High-Speed Welding of Steel Sheets by the Tandem Pulsed Gas Metal Arc Welding System†

UEYAMA Tomoyuki*, OHNAWA Toshio*, YAMAZAKI Kei, TANAKA Manabu***, USHIO Masao**** and NAKATA Kazuhiro*******

Abstract

In tandem gas metal arc (GMA) welding, it is important to prevent adverse effects caused by electromagnetic interference between the two adjacent arcs to create good metal transfer. In the tandem pulsed GMA welding system, newly developed by the authors, pulse peak currents are fed simultaneously to the leading and trailing electrodes in principle and a unique pulse timing control is employed in which the end of a pulse peak current for the trailing wire is delayed by 0.5 ms from that for the leading wire to prevent the arc extinguishing By using the tandem pulsed GMA welding system, the effects of the inter-wire distance, inclination angle and welding current (wire feed rate) ratio between the two wires have been investigated to study the essential requirements for the welding torch configuration and the allocation of welding currents to obtain sound weld beads with the absence of undercut and humping in the high speed welding of steel sheets. When the welding speed was 3 m/min, a sound weld bead with uniform width was obtained with the trailing wire set at 9-degree push angle regardless of the inclination angle of the leading wire. The inter-wire distance greatly affected the weld bead formation in high speed welding. That is, the maximum welding speed was improved with the proper inter-wire distance in the range 9 to 12 mm. In the proper range of welding current ratio, I_T/I_L=0.31 to 0.5, the maximum welding speed achieved was 4 to 4.5 m/min, which is 275% higher at the maximum when compared with single wire pulsed GMA welding (at a maximum welding speed of 1.2 m/min).

KEY WORDS: (Tandem pulsed GMA welding), (High speed welding), (Steel sheet), (Bead formation), (Torch configuration), (Current ratio), (Lap joint), (Pulse timing control)

1. Introduction

Nowadays, reduction of welding construction costs is strongly required and therefore, to cope with this demand in the field of arc welding, there has been a noticeable trend towards increasing welding efficiency, improving at the same time the quality of welds. Especially, in the field of steel sheet welding such as the automobile industry, a great effort to shorten the welding time for production lines to the second has been made. In this trend, advanced arc welding processes have been demanded in order to improve markedly welding speeds and deposition rates for one pass welds, in addition to the demands for automatization and robotization of arc welding processes.

Among arc welding processes, GMA welding such as CO2/MAG welding and MIG welding is advantageous because it is more convenient and cost effective over the other welding processes, and is 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, this process is believed to play the main role in the fabrication technology today and in the future.

However, in conventional GMA welding, the use of high welding speeds needs high welding currents (high wire melting rates). Consequently, the arc force becomes stronger due to the increased current, and it influences the behavior 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 has been regarded as the practical maximum rate in conventional GMA welding used for steel sheets [3) 4)].

To solve these problems, optimization of the chemical composition of wires and the pulse current waveform control was examined to minimize the arc length with the

† Received on July 1, 2005
* Daihen Corporation
** Graduate Student, Osaka University
*** Associate Professor
**** Professor Emeritus
***** Professor

Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

absence of short-circuiting by reducing the size of the molten droplet per each pulse, and thereby the maximum welding speed was improved to be approximately 2 m/min with the single wire pulsed GMA welding process[5]. Some other research reports clarified that it was possible to weld car chassis parts at 1.8 m/min using band-shape wires called strip wire that produced an elliptical-shape arc and thereby deconcentrated the arc heat [6) 7)].

In any case, with the above solutions for improving the single wire GMA welding process, the maximum welding speed is believed to be up to 2 m/min, which is only 20 to 30 % higher as compared with conventional welding speeds.

A tandem GMA welding process 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 beads can be obtained without undercut and humping even in high speed welding. Therefore, it is expected to be an advanced GMA welding process that provides a significant improvement in the welding speed. With this tandem GMA welding process, high speed welding at 2.5 to 3 m/min was possible for practical applications [8)-13)].

This paper describes the control method for stabilizing arcs employed in the tandem pulsed GMA welding system newly developed by the authors and 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 in high-speed welding of steel sheets.

2. Control Method for Stabilizing Arcs in Tandem Pulsed GMA Welding

2.1 Components of the tandem pulsed GMA welding system

Figure 1 shows the components of the tandem pulsed GMA welding robot system used for this study. This system was composed of two welding power sources, two wire feeders, one welding torch and one welding robot.

