Effects of torch configuration and welding current on weld bead formation in high speed tandem pulsed gas metal arc welding of steel sheets

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Undercut and humping bead are the common defects that limit the maximum welding speed of tandem pulsed gas metal arc (GMA) welding. In order to increase the maximum welding speed, effects of the inclination angle, interwire distance and welding current ratio between the leading wire and trailing wire on bead formation in high speed welding are investigated. The undercut and humping bead is attributed to the irregular flow of molten metal towards the rear part of the weld pool. This irregular flow can be prevented by the trailing wire with a push angle from 5° to 13°, which provides an appropriate component of arc force in the welding direction. The irregular flow is also related to the distance between the leading wire and the trailing wire, and the flow becomes regular when the distance is in the range 9–12 mm. Moreover, the stabilisation of the bulge of the weld pool between the two wires, the presence of enough molten metal below the trailing arc, and the reduced velocity of molten metal flow towards the rear part of the weld pool, are essential to increase the maximum welding speed. These conditions can be obtained by adjusting the ratio of the leading arc current to the trailing arc current. A maximum welding speed as high as 4–4·5 m min^{-1} is achieved by setting the current ratio to a value ranging from 0·31 to 0·5.

Keywords: High speed welding, Humping, Steel sheet, Tandem GMA welding, Torch configuration, Undercut, Welding current ratio

Introduction

Currently, reduction of welding construction costs is urgently sought, and therefore, to cope with this demand in the field of arc welding, there has been a noticeable trend of increasing welding efficiency, accompanied by improvements in the quality of welds. Particularly in the field of steel sheet welding, such as in the automobile industry, great efforts to shorten the welding time in production lines have been made. In this respect, there are demands for advanced arc welding processes in order to markedly improve welding speeds and deposition rates per one pass weld, in addition to the demands for automatisation and robotisation of arc welding processes.

Among arc welding processes, gas metal arc (GMA) welding processes, such as metal active gas welding and metal inert gas welding, are advantageous because they are more convenient and cost-effective than the other welding processes, and they have been widely adopted in various industries. In addition, the GMA welding process can easily be applied to automatic welding in combination with robots and automatic welding equipment. Therefore, it is believed that this process will play the main role in fabrication technology today and in the future.

However, in conventional GMA welding, the use of high welding speeds necessitates high welding currents (high wire melting rates). Consequently, the arc force becomes stronger due to the increased current, and this influences the behaviour of the weld pool, causing serious problems[1,2] of welding imperfections, such as undercut and humped weld beads. Hence, a welding speed of 1·5 m min^{-1} has been regarded as the practical maximum rate in conventional GMA welding used for steel sheets.[3–5]

To solve these problems, optimisation of the chemical composition of wires and the pulse current waveform control was investigated to minimise the arc length without short-circuiting by reducing the size of the molten droplet per pulse; the maximum welding speed was thereby improved to approximately 2 m min^{-1}with the single wire pulsed GMA welding process.[6] Some other research reports clarified[7,8] that it was possible to

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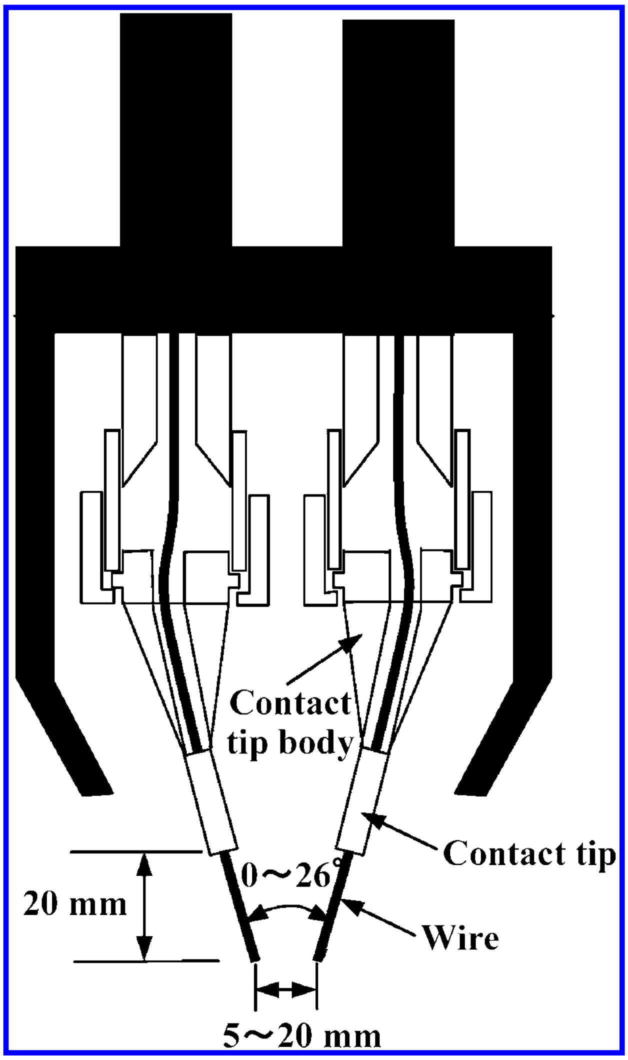


1 Evaluated tandem pulsed GMA welding torch configuration

weld car chassis parts at 1·8 m min^{-1} using band-shaped wires called strip wire, which produced an elliptical arc and thereby deconcentrated the arc heat.

In all cases of the above solutions for improving the single wire GMA welding process, the maximum welding speed is believed to be up to 2 m min^{-1}, which is only 20–30% higher than conventional welding speeds.

A tandem GMA welding process[9–14] is suggested, in which two welding wires are fed into one welding torch, and the adjacent two arcs are generated to form one weld pool during welding. With this welding process, the arc heat can be deconcentrated due to two separate arcs, the arc force balance between the leading and trailing arcs can be controlled, and thereby sound weld bead can be obtained without undercut and humping even in high speed welding.[9]

In submerged arc welding, multiple electrode processes have been used in many fields since 1954.[15] Viano *et al.*[16] reported that high speed welding can be achieved without sacrificing joint quality in four wire (double tandem) welding processes.

