SPATTER AND FUME REDUCTION IN CO_2 GAS-SHIELDED ARC WELDING BY REGULATED GLOBULAR TRANSFER

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ABSTRACT

The CO_2 gas-shielded arc welding process with solid wire is widely used in Japan due to its good weld quality, high efficiency and reasonable wire and shielding gas costs. However, this process has its drawbacks, especially in the globular transfer mode at a high welding current, where significant amounts of spatter and fume are generated. To solve this problem, the author has investigated how to control globular transfer with a special pulsed current and has developed a regulated method and power source for practical use. The present report discusses the mechanism of this new method of regulating the globular transfer of molten droplets, in which each droplet is squeezed at its upper part in peak current duration and is detached silently in base current duration. Also various effects are reported concerning this new method and its application in the welding robot system for fabricating steel frames for buildings.

__IIW-Thesaurus keywords__: CO_2; Controls; Fume; Gas shielded arc welding; Globular transfer; Spatter, Waveform.

1 Introduction

The conventional CO_2 gas-shielded arc welding process (hereafter, the conventional process) offers high welding efficiency and cost-effective performance since it does not need very expensive shielding gas such as argon; for this reason, this process is widely used in Japan [1]. However, it has the drawback of generating a large amount of spatter. To reduce this, there has been a great deal of research and development [2-4], and as a result, a reduction of spatter in a low-current short-circuit transfer mode to a low level equivalent to that in Ar-rich-gas-mixture shielded arc welding has been realized. Among these low-current short-circuit transfer processes, the cold metal transfer (CMT) method especially realizes spatter-free welding by retracting the welding wire when the short circuit occurs, thus mechanically releasing the short circuit, and by controlling the low welding current [4]. On the other hand, in the pulsed MAG/MIG welding method, Ar-rich-gas is used. A rectangular pulse current waveform synchronizes one droplet per pulse and the transfer mode becomes possible, resulting in significant spatter and fume reduction [5-6].

However, when CO_2 gas-shielded arc welding uses higher currents, the metal transfer mode becomes globular in which large metal droplets irregularly transfer, causing a significant increase in spatter. Since these droplets show complicated and extremely unstable behaviour in this high current range, the metal transfer control has been thought to be difficult. Even today, 50 years after the CO_2 gas-shielded arc welding process was developed, no practical methodology for low spatter welding with a high-current globular-transfer mode has been developed.

To meet this challenge, the author has investigated the methodology of controlling the metal transfer by using pulsed currents and has successfully developed an advanced form of pure CO_2 gas-shielded arc welding process (hereafter, the advanced process), featuring low spatter and fume by realizing a regular formation and detachment of metal droplets. The present paper discusses the advantages of this advanced process, featuring a regulated globular transfer and reports on its typical performances, applied in the welding robot system for steel frames for buildings.

2 Experimental method

The experimental apparatus is schematically shown in Figure 1. In this apparatus, a welding current with an intended waveform can be generated by applying an arbitrary 0-10 V input signal (DC, CW from function generator into the transistor generated regulated power source). The external characteristic of the power source was set up in a constant current mode and the DCEP polarity was used. The wire feed speed was controlled by a feeding system

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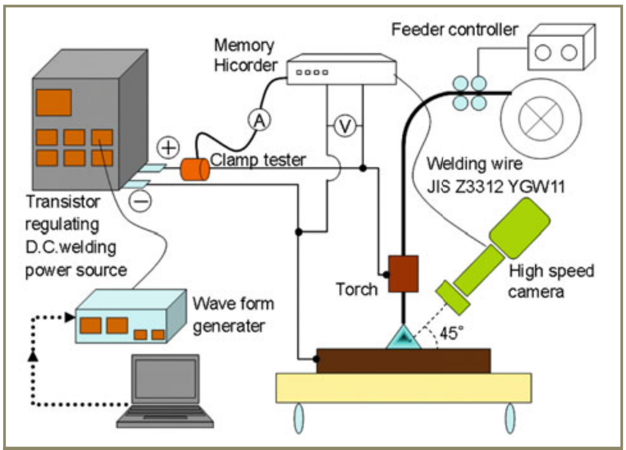


