in welding of thin aluminium alloys at high speed are a low joint gap tolerance, burn through, holes in the bead, and poor wetting characteristics. The performance of some typical welding processes with respect to these problems is investigated in the present work. The welding wire used is Al–Mg alloy A5356 of diameter 1·2 mm and the base metal is Al–Mg alloy A5052. The thicknesses of the top and bottom sheets for the lap joint are 1·2 and 1·5 mm respectively.

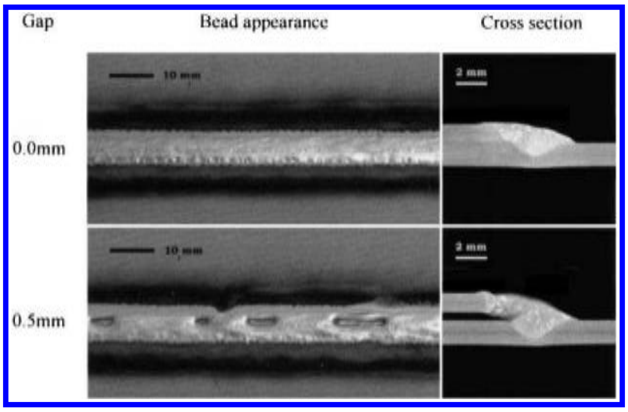
Dc pulsed MIG arc welding

The dc pulsed MIG arc welding process is very frequently used for joining aluminium alloys. As a result of its higher productivity than tungsten inert gas arc welding, and lower capital investment and greater convenience in use than laser welding, this process is widely accepted by fabricators. When it is used for high speed welding of thin aluminium alloys, the problems encountered are burn through, formaion of holes in the bead, and low gap tolerance.

Figure 2 shows the bead appearances and cross-sections of lap joints welded at a travel speed of 4 m min^{-1}. Although appropriate bead penetration is attained at a wire feedrate of 13 m min^{-1} (welding current 215 A) when the joint gap is zero, holes are formed in the bead. For a 0·5 mm joint gap, there is a failure to bridge the gap due to excessive heat input, leading to burning down of the edge of the top sheet. Reducing heat input by decreasing welding current can avoid this burning down of the top sheet edge, but leads to the problem of poor penetration. Moreover, since welding current is proportional to wire feedrate, the amount of deposit metal is small at low welding current. Less deposit metal means impaired ability to fill the joint gap. As a result, reducing the welding current cannot solve the problem of gap bridging. In conclusion, dc pulsed MIG arc welding is not applicable for high speed welding of thin aluminium alloys.

Laser beam welding

Laser beam welding processes usually use a high power density laser beam. Penetration depth is readily controlled by adjustment of the laser output power and welding speed. Higher welding speed requires greater laser power, hence greater capital investment. Although the productivity is sufficiently high, low joint gap tolerance is the greatest problem owing to difficulties in high speed feeding of the filler wire, melting of the wire by the laser beam, and transferring the molten wire to the weld pool uniformly. To eliminate the joint gap, accuracy is the principal requirement for the weldment and jig. Sometimes a pressure roller running ahead of the laser beam is necessary to maintain a zero joint gap during welding. These requirements restrict the application range of laser beam welding.



3 Effect of joint gap on bead appearance and cross-section (optical) for dc pulsed MIG arc and laser beam hybrid welding at speed of 4 m min^{-1} (wire feedrate 8·5 m min^{-1}, welding current 135 A, arc voltage 17·1 V, and laser power 2 kW)

Dc pulsed MIG arc and laser beam hybrid welding

The dc pulsed MIG arc and laser beam hybrid welding process has been developed to make better use of the advantages and overcome the disadvantages of both dc pulsed MIG welding and laser beam welding. The advantages of the dc pulsed MIG welding process, such as a low cost energy source and straightforward addition of deposit metal to the weld pool, assist in solving such problems in laser beam welding as large capital investment in laser equipment of great output power and low tolerance of joint gap due to a lack of deposit metal. The advantages of laser beam welding, such as high welding speed and deep penetration, can solve such problems in dc pulsed MIG welding as low productivity and lack of penetration in high speed welding or thick plate welding. This hybrid process is highly effective for welding of plates thicker than 3 mm.