Therefore, it is an advanced GMA welding process that is expected to provide a significant improvement in the welding speed. With this tandem GMA welding process, high speed welding at 2·5–3 m min^{-1} was possible for practical applications. However, in the above investigations, the examined essential factors[14] that affect high speed welding performance are not enough to maximise the performance of the tandem GMA welding process in practical applications.

In the present research, the effects of the configuration of the two wires and the allocation of welding currents (wire feed rates) for the two wires on weld bead formation have been studied with the tandem pulsed GMA welding process, in which two wires are fed with pulsed welding currents supplied independently, in order to clarify the essential requirements for sound weld beads without undercut and humping in the high speed welding of steel sheets.

Components of tandem pulsed GMA welding robot system

The tandem pulsed GMA welding robot system used for this study was composed of two welding power sources, two wire feeders, one welding torch and one welding robot.

With regard to the pulsed GMA welding power sources, two digital inverter controlled units were connected independently to the leading and the trailing wires. The parameters of pulsed welding current waveform were set independently for each of the power sources by the teaching pendant of the robot. For convenience, the pulse timing control for the two power sources was not employed, in order to allocate welding currents over a wide range for the leading and trailing wires.

The tandem pulsed GMA welding torch had two electrically isolated contact tips and supplied welding currents to the two wires through the contact tips to generate two arcs between the wires and base metal. The experimental torch[17] shown in Fig. 1 was used. This torch could be set with the inclination angle between the two wires at up to 26° and the interwire distance 5–20 mm in several steps at the tip-to-base metal distance of 20 mm by changing the contact tip body and contact tip.

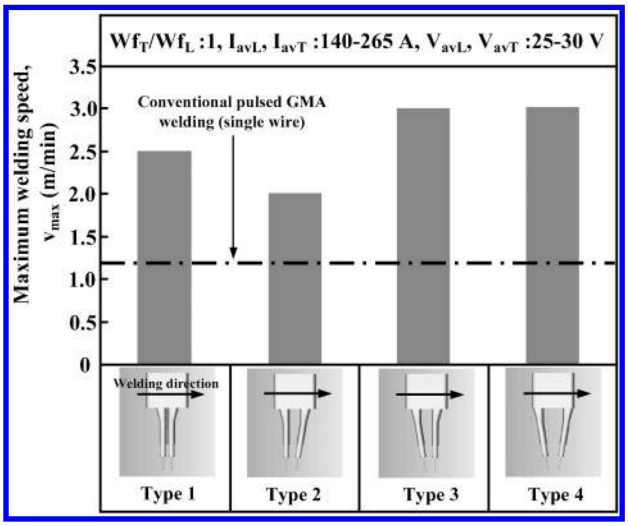
Four roll driven wire feeding units that could feed the leading and trailing wires at a maximum speed of 24 m min^{-1} were used. The wire feeding units were equipped with encoder feedback controlled dc motors to minimise the fluctuation in wire feed rate caused by the fluctuations in ambient temperature and input voltage.

As to the welding robot, the independently multiple articulated model with a maximum payload capacity of 16 kg was used, taking into account the weight of the experimental torch for high speed welding. The sequence for the entire system was controlled by the robot controller through the input from the teaching pendant.

Experimental procedures and material used

Bead-on-plate welding was carried out in the flat position, using the tandem pulsed GMA welding process with a tip-to-base metal distance of 20 mm. The welding performance was evaluated in terms of the maximum welding speed at which sound weld bead could be made without undercut and humping.

Since the amount of deposited metal for the unit welding length was expected to affect the occurrence of undercut and humped weld bead, the welding



2 Comparison of maximum welding speed among torch configurations

parameters for the leading and trailing wires were set so that the amount of wire fed for the unit welding length was constant and independent of the welding speed. That is, the welding parameters were set so that the product of dividing the sum of the leading wire feed rate W_{fL} (m min^{-1}) and the trailing wire feed rate W_{fT} by the welding speed v (m min^{-1}) could be 5. For example, when the welding speed was 2 m min^{-1}, $W_{fL}+W_{fT}$ was 10 m min^{-1}. With this setting, the amount of deposited metal for the unit welding length could be kept constant at welding speeds of 1–5 m min^{-1}. The arc voltage was set by adjusting the output voltage to obtain the arc length suitable for the pulsed spray arc that contained short-circuiting transfers at several times per second.

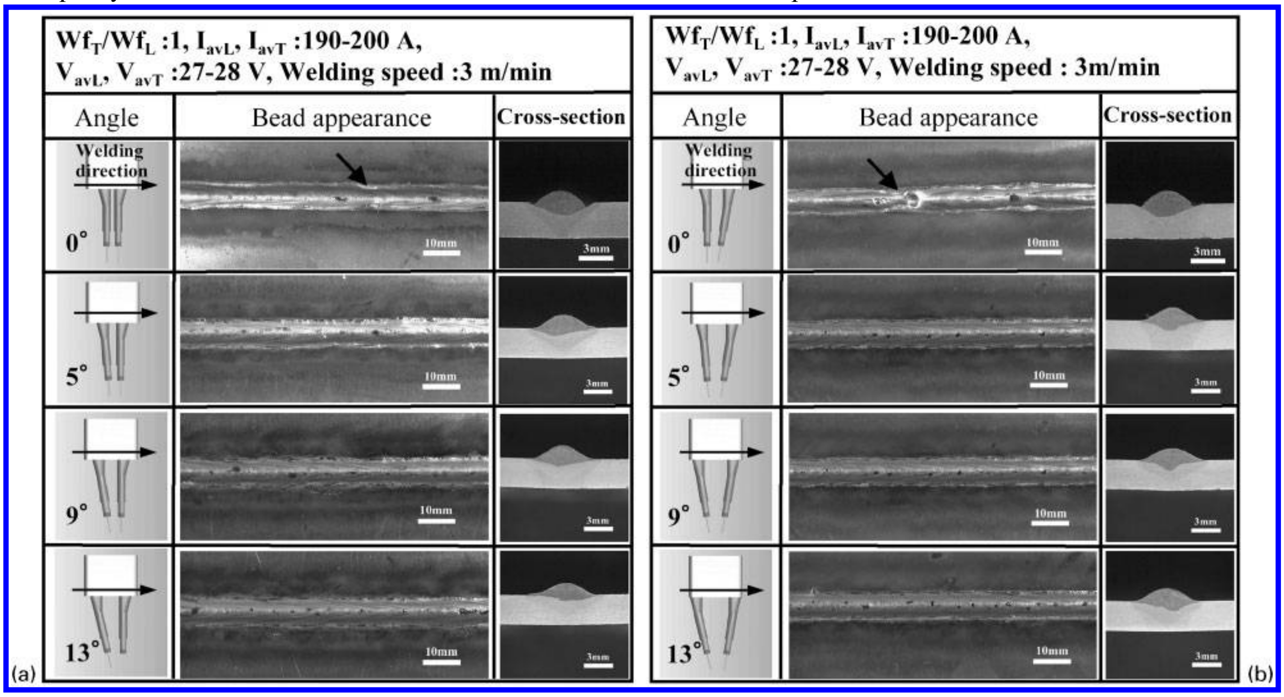
In order to study the behaviour of the weld pool in high speed welding, it was recorded by a digital high speed video camera with a 957 nm interference filter. The recording rate was set mainly at 1000 frames s^{-1} and partly at 5000 frames s^{-1}. The video camera was set at angles of 30° upwards from the horizontal level and mainly 90° to the welding direction, and in some cases it was set at 45° backwards or forwards in relation to the welding direction.