Figure 1 – Schematic diagram of experimental apparatus

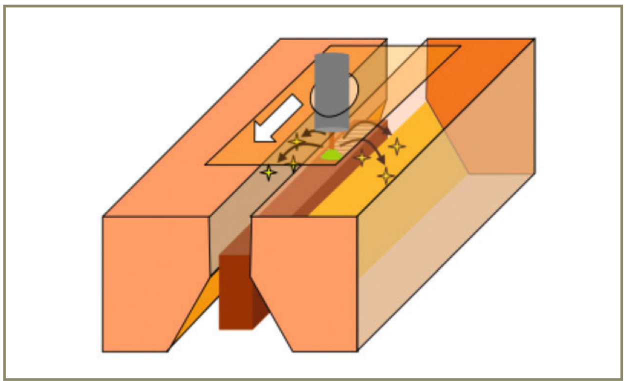


Figure 2 – Schematic diagram of spatter collecting system

independent of the power source. A 1.2 mm diameter solid wire corresponding to JIS (Japan Industry Standard) Z 3312 YGW11 was used for the welding wire, and pure CO_2 was used for the shielding gas (gas flow rate 25 l/min). JIS SM490A steel plates were used for the base metal. The welding speed was 5 mm/s, and the contact tip to base metal distance was 25 mm.

The spatter collecting system is schematically shown in Figure 2. Spatter was collected by conducting the experiments in a copper box so that all spatter generated was captured. Measurements were repeated three times under the same conditions. Inverter controlled DC welding power source (made by DAIHEN Co.) was used for the conventional process.

Fume emission rates were measured by means of the suction method using the air sampler in compliance with JIS Z 3930. In the fume collecting chamber ,shown in Figure 3, bead-on-plate welding was performed for 30 s, then fumes emitted were collected by the air sampler (suction rate: 1.8 m^3/min) for 3 min (sufficient duration after which no residual fume was recognized in the chamber) on the filter (made by Gelman Science Co.). The filter was weighed before and after use to obtain the fume emission rate per unit time (mg/min). At the same time, the melting rate of wire was measured to obtain the fume emission rate per unit weight of wire (mg/g). Measurements were repeated three times under the same conditions.

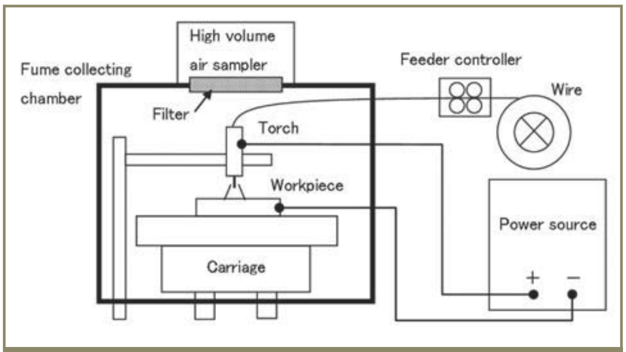


Figure 3 – Schematic diagram of fume collecting system

3 Features of the advanced process

3.1 Regulated globular transfer

With a high-current globular-transfer mode in CO_2 gas-shielded arc welding, the arc is constricted by a thermal pinching force. This force concentrates at the lower part of the metal droplet, causing the arc force to repel it upwards, so becoming larger with time; hence the large droplet detaches from the wire tip and repulses against the repelling force of the arc. Figure 4 shows an example of spatter generation behaviour in the conventional process. The globular transfer phenomenon was observed by a high-speed camera, and as a result, it has been found that spatter generation mechanisms in conventional CO_2 gas-shielded arc welding can roughly be classified into the following three patterns:

1. The metal droplet and part of the weld pool are blown off at the moment of arc re-ignition, just after the metal droplet short-circuits with the weld pool - Figure 5 a).
2. The large metal droplet detaches itself as it is repelled upwards by the force of the arc, and scatters in rotation - Figure 5 b).
3. As soon as the droplet detaches itself, the arc moves from the lower part of the droplet to the wire tip, and, in turn, the high current arc blows off the molten metal, still remaining on the wire.