As for 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. In this case, each wire can be operated by using either independent or phase control of pulsed current waveforms.

In general, phase control of pulsed currents is used for the leading and trailing wires to assure sufficient arc stability and prevent spatter generation.

The tandem pulsed GMA welding torch arranged 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. An experimental torch [14)] shown in **Fig. 2** was used. This

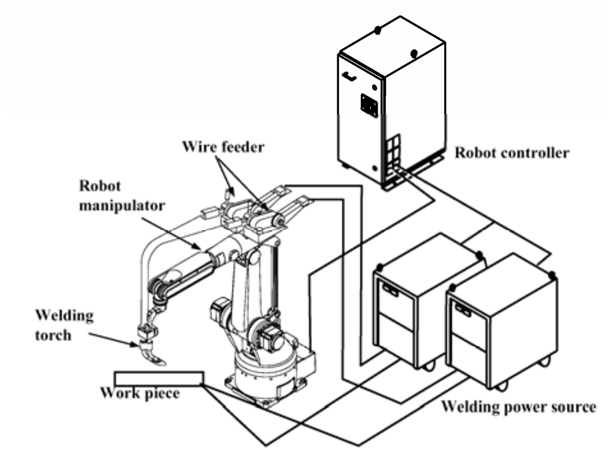

Fig. 1 Schematic diagram of tandem pulsed GMA welding system

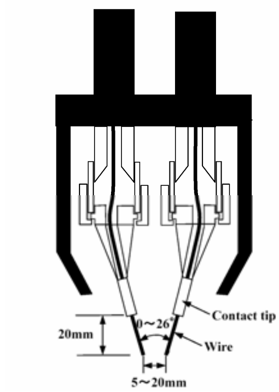

Fig. 2 Evaluated tandem pulsed GMA welding torch configuration

torch could be set with the inclination angle between the two wires at up to 26 degrees and the inter-wire distance 5 to 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 were used. The wire feeding units were equipped with encoder-feedback-controlled DC motors to minimize the fluctuation of wire feed rate caused by the fluctuation of ambient temperature and input voltage.

As for the welding robot, the independently multiple-articulated model having a maximum pay load 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.

2.2 Control of welding current waveforms

In tandem pulsed GMA welding, pulse timing control[8)] of welding current and voltage waveforms is important to stabilize the two arcs generated at the adjacent two wires. Pulse timing control is effective, not only to prevent spatter generation with the metal transfer synchronized with pulsed currents in conventional single wire welding, but also to suppress adverse effects of the arc interference between the two wires. In this control, it is desirable to use an appropriate method by the mean current which leads as high as in practical application.

For pulse timing control, two types of controls are possible as shown in **Fig. 3**. There are staggered-pulse control in which pulsed currents are fed alternately to two wires and simultaneous-pulse control in which pulsed currents are fed in the sample phase to both wires.

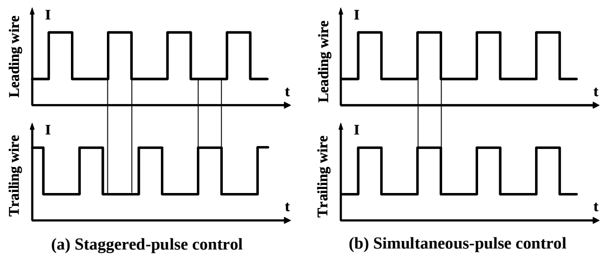

Fig. 3 Pulse timing controls

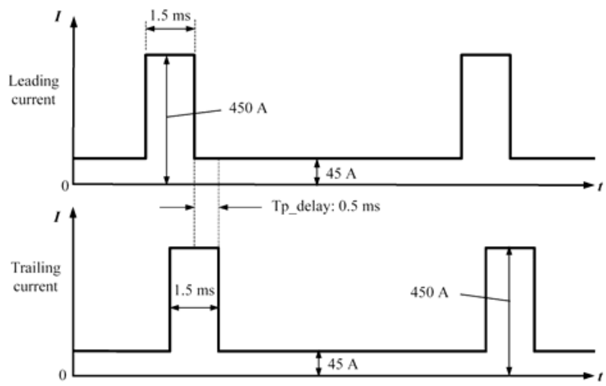

Fig. 4 Pulse timing control with 0.5ms-delayed pulse peak current for trailing electrode wire

The present system uses the pulse timing control illustrated in **Fig. 4**, which uses basically the simultaneous-pulse control that feeds pulsed currents in the same phase to the two electrode wires but the end of a pulse peak current for the trailing electrode is delayed by 0.5 ms from that for the leading wire to prevent the arc interference between the two wires and thereby preclude arc extinguishing [15].