In this experiment, base metal of mild steel sheet 3·2 mm thick, 65 mm wide and 450 mm long was used; the welding solid wire had a diameter of 1·2 mm, and the shielding gas was 80%Ar–20%CO_2 at a flowrate of 50 L min^{-1}.

Effect of inclination angle between two wires

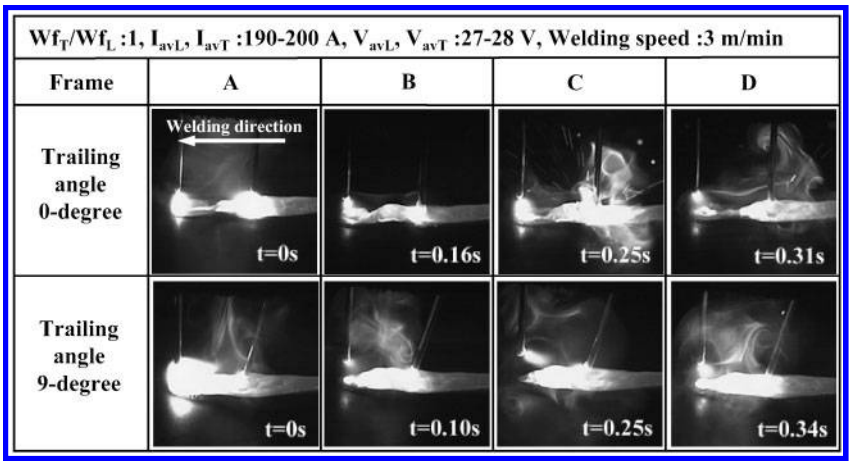
Bead-on-plate welding was carried out to evaluate the maximum welding speed necessary to obtain sound weld beads; the tip-to-base metal distance was kept at 20 mm, the interwire distance was kept at 12 mm, and the wire feed rate ratio was controlled at $W_{fT}/W_{fL}=1$ (where W_{fL} and W_{fT} are 5–10 m min^{-1}). The leading wire was set at a 0° or 9° drag angle in combination with the trailing wire set at a 0° or 9° push angle. The results are shown in Fig. 2, in which a dashed line indicates the maximum welding speed in single wire pulsed GMA welding (with a 10° push angle torch) for comparison. In tandem pulsed GMA welding, the maximum welding speed achieved was 2 m min^{-1} or higher with any of the inclination angles between the two wires, which was approximately 65% higher than that in single wire pulsed GMA welding (at a maximum welding speed of 1·2 m min^{-1}). When the trailing wire was set at a push angle (type 3 and type 4), the maximum welding speed achieved was 3 m min^{-1}, which is an improvement of approximately 150% over the single wire pulsed GMA welding process. However, when the welding speed was 3·5 m min^{-1}, exceeding the maximum welding speed with either the type 3 or type 4 torch configuration, sound weld bead could not be obtained, due to humping.

Figure 3 shows the bead appearance and penetration of bead-on-plate welds where the interwire distance was



a Leading wire angle 0°; *b* Leading wire angle 9°

3 Effect of trailing wire angle on bead appearance and cross-section



4 Comparison of weld pool formation between trailing wire angle with 0° and 9° push angle

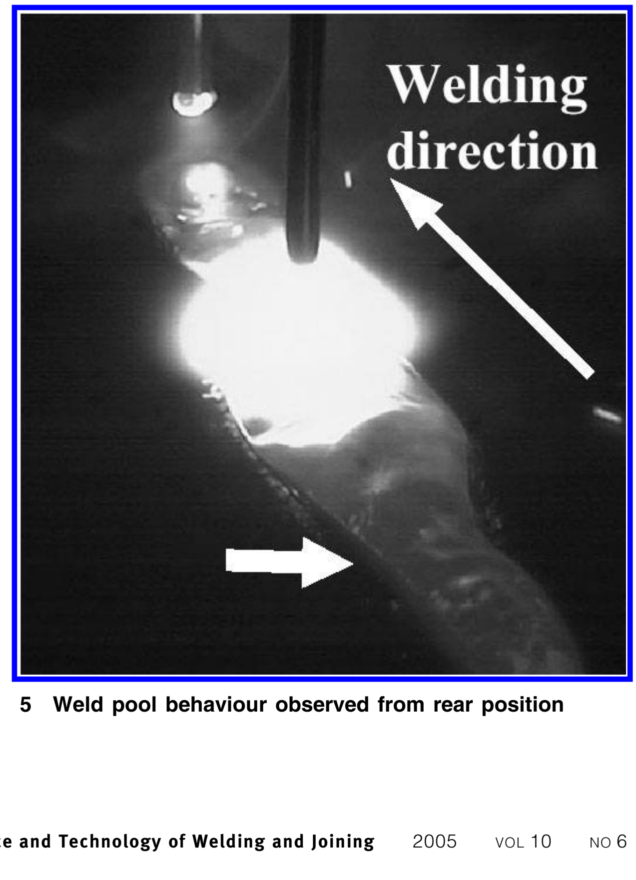
set at 12 mm, the leading wire was set at a 0° or 9° drag angle, the trailing wire was set at various push angles in steps from 0° to 13°, and the welding speed was 3 m min^{-1}. The wire feed rate ratio between the leading and trailing wires was set at $W_{fT}/W_{fL}=1$ (where W_{fL} and W_{fT} are 7·5 m min^{-1}). When both the leading and trailing wires were set at a 0° angle (type 1), the weld bead exhibited irregular widths like those of humped weld beads, and undercut was observed at the narrowed part of the weld bead at the location indicated by an arrow in Fig. 3*a*. As shown in Fig. 3*b*, when the trailing wire was set at 0° with the leading wire set at a 9° drag angle (type 2), the weld bead exhibited humping. In contrast, when the trailing wire was set at a 5° or larger push angle, sound weld beads were formed regardless of the leading wire angle. The penetration depth was not greatly affected by the trailing wire angle. Furthermore, as the push angle of the trailing wire increased, the height of the weld reinforcement decreased and the bead width increased. In this experiment, sound weld bead with a regular width was obtained in the range of 5° to 13° push angles for the trailing wire.