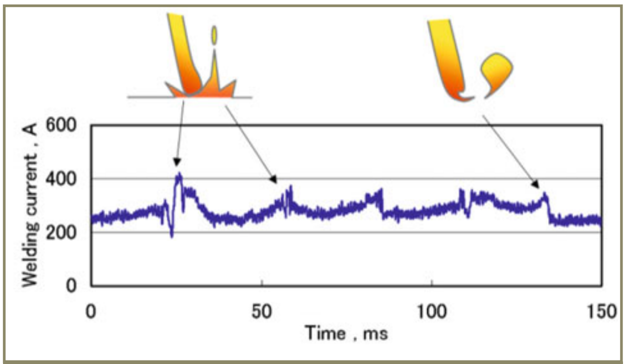
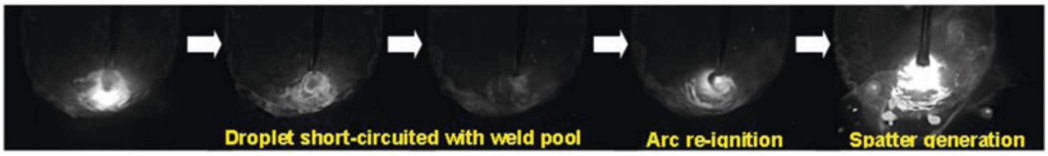
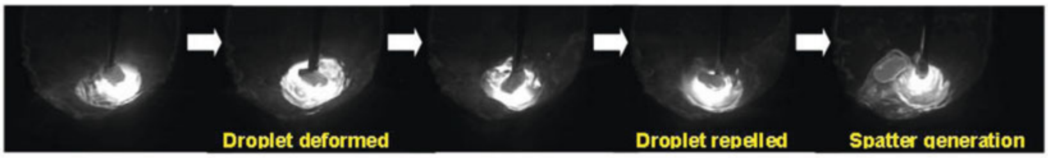


Figure 4 – Example of spatter generation behaviour in the conventional process



a) Spatter generation induced by a short-circuited metal droplet



b) Spatter generation induced by a metal droplet repelled upwards

Figure 5 – Spatter generation in the conventional CO$_2$ gas-shielded arc welding

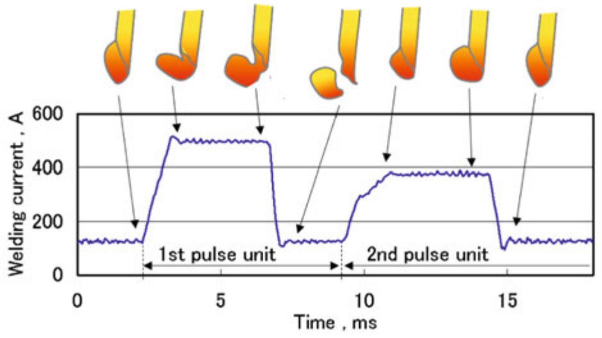


Figure 6 – Example of droplet transfer behaviour in the advanced process

For spatter reduction, these phenomena suggest that metal droplets need to be prevented from short-circuiting and being repelled and deformed excessively. Also, the welding current should be lower at the moment of metal detachment. Figure 6 shows an example of droplet transfer behaviour in the advanced process. This metal transfer phenomenon is different from the one droplet per pulse transfer mode of pulsed MAG/MIG welding. The droplet's upper part squeeze regularly only in the 1st pulse unit of higher pulse, and the droplet detaches at a low current in the base period of the 1st pulse unit. After detachment, the wire is melted continuously and large molten droplet is formed at the end of the wire. This droplet is pushed up along the wire due to the strong arc force in the pulse peak period of the 2nd pulse unit, but in the base period of the 2nd pulse unit, it begins to slide downward due to the decrease of arc force and it is hung on the wire end. As restarting the 1st pulse unit, it rapidly squeezes and detaches from the wire and is transferred to the pool. This is the one droplet per one cycle of two pulses transfer mode. The metal transfer phenomenon in the advanced process is shown in Figure 7. After the metal droplet is formed, its upper part is squeezed by the pulse peak current of 1st pulse unit, and is detached at a low current in the base period of the 1st pulse unit. Thereby, this detached droplet is absorbed silently into the weld pool, while, at the same time, the low current arc moves from the metal droplet to the wire tip during the base period, which greatly reduces the blowing-off of the remaining molten metal on the wire tip. By optimizing the pulse current for each timing of droplet formation (2nd pulse unit parameter) and detachment (1st pulse unit parameter), the metal droplet can be controlled so as to transfer at a constant size regularly, thereby preventing its short-circuiting and deformation as shown in Figure 4.

Metal transfer frequencies in both the conventional and advanced processes are shown in Figure 8. The frequency in the former process varies greatly; by contrast, the advanced process exhibits greatly regulated and higher metal transfer frequencies. Clearly, in this process,