Figure 5 shows current and voltage waveforms with a 0.5 ms delay for the trailing wire and high speed video records synchronized with the waveforms. Frame (a) is the beginning of the peak period of the leading arc. Frame (b) is the beginning of the peak period of the trailing arc. Frame (c) and (d) are peak periods of both arcs. Frame (e) is the end of the peak current of the leading arc. Frame (g) and (h) shows that the cathode of the trailing arc goes back to the area under the tip of the trailing wire. When the two wires were energized with pulse peak currents, the two arcs were attracted between both wires, but the attraction hardly caused arc extinguishing because the directivity of the arcs was sufficient. After this period, at the end of the pulse peak, current was delayed by 0.5 ms for the trailing wire and the trailing arc was directed on the extension line of the welding wire by its directivity. Subsequently, the base current period began and thereby the arc of the trailing wire was maintained stable without extinguishing.

2.3 Control for stable arc length

In order to stabilize arcs in tandem pulsed GMA welding, pulse timing control for the two wires is necessary. In addition, independent control for stable arc length for each wire is indispensable to overcome some disturbance with which each wire may be involved.

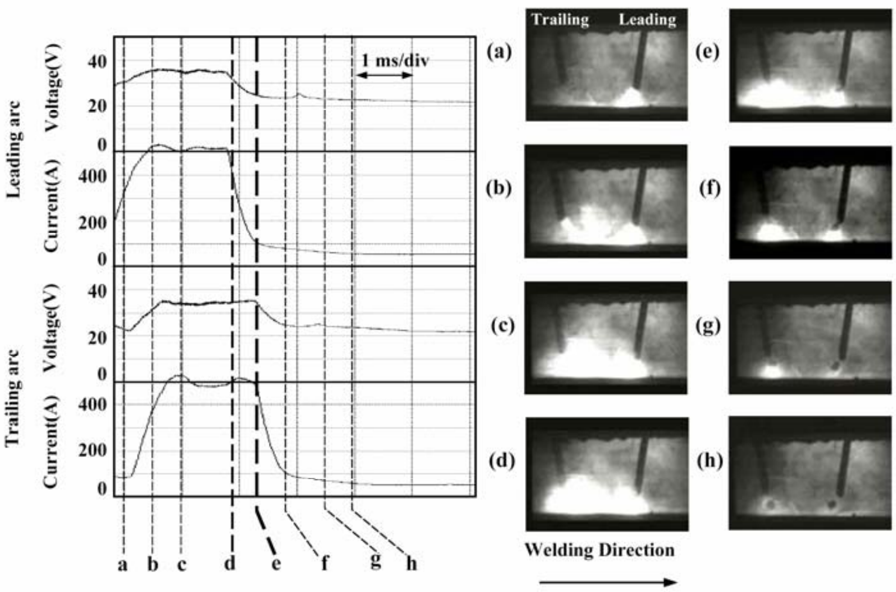

Fig. 5 Arc phenomena in pulse timing control with 0.5ms-delayed pulse peak currents for the trailing electrode wire

With the present system, pulse peak current, pulse width and base current for the leading wire are kept constant, respectively, and arc length control is conducted by pulse frequency modulation (PFM) in which arc voltage is fed back and the base current time alone is modulated [16]. As for the trailing wire, the end of a pulse peak current is delayed by 0.5 ms from that for the leading wire, and arc length control is conducted by pulse peak modulation (PPM) in which the pulse peak current is modulated in response to the arc load. By employing this method, a stable arc length control has been established, which is hardly affected by some disturbance during welding.

3. Optimum Parameters for Tandem Torch Configuration

3.1 Experimental procedures and materials

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 parameters for the leading and trailing wires were set so that the amount of wire fed for the unit welding length was constant independently 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 Wf_L (m/min) and the trailing wire feed rate Wf_T by the welding speed v (m/min) could be 5. For example, when the welding speed was 2 m/min, Wf_L+Wf_T was 10 m/min. With this setting, the amount of deposited metal for the unit welding length could be kept constant at the welding speeds 1 to 5 m/min. The arc voltage was set by adjusting the output voltage to obtain an arc length suitable for the pulsed spray arc that contained short-circuiting transfers at several times per second.