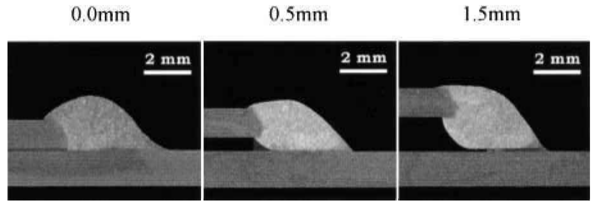
When this process is used to weld aluminium alloy sheets thinner than 2 mm, an obvious improvement in joint gap tolerance cannot be expected. Figure 3 shows an example of lap joint welding in which the thickness of the top sheet is 1·2 mm and that of the bottom sheet is 1·5 mm. Correct penetration depth is attained by carefully selecting the parameters of the pulsed MIG arc and the laser beam power. Welding current is reduced to 135 A to allow for the addition of the laser beam. Although the welding result is good when joint gap is zero, welding fails for a 0·5 mm joint gap.

It is evident in comparison with Fig. 2 that substituting laser power for a proportion of the MIG arc power to ensure correct penetration can avoid formation of holes in the weld bead when joint gap is zero. This suggests that the weaker arc force produced by lower welding current could improve the stability of metal flow in the weld pool and contribute to bead integrity.

However, a reduction in the arc force by decreasing the welding current is accompanied by a reduction in deposit metal because welding current is proportional to wire feedrate. The wire feedrate is reduced from 13 to 8·5 m min^{-1} so that the welding current can be decreased from 215 to 135 A. A reduced ability to bridge the joint gap is mainly due to the shortage of deposit metal. Consequently, it is difficult to reach a compromise between arc force and the amount of deposit metal. The dc pulsed MIG arc and laser beam hybrid welding process is thus unsatisfactory for high speed welding of aluminium alloy sheets.

Ac pulsed MIG welding

The ac pulsed MIG welding process has been used for the manufacture of aluminium alloy car bodies because its peculiar features, such as low heat input and sufficient deposit metal, can solve the problems of burn through and failure in bridging the joint gap. One valuable characteristic of this process is that welding current depends on EN ratio in addition to wire feedrate. At a certain wire feedrate, welding current decreases as EN ratio increases. The decrease of welding current also leads to a reduction of arc voltage to maintain the same arc length. Consequently, increasing EN ratio can reduce heat input without decreasing the amount of deposit metal.[3] Another valuable characteristic of this process is that the average temperature of molten droplets transferred from the wire tip to the weld pool is lower than that in dc pulsed MIG welding.[5] The deposit metal does not spread widely on the base metal surface and thus can be effectively used to fill the joint gap. These characteristics contribute to the great tolerance of joint gap and distinguished capacity for avoiding burn through. The ac pulsed MIG welding process is thus appropriate for the welding of thin aluminium alloy sheets.



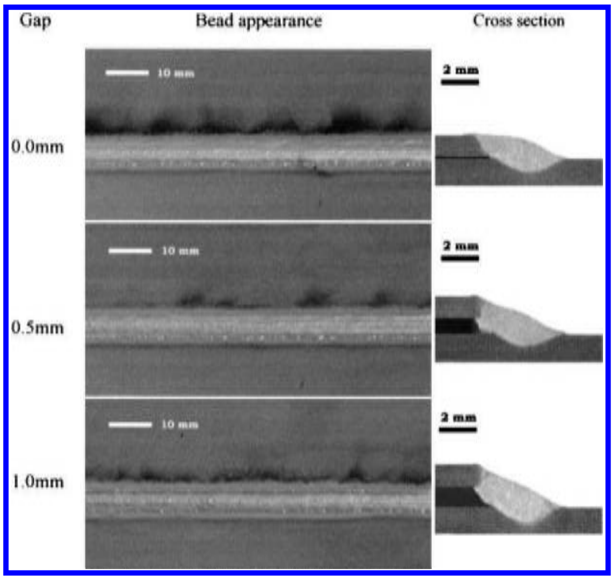
4 Effect of joint gap on cross-sections (optical) obtained for ac pulsed MIG arc welding at speed of 3 m min^{-1} (wire feedrate 12 m min^{-1}, welding current 130 A, arc voltage 16·6 V, and electrode negative (EN) ratio 30%)

However, when welding speed is greater than 2 m min^{-1} the low heat input is no longer an advantage because lack of penetration becomes a problem. Figure 4 shows an example in which the welding speed is 3 m min^{-1} and wire feedrate is 12 m min^{-1}. Although the potential ability to bridge the joint gap is great, welding fails owing to a lack of penetration when the joint gap is 1·0 mm in width. Obviously the ac pulsed MIG welding process is unsatisfactory for high speed welding of aluminium alloy sheets.