As discussed above, the push angle of the trailing wire has been shown to be effective at improving welding speeds in tandem pulsed GMA welding.

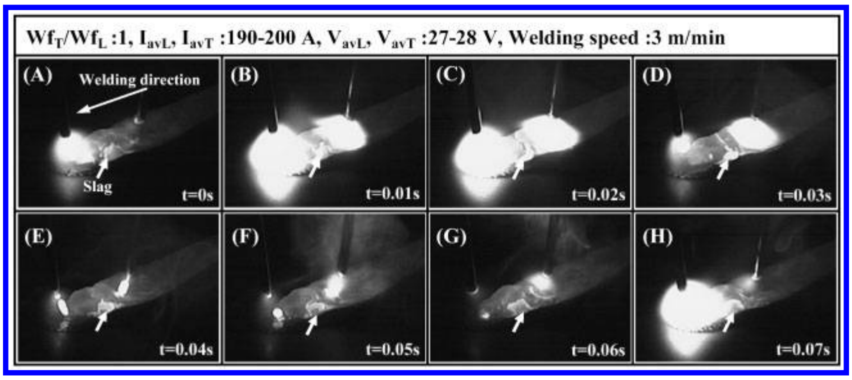
Figure 4 shows the weld pool behaviour when bead-on-plate welding was carried out at a welding speed of 3 m min^{-1}, with the torch arrangements of type 1, in which both the leading and trailing wire angles were set at 0°, and type 3, in which the leading wire angle was set at 0° and the trailing wire was set at a 9° push angle. With the type 1 arrangement, in which both wires were set in parallel, a bulge of molten metal was produced between the two wires in the weld pool, as shown in frame B, a large volume of bulged molten metal flew backwards irregularly, and the arc of the trailing wire ran on the flowing bulged molten metal, as shown in frame C, and consequently the wire stuck in the bulged molten metal, leading to repeat short-circuiting and arc re-striking, causing a lot of spatter. The recovered arc caused the molten metal to flow backwards, and a solid surface was sometimes exposed underneath the trailing arc. When the welding was continued under these conditions, the molten metal became narrower behind the trailing wire. This phenomenon of narrowing of the molten metal was recorded by the camera pointed from the rear of the trailing arc, as indicated by the thicker arrow in Fig. 5. At the narrowed area, the toe of the weld pool was gouged by the trailing arc and was not filled with the molten metal; consequently, undercut occurred. After the trailing arc ran on the bulged molten metal, most of the molten metal in front of the trailing wire was driven away, as shown in frame D of Fig. 4, and then the molten metal started to bulge again between the two wires as welding proceeded, and this phenomenon was repeated. As a result, irregular weld bead like humped weld bead was formed.

In contrast, with the type 3 arrangement, in which the trailing wire was set at a 9° push angle, the above mentioned phenomenon of the molten metal irregularly flying backwards out of the weld pool did not occur, as shown in Fig. 4. Consequently, sound weld bead was obtained.

Therefore, in order to obtain sound weld beads in high speed welding, it is considered important to prevent the irregular backward flow of the bulged molten metal



5 Weld pool behaviour observed from rear position

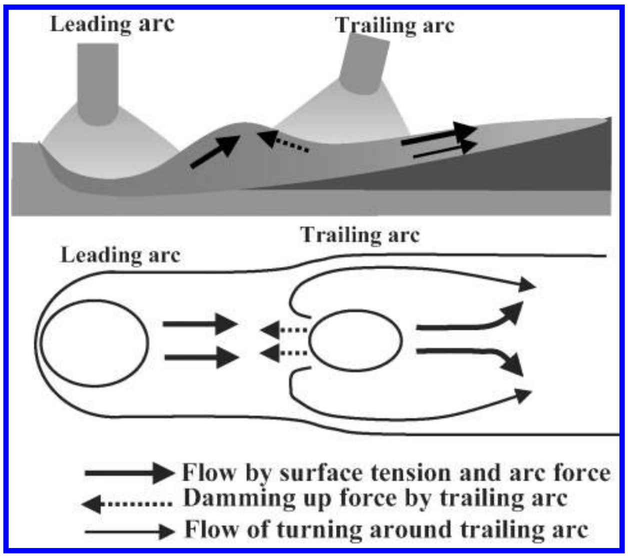


6 Floating slag on the surface of the bulged molten metal in tandem pulsed GMA welding

out of the weld pool that can be formed between the two wires.