This experiment used the base metal of mild steel sheet having dimensions of 3.2 mm thickness-65 mm width-450 mm length, the welding solid wire having a diameter of 1.2 mm and the shielding gas of 80%Ar-20%CO_2 mixture at a flow rate of 50 liter/min.

3.2 Effect of inclination angle between two wires on weld bead formation

Bead-on-plate welding was carried out to evaluate the maximum welding speed to obtain sound weld beads, in which the tip-to-base metal distance was kept at 20 mm, the inter-wire distance was kept at 12 mm, the wire feed rate ratio was controlled at Wf_T/Wf_L=1 (where Wf_L and Wf_T: 5 to 10 m/min). The leading wire was set at a 0-degree or 9-degree drag angle in combination with the trailing wire set at a 0-degree or 9-degree push angle. The results are shown in **Fig. 6**, in which a dashed line indicates the maximum welding speed in single wire pulsed GMA welding (with a 10-degree push angle torch) for comparison. In tandem pulsed GMA welding, the maximum welding speed achieved 2 m/min or higher with any of the inclination angles between the two wires, and was approximately 65% higher than that in single wire pulsed GMA welding (at a maximum welding speed of 1.2 m/min). When the trailing wire was set at a push angle (Type 3 and Type 4), the maximum welding speed achieved 3 m/min, improving the welding speed by approximately 150% over the single wire pulsed GMA welding process. However, when the welding speed was 3.5 m/min exceeding the maximum welding speed with either Type 3 or Type 4 torch configuration, sound weld bead could not be obtained due to humping.