Laser assisted ac pulsed MIG welding process

In view of the above mentioned advantages and disadvantages of each welding process in high speed welding of thin aluminium alloys, it is evident that the combination of an ac pulsed MIG arc and a laser beam can offer optimal performance. The ac pulsed MIG technique can provide sufficient deposit metal to ensure considerable tolerance of joint gap at a lower welding current in comparison with dc pulsed MIG. Furthermore, switching of current polarities between electrode positive and electrode negative in every pulse cycle interrupts the plasma jet flowing from the wire tip to the weld pool, thus weakening the MIG arc force. Weak arc force contributes to the stability of the weld pool so that formation of holes in the bead can be readily avoided. On the other hand, adding a laser beam to an ac pulsed MIG arc can solve the shallow penetration problem in ac pulsed MIG welding at high speed. The laser beam acting ahead of the arc preheats the surface of the joint so that the wetting characteristics of the deposit metal are also improved.

Figure 5 shows the bead appearances and cross-sections obtained using laser assisted ac pulsed MIG welding. The wire feedrate is 13 m min^{-1} to ensure sufficient deposit metal for joint gap bridging, and welding current is only 135 A at 30% EN ratio to allow for the addition of an appropriate laser power. Bead appearances are very good and bead shapes are reasonable, with good wetting characteristics. Gap tolerance is up to 1 mm, that is, close to the thickness of the top sheet (1·2 mm).



5 Effect of joint gap on bead appearance and cross-section (optical) for laser assisted ac pulsed MIG welding at speed of 4 m min^{-1} (wire feedrate 13 m min^{-1}, welding current 135 A, arc voltage 16·9 V, EN ratio 30%, and laser power 2·5 kW)

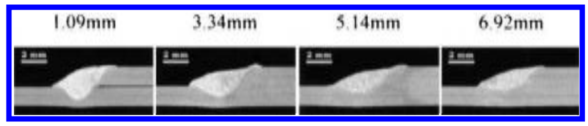
EFFECT OF LASER BEAM DIAMETER IN LASER ASSISTED AC PULSED MIG PROCESS

The diameter of the laser beam waist is a very important index of the characteristics of laser beam. It also determines the field of application of laser processing. A laser having a thick beam waist, such as a high power diode laser, is generally used for material surface processing because shallow penetration is required. Conversely, a laser having a thin beam waist, such as a YAG or CO_2 laser, is generally used for welding and cutting because the energy density is sufficiently high to produce a keyhole. The YAG type laser is also frequently used in researches on thick plate joining using the hybrid MIG arc and laser beam welding process. However, the effect of laser beam diameter on thin sheet welding remains uncertain at present.

One of the objectives of the present work is to investigate the effect of laser beam diameter on the welding result for aluminium alloy sheets. A YAG laser having 1·06 μm wavelength and 1·09 mm beam waist was used for the investigation. The diameter of the laser beam was changed by adjustment of the distance from the laser torch to the surface of the base metal. The distance between the centre of the laser beam and the wire tip at a wire extension of 15 mm was set to 3 mm to ensure no interference between the laser beam and MIG nozzle even if the diameter of the laser beam was as great as 7·0 mm. The welding materials used are the same as those in the previous section, except that the thickness of the top sheet is 1·5 mm.

Effect of laser beam diameter on bead shape

Figure 6 shows the effect of laser beam diameter on bead shape in laser assisted ac pulsed MIG welding. As the laser beam diameter changes from 1·09 to 6·92 mm, penetration depth decreases and bead width increases. Since measurements by the authors showed that over the present laser beam diameter range the heat input in laser assisted ac pulsed MIG welding was 16–20% greater than the sum of the heat inputs in individual ac pulsed MIG welding and individual laser beam welding, it is thought that laser beam diameter has little effect on the heat input in laser assisted ac pulsed welding in the present work and the change of penetration depth is due to the manner in which



6 Effect on bead shape (optical) of varying laser beam diameter (wire feedrate 13 m min^{-1}, welding current 135 A, arc voltage 16·8 V, EN ratio 30%, laser power 2·0 kW, and welding speed 4 m min^{-1})

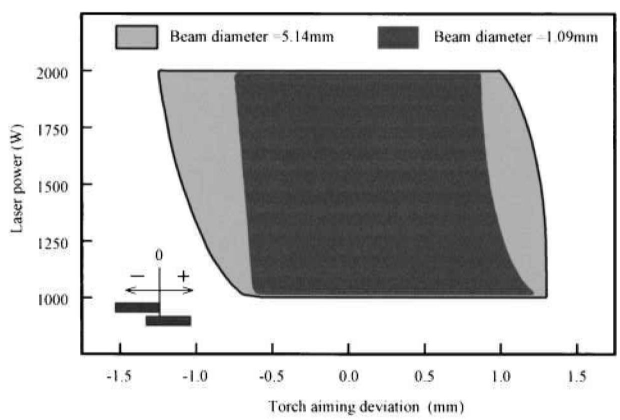
laser beam preheats the joint. The shapes of the bead cross-sections reveal that heat conduction is the major mechanism for formation of the weld pool. For the small beam diameters, laser energy concentrates in the centre area of the joint, deepening the penetration. Conversely, using a large beam diameter, a wide region of the joint surface is preheated, with the result that wide beads are obtained and wetting characteristics are improved.