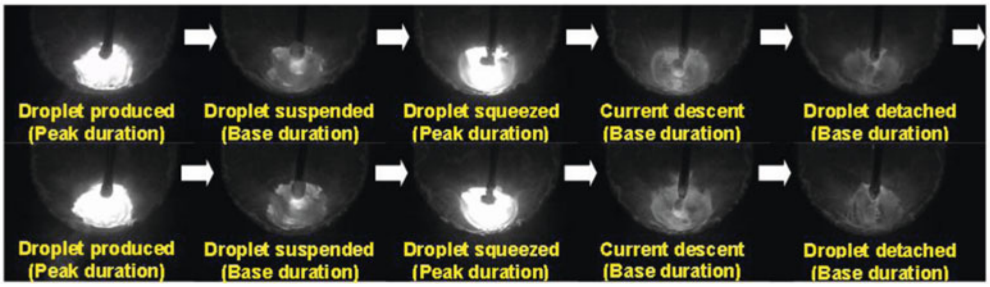


Figure 7 – Metal droplet transfer phenomenon in the advanced process

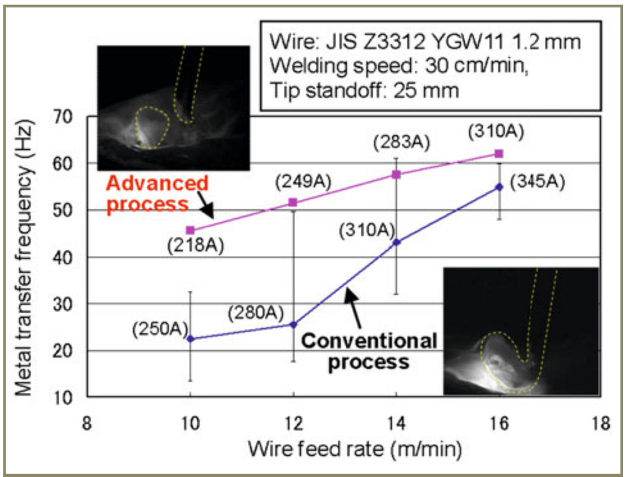


Figure 8 – Comparison of metal transfer frequencies

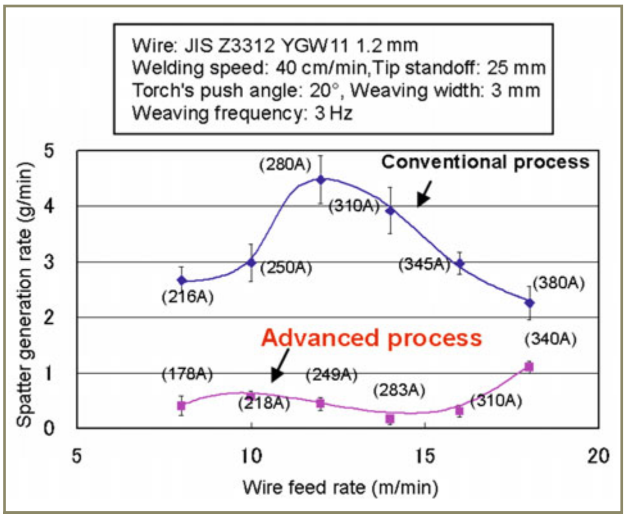
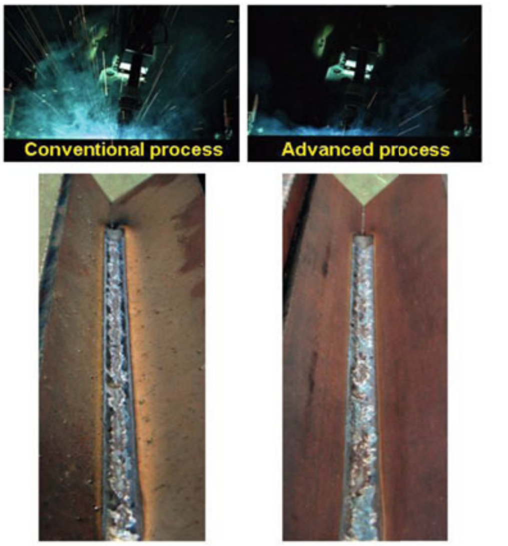


Figure 9 – Comparison of spatter generation rates in flat fillet welding



a) Conventional process b) Advanced process

(Wire feeding rate: 15 m/min).

Figure 10 – Comparison of spatter during and after welding

smaller metal droplets detach themselves, compared to the conventional process.

3.2 Reduction of the spatter generation rate

The spatter generation rate in flat fillet welding by both the conventional and advanced processes are shown in Figure 9. The globular transfer control in the latter process significantly reduces the spatter generation rate and, at a wire feeding rate of 12-16 m/min, it is decreased by 10 % as compared to the conventional process. Figure 10 compares the two welding processes on spatter generation during welding and on post-weld spatter adhesion on the welds. Obviously, in the conventional process, there is a large amount of spatter near the weld bead, whereas the advanced process produces a better-looking bead with less spatter adhesion.

3.3 Reduction of the fume emission rate

In recent years, manufacturing industries have shown a growing concern in occupational health and safety, and they have made intense efforts not only to maintain the employees' health and safety in the workplace, but also to provide more comfortable working environments. In the welding fabrication field in particular, there has been an increasing desire for fume and spatter reduction [1].