Figure 7 shows the bead appearance and penetration of

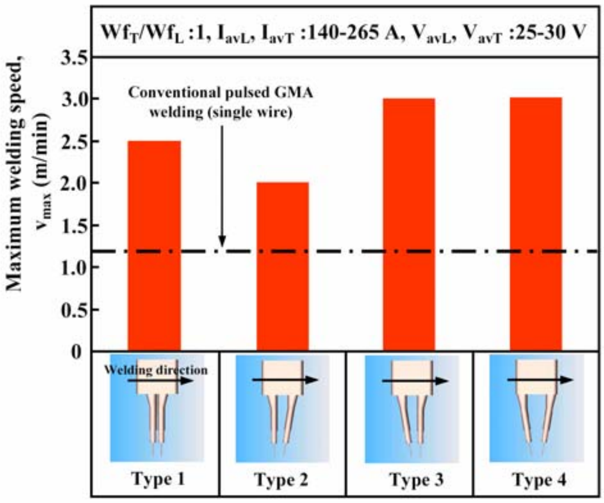

Fig. 6 Comparison of maximum welding speed among torch configurations

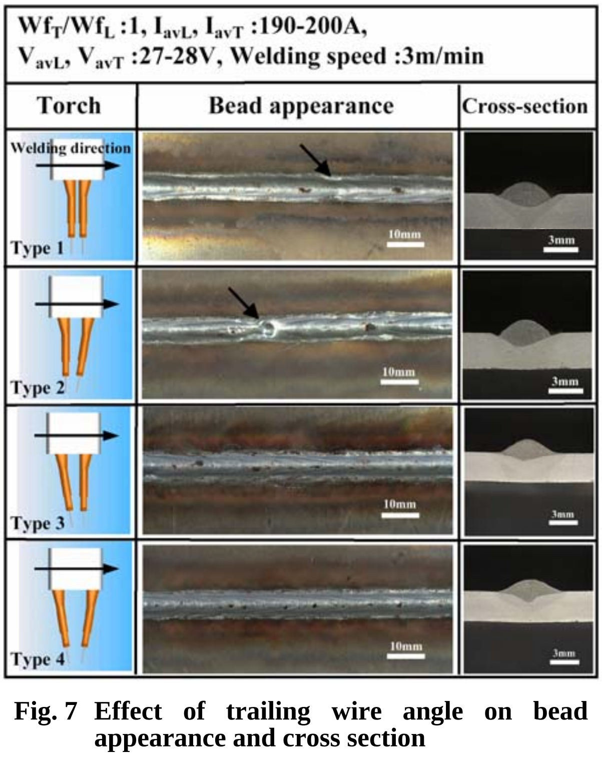

Fig. 7 Effect of trailing wire angle on bead appearance and cross section

bead-on-plate welds when the inter-wire distance was set to be 12 mm, the leading wire was set at a 0-degree or 9-degree drag angle in combination with the trailing wire set at a 0-degree or 9-degree push angle, and the welding speed was 3 m/min. The wire feed rate ratio between the leading and trailing wires was set at $Wf_T/Wf_L=1$ (where Wf_L and Wf_T: 7.5 m/min). When both the leading and trailing wires were set at a 0-degree 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 pointed with an arrow in **Fig. 7**. When the trailing wire was set at 0 degree with the leading wire set at a 9-degree drag angle (Type 2), the weld bead exhibited humping. In contrast, when the trailing wire was set at a 9-degree push angle, sound weld beads were formed regardless of the leading wire angle.

Figure 8 shows the behavior of the weld pool formation observed from the front position at a recording speed of 5000 frames/s where the trailing wire was set at a 9-degree push angle. As shown in the frames C through E, the weld pool was observed to become wider in front of the trailing arc. The molten 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 the frames A through C. However, as shown in the frames D through 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, and thereby welding can be conducted successfully, maintaining the bulged molten metal in a stable condition. From the specific movement of part of the floating slag as shown in the frames E through H, it has been clarified that the molten metal flows at the periphery of the area underneath the trailing arc.

In other words, as shown with dotted arrows in **Fig. 9**, it can be considered that a certain degree of push angle for the trailing wire produces the effective arc force component to dam up a large volume of molten metal that 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 in forming sound weld beads with smaller reinforcement and larger width.

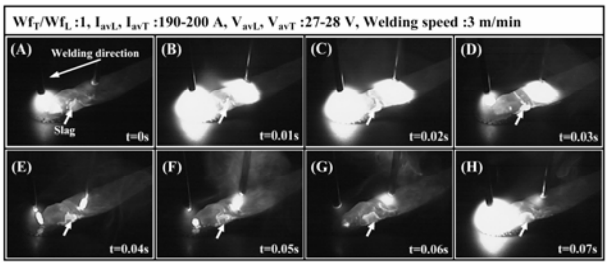

Fig. 8 Floating slag on the surface of the bulged molten metal in tandem pulsed GMA welding

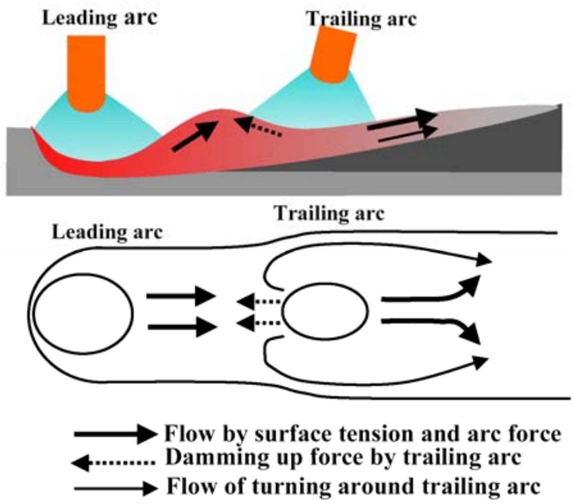

Fig. 9 Conceptual illustration of metal flow in weld pool

The experimental results discussed above coincide with the researches made by Nomura, et al [17] and Ito, et al [18] which reported that high speed welding by tandem submerged arc welding chose the specific electric connection and AC and DC power sources combination so that the trailing arc was directed towards the welding progressive direction in order to obtain sound weld beads.

3.3 Effect of inter-wire distance on weld bead formation

Figure 10 shows the effect of inter-wire distance on the maximum welding speed to obtain sound weld beads in the use of the Type 4 torch configuration in which the leading and trailing wires were set at a 9-degree drag angle and a 9-degree push angle respectively, and the inter-wire distance D_E was changed from 5 to 20 mm. When D_E was 5 mm, the maximum welding speed was 2 m/min, and as D_E increased the maximum welding speed increased to 3 m/min where D_E was in the range 9 to 12 mm. However, where D_E was over 12 mm, the maximum welding speed decreased to 1.5 m/min with D_E of 20 mm.