High speed video observation indicated that a keyhole was not formed even when the laser beam diameter was 1·09 mm. The reasonable bead shapes suggest that keyhole formation is not necessary in welding aluminium alloy sheets.

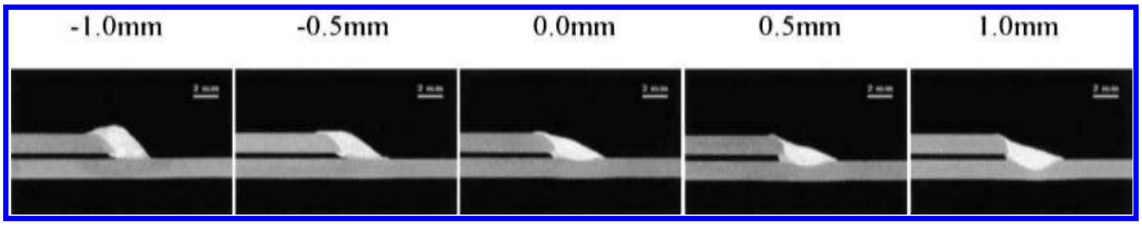
Effect of laser beam diameter on tolerance of torch aim deviations

Tolerance of torch aim deviations is very important in high speed welding of aluminium alloy sheets because weldment deformation and dislocation are comparable to the thickness of the base metal. Furthermore, joint tracking is very difficult in high speed welding with the result that adaptive control is almost impossible. Improvement of tolerance of torch aim deviations is always desirable.

The effect of laser beam diameter on tolerance of torch aim deviations is shown in Fig. 7 for different laser output power settings. A lap joint between 1·5 mm thickness sheets with a 0·5 mm joint gap was used for the investigation and welding results were judged in terms of joint appearance after welding. The range of laser output power investigated was from 1 to 2 kW. Obviously the tolerance of torch aim deviations exhibited by the 5·14 mm diameter laser beam is greater than that for the 1·09 mm diameter laser beam in laser assisted ac pulsed MIG welding. The difference in tolerance becomes greater as laser output power increases. When the torch aim deviates far from the joint centreline to the top sheet side, welding fails on the surface of the bottom sheet owing to an absence of penetration. When the torch aim deviates from the joint centreline to the bottom sheet



7 Effect of laser beam diameter on tolerance of deviations in torch aim (wire feedrate 13 m min^{-1}, welding current 135 A, arc voltage 16·8 V, EN ratio 30%, and welding speed 4 m min^{-1})



8 Effect of torch aim deviations on bead shape at 2 kW laser output power (optical)

side, welding fails at the edge of the top sheet owing to the diversion of deposit metal from the edge.

Some of the cross-sections corresponding to 2 kW laser output power and 5·14 mm laser beam diameter in Fig. 7 are shown in Fig. 8. Penetration decreases as torch aim deviates from the joint centreline to the top sheet side. Penetration increases as torch aim deviates from the joint centreline to the bottom sheet side. Laser output power should be increased to ensure increased penetration depth when the laser beam is defocused. The present authors were unable to implement such an increase because 2 kW is the maximum output power of the YAG laser generator used for the present experiments.

The effect of laser output power on penetration depth was also examined. Penetration depth increases as laser output power increases so that penetration depth can be controlled readily by adjustment of laser output power.

Effect of laser beam diameter on tolerance of joint gap

Figure 9 shows the effect of laser beam diameter on tolerance of joint gap. The laser output power was set at 2 kW. Welding results were again judged in terms of joint appearance after welding. The gap tolerance for the 5·14 mm diameter laser beam is greater than that for the 1·09 mm diameter beam over a wide range of torch aim deviation.