Figure 6 shows the behaviour of the weld pool formation observed from the front position at a recording speed of 5000 frames s^{-1}, where the trailing wire was set at a 9° push angle. As shown in frames C–E, the weld pool was observed to become wider in front of the trailing arc. The floating slag on the surface of the bulged molten metal that was formed between the two wires seemed to be driven backwards by the leading arc, as shown in frames A–C. However, as shown in frames D–G, the slag was suppressed by the trailing arc and therefore it did not easily move backwards out of the weld pool, remaining on the surface of the bulged molten metal. These records reveal that the trailing arc dams up the backward flow of the molten metal produced by the leading arc, so welding can proceed successfully, maintaining the bulged molten metal in a stable condition. From the specific movement of part of the floating slag as shown in frames E–H, it has been clarified that the molten metal flows at the periphery of the area underneath the trailing arc.

In other words, as indicated by dotted arrows in Fig. 7, it can be considered that a certain value of push angle for the trailing wire produces the effective arc force component that dams up a large volume of molten metal, which tends to flow backwards irregularly out of the weld pool. It can also be presumed that stable formation of the bulge of the weld pool and the specific flow of molten metal around the trailing arc are effective at forming sound weld beads with smaller reinforcement and larger width. The experimental results discussed above coincide with the findings of Nomura *et al.*[18] and Ito *et al.*,[19] which showed that in the case of tandem submerged arc welding the trailing arc directed towards the welding progressive direction was essential in order to obtain sound weld beads at high welding speeds.



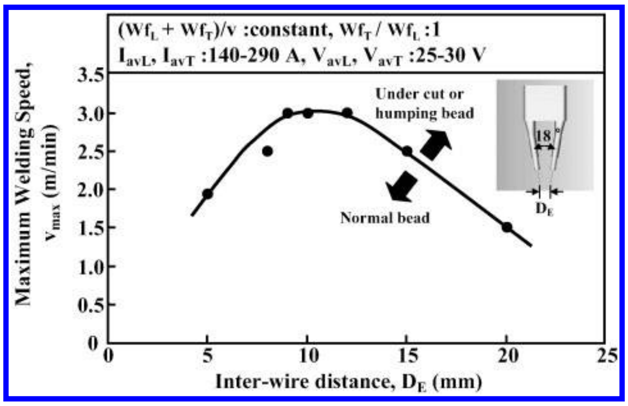
7 Conceptual illustration of metal flow in weld pool

Effect of distance between two wires

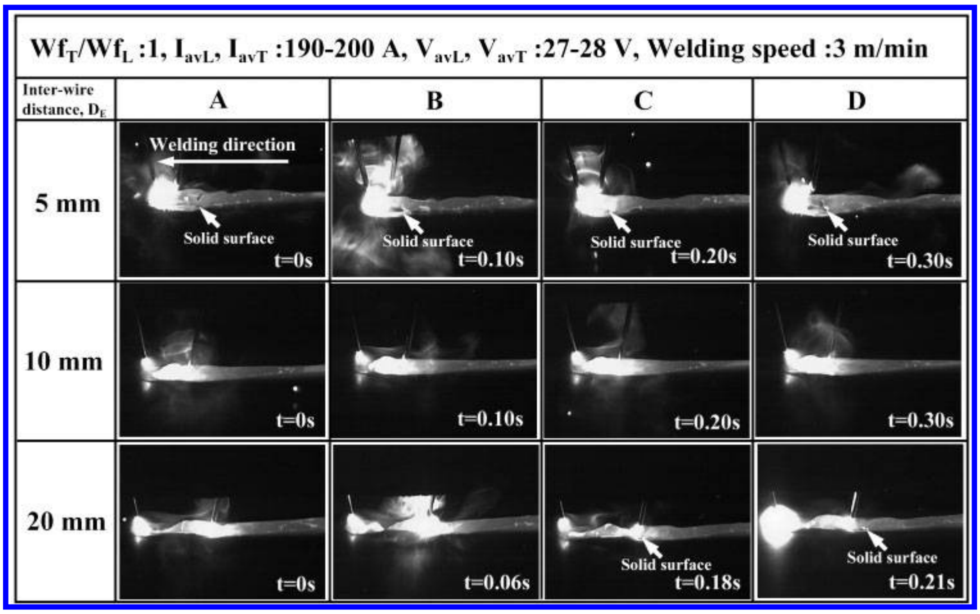
Figure 8 shows the effect of interwire distance on the maximum welding speed necessary to obtain sound weld beads with the use of the type 4 torch configuration, in which the leading and trailing wires were set at a 9° drag angle and a 9° push angle respectively, and the interwire distance D_E was changed from 5 to 20 mm. When D_E was 5 mm, the maximum welding speed was 2 m min^{-1}, and as D_E increased, the maximum welding speed increased to 3 m min^{-1}, where D_E was in the range 9–12 mm. However, when D_E was over 12 mm, the maximum welding speed decreased to 1·5 m min^{-1}, with D_E of 20 mm.

These results suggest that the interwire distance is an important factor in successful high speed welding, by maintaining the bulge of the weld pool produced by the leading and trailing wires in a stable condition.

In order to confirm how the interwire distance affects the behaviour of the weld pool, the following experiments were conducted. Figure 9 shows the images of the molten metal recorded by a high speed video camera during bead-on-plate welding at a welding speed of 3 m min^{-1}, with interwire distances of 5, 10 and 20 mm.



8 Effect of interwire distance on maximum welding speed



9 Comparison of weld pool formation with different interwire distances

When the interwire distance was 5 mm, the arcs generated from the two wires were combined, thereby forming an arc shape similar to that in single wire GMA welding. In frames A–D, a solid surface was exposed at the weld pool just behind the arc, and as shown in frames B and C, the exposed solid surface remained unfilled with the molten metal. This phenomenon occurred in quick succession during welding, causing humped weld beads. In this case, it can be considered that the component of the trailing arc force in the welding direction was not enough to dam up the molten metal that was driven backwards by the leading arc, thereby causing humped weld beads by the mechanism similar to that in single arc welding.

When the interwire distance was 20 mm, most of the molten metal produced by the leading arc flew backwards to form the bulge of the weld pool in front of the trailing arc as welding proceeded (frame A), and soon the bulged molten metal became difficult to dam up by the trailing arc. Afterwards, a large volume of molten metal began to flow, and then the trailing arc ran on the bulged molten metal grown behind the leading arc, causing a lot of spatter due to short-circuiting (frame B). Then the molten metal was immediately pushed to flow backwards, and an exposed solid surface was observed underneath the trailing arc (frame C). Once this phenomenon occurred, the exposed solid surface remained unfilled with the molten metal, as observed in frame D, causing intermittent weld beads. Immediately after this, the molten metal flew out from the area under the leading arc and formed the bulge of the weld pool again in front of the trailing arc.