Figure 11 shows the appearance and penetration of the weld beads obtained at a welding speed of 3 m/min with variations of inter-wire distances. At the inter-wire

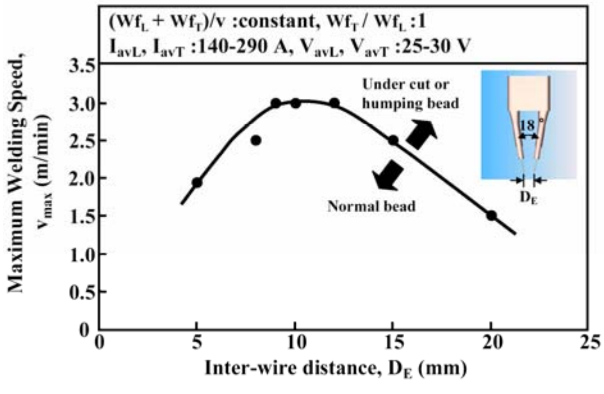

Fig. 10 Effect of wire inter-distance on maximum welding speed

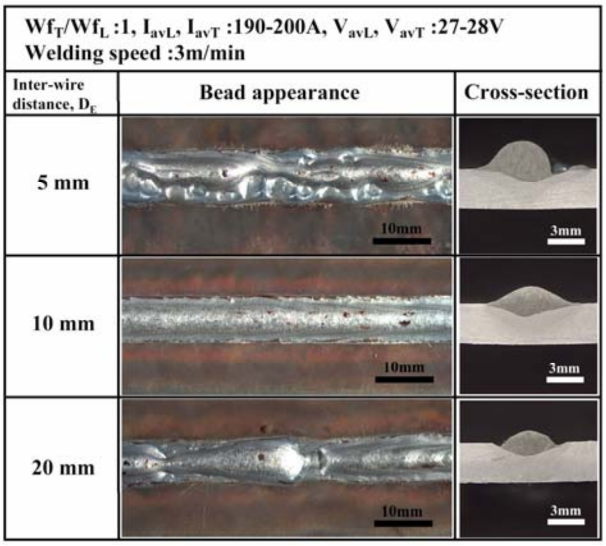

Fig. 11 Comparison of bead appearance and cross section among wire inter-distances

distance D_E =10 mm, good weld bead appearance and penetration shape were obtained. In contrast, the inter-wire distances D_E =5 and 20 mm, resulted in humped weld beads.

4. Effect of Welding Current Ratio between Two Wires on Weld Bead Formation

In Chapter 3, it is suggested that the balance between the leading and trailing arc forces acting onto 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) can be an important factor to improve weldability in high speed, tandem pulsed GMA welding

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

Figure 12 shows the maximum welding speed as a function of the welding current ratio (I_T/I_L) that was obtained by setting the wire feed rate ratio between the trailing and leading wires (Wf_T/Wf_L) in the range 0.2 to 1.33. At the lowest welding current ratio I_T/I_L= 0.22 (where Wf_T/Wf_L=0.2), the maximum welding speed achieved only 2.5 m/min, however, this speed increased as the ratio I_T/I_L increased. The maximum welding speed is 4.0 m/min in the range I_T/I_L=0.31 to 0.5 and is 4.5 m/min at the highest in the range I_T/I_L=0.35 to 0.4. That is, by setting the proper current ratio 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 process (1.2 m/min at the maximum) as shown with a dashed line in the figure.

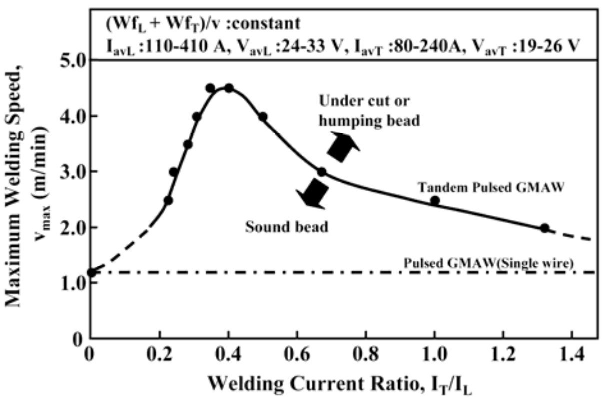

Fig. 12 Effect of welding current ratio on maximum welding speed

However, when the current ratio exceeded I_T/I_L=0.5, the maximum welding speed became lower than 4 m/min, and it was only 2 m/min at I_T/I_L=1.32 (where Wf_T/Wf_L=1.33).

Within the present experiment, it can be said that the current ratio to obtain the maximum welding speed of over 4 m/min in tandem pulsed GMA welding must be in the range I_T/I_L=0.31 to 0.5, otherwise marked improvement in welding speed cannot be expected. This result coincides with the research report by Nomura, et al[19] which clarified that the welding current ratio had to be set in an optimum range to obtain sound welds in high speed tandem submerged arc welding.