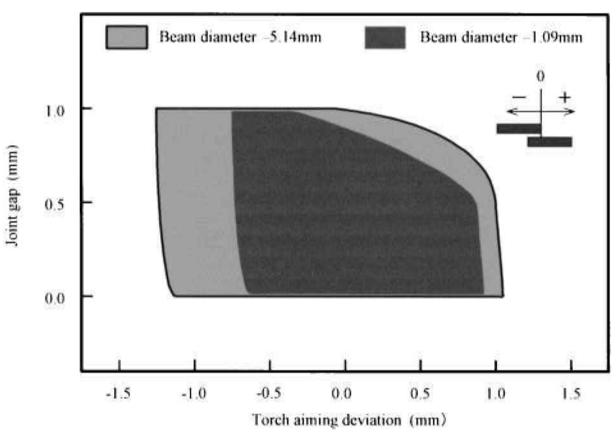
The flare joint is another type of joint frequently used in welding thin sheets. Figure 10 shows the effect of laser beam diameter on tolerances of joint gap and deviations in torch aim for welding of flare joints. Both tolerance of joint gap and tolerance of torch aim deviations are improved by defocusing the laser beam. When the torch aim deviates far from the joint centreline to one side, welding fails on the surface of the opposite sheet because of an absence of penetration. When joint gap becomes excessively wide, some molten droplets fall deep into the gap, so that the deposit metal becomes insufficient for bead formation and welding fails.

Considering the above results, namely, that a defocused laser beam can improve the wetting characteristics of the deposit metal and the tolerances of joint gap and torch aim deviations, it is preferable to use a defocused YAG laser beam or a diode laser having a relatively thick beam waist for laser assisted ac pulsed MIG welding of aluminium alloy sheets. The laser beam is defocused empirically to a diameter that is of the same order of magnitude as the bead width in the present work.

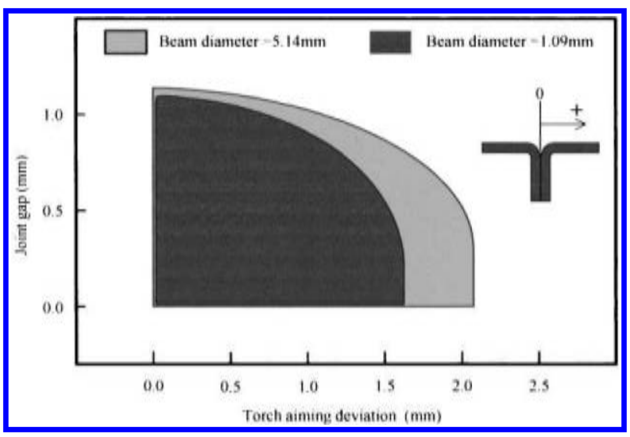
CONCLUSION

A laser assisted ac pulsed MIG welding process is proposed and the basic characteristics are investigated.

The main problems in high speed welding of aluminium alloy sheets are burn through and failure in bridging the joint gap. The dc pulsed MIG arc and laser beam hybrid welding process is not satisfactory in overcoming the problems because of the difficulty in reaching a compromise between heat input and lack of deposit metal. The laser assisted ac pulsed MIG process, created by substituting ac pulsed MIG for dc pulsed MIG welding, is a practical solution. The ac pulsed MIG process can supply effectively the desired deposit metal for gap bridging and avoid excessive heat input. Furthermore, the feature of low heat input in ac pulsed MIG welding provides the flexibility to add laser power to the vicinity of the arc so that penetration depth is readily controlled. Weld pool stability is also improved, which can be attributed to the weak arc force and low droplet temperature characteristic of ac pulsed MIG welding. As a result, thin aluminium alloys can be joined at a high speed of 4 m min^{-1} with sufficient tolerances of joint gap and torch aim deviations.



9 Effect of laser beam diameter on tolerance of joint gap (wire feedrate 13 m min^{-1}, welding current 135 A, arc voltage 16·8 V, EN ratio 30%, laser power 2·0 kW, and welding speed 4 m min^{-1})



10 Effect of laser beam diameter on tolerances of joint gap and deviations in torch aim for flare joint configuration (wire feedrate 14 m min^{-1}, welding current 150 A, arc voltage 17·2 V, EN ratio 30%, laser power 1·5 kW, and welding speed 4 m min^{-1})

Because defocusing the YAG laser beam can further improve the tolerances of joint gap and torch aim deviations, it is possible for a high power diode laser having a relatively thick beam waist to be used in the present laser assisted ac pulsed MIG welding system. Consequently, the initial capital investment and running cost can be reduced.

As a result of these features, it is foreseeable that selection of the laser assisted ac pulsed MIG welding process will be appropriate for high speed joining of thin aluminium alloys in mass production of vehicles and in other industries.

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