When the interwire distance was 10 mm, the molten metal between the two wires was suppressed by the trailing arc. Therefore, no solid surface was exposed underneath the leading arc in high speed welding. In this condition, welding progressed with the absence of humping and undercut, because the penetration area was presumably filled with the molten metal. Figure 10 shows the appearance and penetration of the weld beads obtained at a welding speed of 3 m min^{-1} with variations of interwire distance. At an interwire distance D_E=10 mm, good weld bead appearance and penetration shape were obtained. In contrast, the interwire distances D_E=5 and 20 mm resulted in humped weld beads.

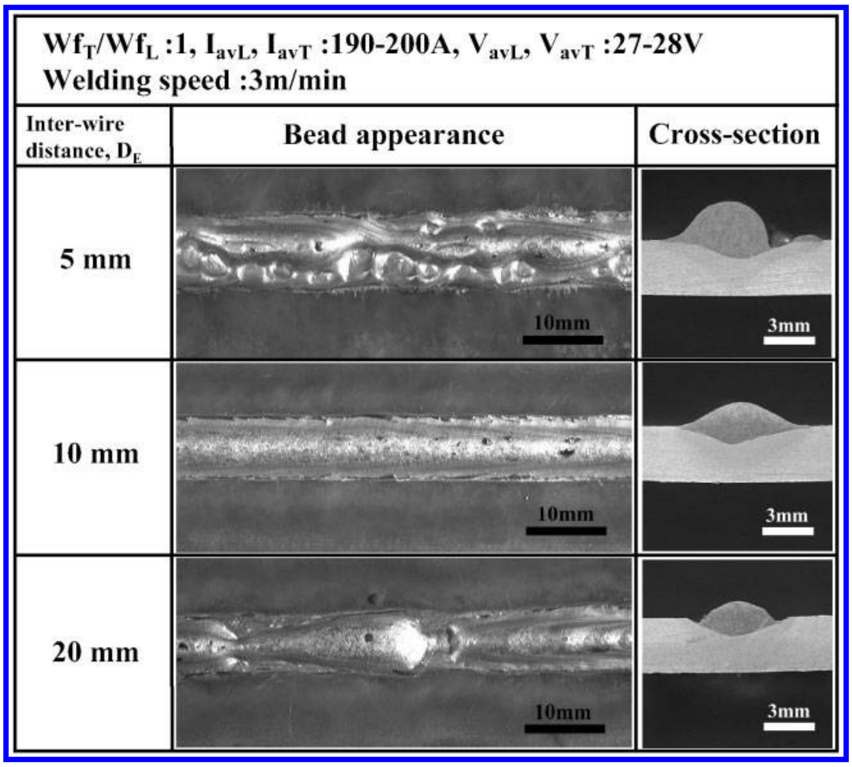
From the aforementioned findings, it can be said that the proper interwire distance for forming sound weld beads in high speed welding varies from 9 to 12 mm. The interwire distance should be minimised within this range to avoid enlargement of the welding torch.

Effect of welding current ratio

In the previous section, it was suggested that the balance between the leading and trailing arc forces acting on the molten metal and how the molten metal fills the penetration area determine the formation of sound weld bead in high speed welding. Therefore, it can be considered that the ratio of the trailing arc current to the leading arc current (trailing arc current I_T/leading arc current I_L) could be an important factor in improving weldability in high speed, tandem pulsed GMA welding, because the current ratio can directly affect the arc forces.

To clarify the effect of the current ratio between the leading arc and trailing arc on the maximum welding speed needed to obtain sound weld beads, the following experiments were conducted using the torch with a wire-to-wire inclination angle of 18° (type 4) and an interwire distance of 9 mm.

Figure 11 shows the maximum welding speed as a function of I_T/I_L, which was obtained by setting the wire feed rate ratio between the trailing and leading wires (W_{fT}/W_{fL}) in the range 0·2–1·33. At the lowest welding current ratio, 0·22 (where W_{fT}/W_{fL}=0·2), the maximum welding speed achieved was only 2·5 m min^{-1}; however, this speed increased as I_T/I_L increased. The maximum welding speed was 4·0 m min^{-1} in the range I_T/I_L=0·31–0·5, and was 4·5 m min^{-1} in the range I_T/I_L=0·35–0·4. That is, if the proper current ratio is set for the trailing and leading arcs, the maximum welding speed with the tandem pulsed GMA welding process could be 275% higher than that with the single wire GMA welding



10 Comparison of bead appearance and cross-section with different interwire distances

process (maximum 1·2 m min^{-1}), as indicated by the dashed line in the figure.

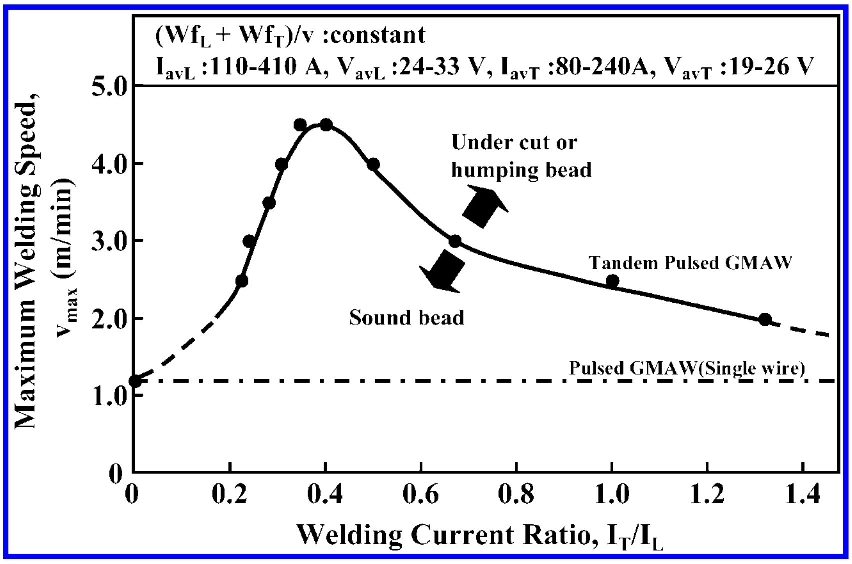
However, when I_T/I_L exceeded 0·5, the maximum welding speed became lower than 4 m min^{-1}, and it was only 2 m min^{-1} at I_T/I_L=1·32 (where W_{fT}/W_{fL}=1·33).