Figure13 shows the appearance and penetration of the weld beads obtained at a welding speed of 4 m/min with variations of the current ratio. At the current ratios I_T/I_L=0.31 and I_T/I_L=0.5, good weld bead appearance and penetration shape were obtained. In contrast, the use of the current ratios, I_T/I_L=0.22 and I_T/I_L=1.32, resulted in humped weld beads. At the current ratio I_T/I_L=0.22 where 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 the current ratio I_T/I_L=1.32 where 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.

5. Advantages of System in High Speed Welding of Steel Sheets

Figure 14 and **15** show examples of lap fillet welds and T-joint horizontal fillet welds produced at high speeds on steel sheets by the tandem pulsed GMA welding system. Fillet welding of a lap joint having a gap of 1.6 mm resulted in regular bead appearance without undercut at a welding speed of 4 m/min. Downhill fillet welding of a lap joint inclined at 20 degrees was also successful at a welding speed of 8 m/min. The leg length and throat thickness of the T-joint horizontal fillet weld were sufficient. From these results, it is obvious that the

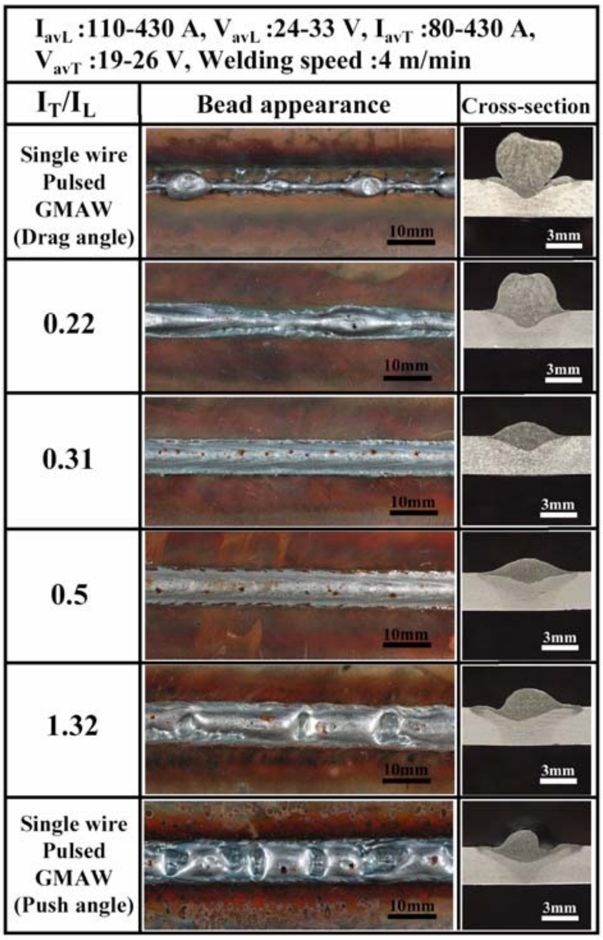

Fig. 13 Comparison of bead appearance and cross section among welding current ratios

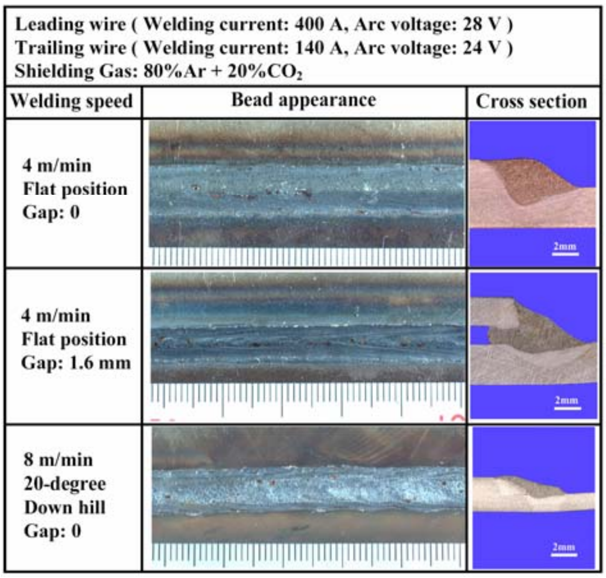

Fig. 14 High speed fillet welding of lap joints

tandem GMA welding process enables high speed welding by using increased deposition rates with two welding wires and individual functions of the leading and trailing wire during welding.