In the present experiment, it can be said that the current ratio needed to obtain the maximum welding speed of over 4 m min^{-1} in tandem pulsed GMA welding must be in the range 0·31–0·5, as otherwise marked improvement in welding speed cannot be expected. This result coincides with the findings of Nomura *et al.*,[20] which clarified that the welding current ratio had to be set in the optimum range to obtain sound welds in high speed tandem submerged arc welding.

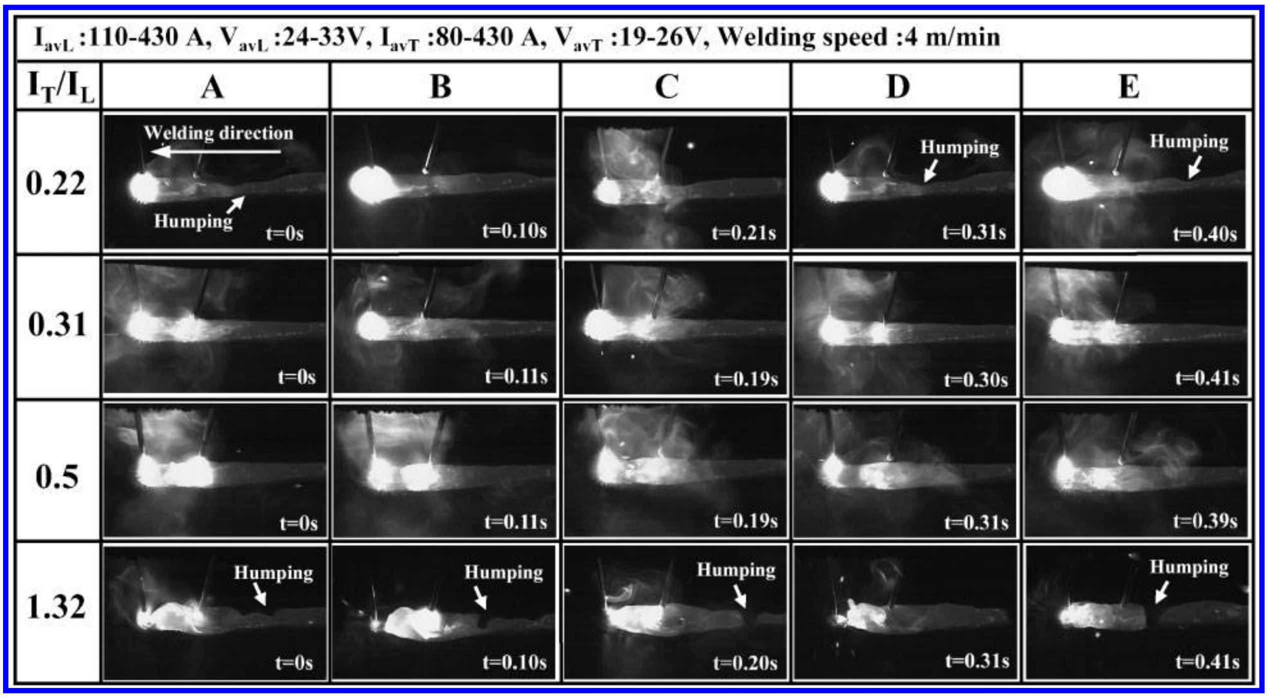
The behaviour of the weld pool at each current ratio was observed with the aid of a high speed video camera, to investigate the mechanism of weld bead formation in high speed welding.

Figure 12 shows the behaviour of the weld pool when bead-on-plate welding was carried out at a welding speed of 4 m min^{-1} and at current ratios of 0·22, 0·31, 0·5 and 1·32.

When the current ratio was set at 0·22 (I_L=410 A; I_T=90 A) in high speed welding at 4 m min^{-1}, the solid surface produced by the strong leading arc appeared in all parts of the penetration area. Underneath the leading arc, the molten metal transferred from the wire and the molten base metal concentrated and flew backwards at the transverse centre of the weld bead, to cause humping. This concentrated molten metal flow was probably caused by the lower temperature. Thus poor wettability of the periphery of the solid surface



11 Effect of welding current ratio on maximum welding speed



12 Effect of welding current ratio on weld pool formation

prevented transverse spreading of the molten metal.[2] The humped weld bead could have been caused by the low trailing arc amperage; that is, the trailing arc force was not enough to suppress the molten metal's backward flow. Another possible reason for the humped weld bead was that the amount of molten metal transferred from the trailing wire was not enough to cover the exposed solid surface area.

When the current ratio was set at 1·32 (I_T=290 A; I_L=220 A), the strong trailing arc dammed up the molten metal produced and driven backwards by the leading arc, and therefore the bulged molten metal between the two wires became unstable. In addition, the trailing arc gouged the molten metal, causing frequent exposure of solid surface at the penetration area behind the trailing arc, and thereby causing humped weld beads.

With the current ratios 0·31 (I_L=385 A; I_T=120 A) and 0·5 (I_L=340 A; I_T=170 A), the weld beads were sound. In these conditions, high speed welding proceeded in a stable manner, the bulge of the weld pool being kept stable at the height of the base metal surface level between the two wires. This suggests that the molten metal's backward flow driven by the leading arc force was suppressed by the trailing arc force, and the weld pool between the two wires was always filled with the molten metal transferred from the trailing wire. Also, almost no arc force induced solid surface was observed behind the trailing arc.

The pulse frequencies of the leading and trailing arcs with the appropriate current ratios described above were 300–350 Hz and 100–140 Hz, respectively. With these frequencies, no sign of an adverse effect of single pulse period (2·9–10 ms) on the formation of sound weld bead was observed in the behaviour of the weld pool.

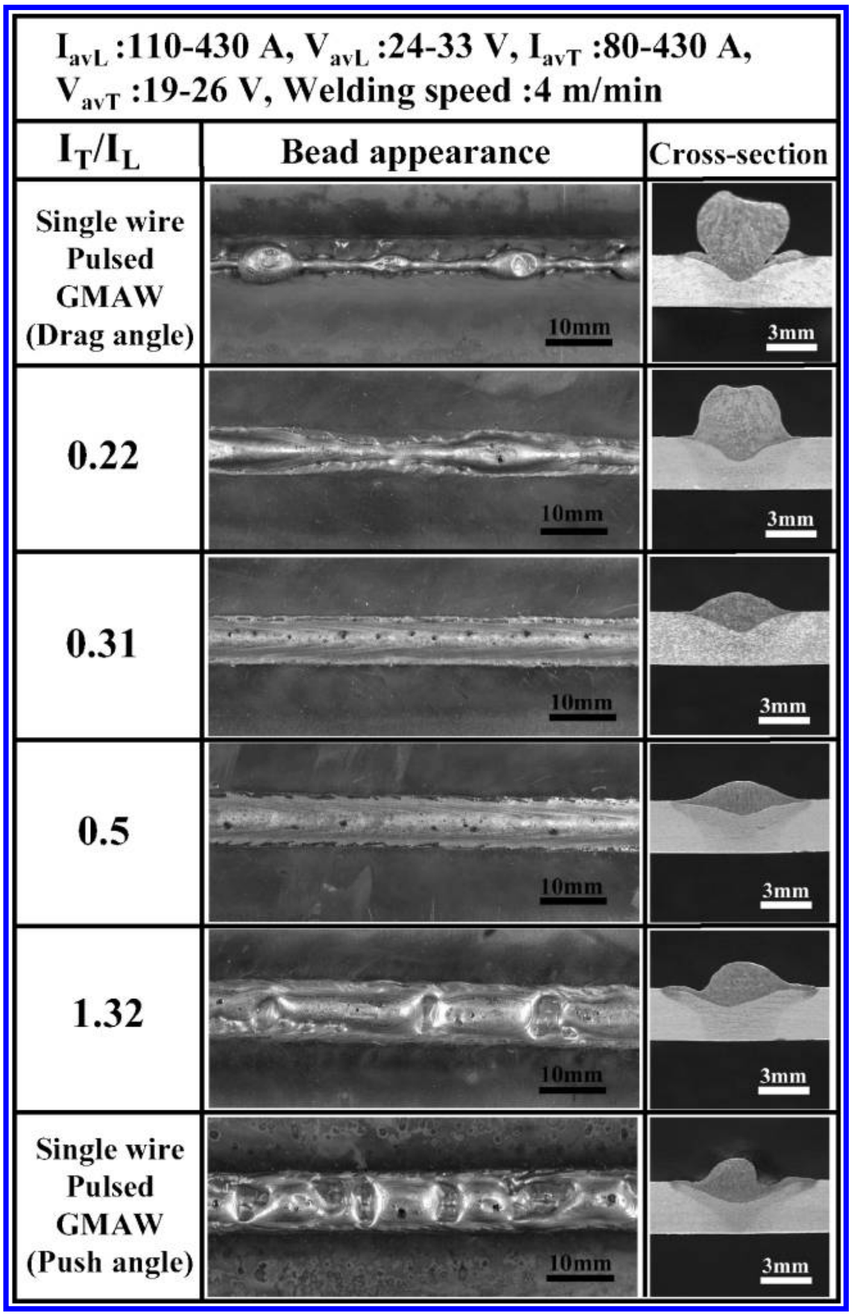
These results suggest that the ratio of the trailing arc current to the leading arc current must fulfil the following three conditions at the same time if sound weld beads are to be obtained in high speed, tandem pulsed GMA welding.

(i) the trailing arc force suppresses the backward flow of the molten metal that is driven by the leading arc
(ii) the solid surface induced by the leading arc force is filled with the molten metal produced by the trailing arc, and therefore the bulge of the weld pool is kept stable between the two wires
(iii) the trailing arc force induces no solid surface.

Figure 13 shows the appearance and penetration of the weld beads obtained at a welding speed of 4 m min^{-1} with different current ratios. At current ratios of 0·31 and 0·5, good weld bead appearance and penetration shape were obtained. In contrast, the use of the current ratios 0·22 and 1·32 resulted in humped weld beads. At a current ratio of 0·22, when the leading wire was set at a drag angle and carried a higher amperage, the appearance of the humped weld bead resembled that of the humped weld bead formed by single wire pulsed GMA welding in which the wire was set at a drag angle. At a current ratio of 1·32, when the trailing wire was set at a push angle and carried a higher amperage, the appearance of the humped weld bead was similar to that of the humped weld bead formed by single wire pulsed GMA welding in which the wire was set at a push angle.

Conclusions

1. The maximum welding speed needed to ensure sound weld beads varied from 2 to 3 m min^{-1} with the use of four variations of the two wire configuration along the welding direction; this was 60–150% higher than the speed obtained with the single wire pulsed GMA welding process. In particular, the use of type 3 and 4 configurations, in which the trailing wire was set at a push angle, was shown to contribute to a great



13 Comparison of bead appearance and cross-section with welding current ratios

improvement in welding speeds, resulting in a 3 m min^{-1} maximum welding speed.

2. When the welding speed was 3 m min^{-1}, sound weld bead with uniform width was obtained with the trailing wire set at a 5° to 13° push angle, regardless of the inclination angle of the leading wire.

3. The interwire distance greatly affected weld bead formation in high speed welding. That is, the maximum welding speed was improved with an interwire distance in the range 9–12 mm.

4. The welding current ratio between the trailing and leading arcs I_T/I_L greatly affected the maximum welding speed. In the appropriate range of welding current ratio, I_T/I_L=0·31–0·5, the maximum welding speed achieved was 4–4·5 m min^{-1}, which was 275% higher at the maximum when compared with single wire pulsed GMA welding.

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