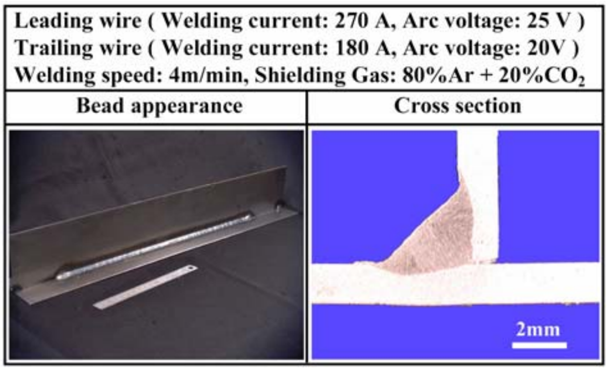

Fig. 15 High speed horizontal fillet welding of T-joints

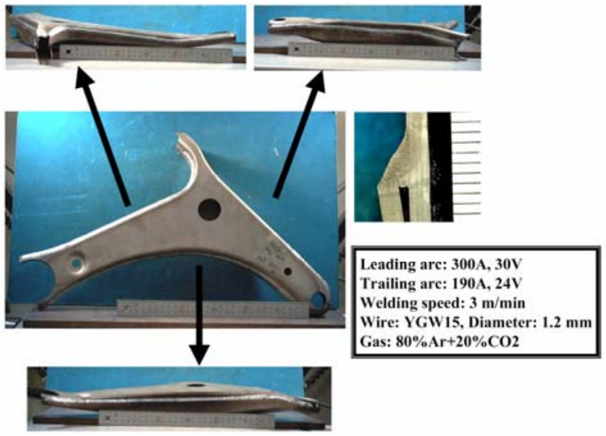

Fig. 16 Application of tandem pulsed GMA welding to lower arm of car

Figure 16 shows a lower arm welding application for the automobile industry. By using tandem pulsed GMA welding system, good welding results are obtained at 3 m/min of welding speed in spite of existing joint gaps. In addition, the newly developed pulse timing control provides almost spatter free welds.

6. Conclusion

The method of controlling welding current waveforms for stabilizing arcs in the use of the tandem pulsed GMA welding system and the effects of the inter-wire distance, inclination angle and welding current (wire feed rate) ratio between the two wires on the formation of weld bead in high speed welding, have been described. The results are summarized as follows.

1. In the tandem pulsed GMA welding system, pulse peak currents are fed simultaneously to the leading and trailing electrodes and unique pulse timing control is employed in which the end of a pulse peak current for the trailing wire is delayed by 0.5 ms from that for the leading wire to prevent arc extinguishing. In addition, arc length control is assured by pulse frequency modulation (PFM) for the leading wire and pulse peak modulation (PPM) for the trailing wire with the pulse timing synchronized with the leading pulse.

2. The maximum welding speed to assure sound weld beads varied from 2 to 3 m/min in the use of four variations of the two wires configuration made along the welding direction, which was 60 to 150 % higher than that with the single wire pulsed GMA welding process. Especially the configurations Types 3 and 4, in which the trailing wire was set at a push angle, has been shown to contribute to a great improvement in welding speeds, resulting in a 3m/min maximum welding speed for obtaining sound weld beads.
3. When the welding speed was 3 m/min, sound weld beads with uniform width were obtained with the trailing wire set at 9-degree push angle regardless of the inclination angle of the leading wire. This is presumably because the push angle of the trailing wire caused an arc force component towards the welding direction to prevent a large volume of molten metal from flowing backwards irregularly from the weld pool, thereby facilitating high speed welding.
4. The inter-wire distance greatly affected the weld bead formation in high speed welding. That is, the maximum welding speed was improved with the proper inter-wire distance in the range 9 to 12 mm.
5. The welding current ratio between the trailing and leading arcs I_T/I_L greatly affected the maximum welding speed. That is, in order to improve the maximum welding speed to obtain sound weld beads in high speed welding, the welding current ratio had to be set in the proper range. In the proper range of welding current ratio, I_T/I_L=0.31 to 0.5, the maximum welding speed achieved 4 to 4.5 m/min, which was 275% higher at the maximum when compared with single wire pulsed GMA welding (at a maximum welding speed of 1.2 m/min).

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