The main source of the fume is the metal vapour emitted from the surface of the metal droplets, superheated by the arc. The fume diffuses in the air due to the expansion of the surrounding gas associated with the droplets' short-circuiting and re-arcing [7-8]. Figure 11 shows the fume emission rates per unit wire weight in both conventional and advanced processes. This rate in the latter process decreases by 50 % in comparison to the conventional process, presumably due to the fact that short-circuiting rarely occurs, and the short metal transfer cycle reduces the time to heat the metal droplets as Figure 7.

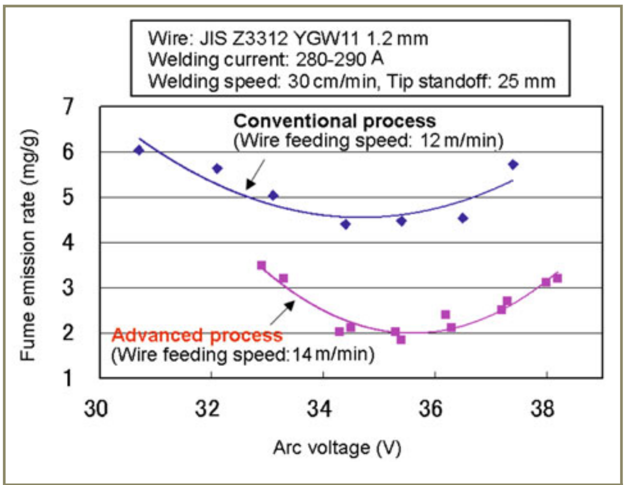


Figure 11 – Comparison of fume emission rates

3.4 Increase in the deposition rate or decrease in heat input

Figure 12 shows the relationship between the welding current and wire melting rate in both conventional and advanced processes. At the same mean current, this rate in the advanced process is approximately 10-20 % higher. Since it uses pulsed currents, the effective current becomes higher, thereby causing a higher Joule heat in the wire extension as compared with the conventional process, which is characterized by relatively small fluctuations of the current. This is the reason for the higher melting rate in the advanced process. Therefore, at the same mean current, this process can provide higher deposition rates and, in turn, welding efficiency is expected to improve. Conversely, at the same melting rate, the advanced process requires a 10-15 % lower mean current than with the conventional process. For example, when comparing a wire-melting rate of 15 m/min, the conventional process requires about 330 A, while the advanced process needs only about 290 A for melting the same amount of wire in the same amount of time. Therefore, for the same deposition rate, the advanced process can decrease heat input as shown in Figure 13 and hence, an improvement in weld metal mechanical properties and a reduction of weld distortion can be expected.

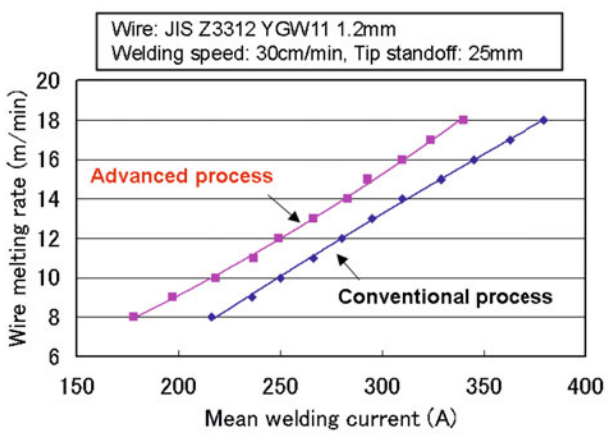


Figure 12 – Relationships between mean welding current and wire melting rate

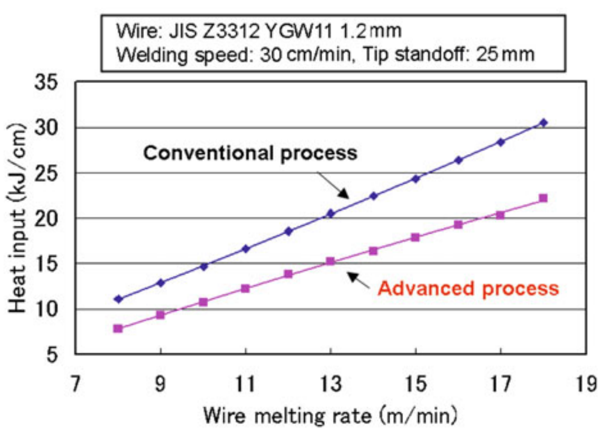
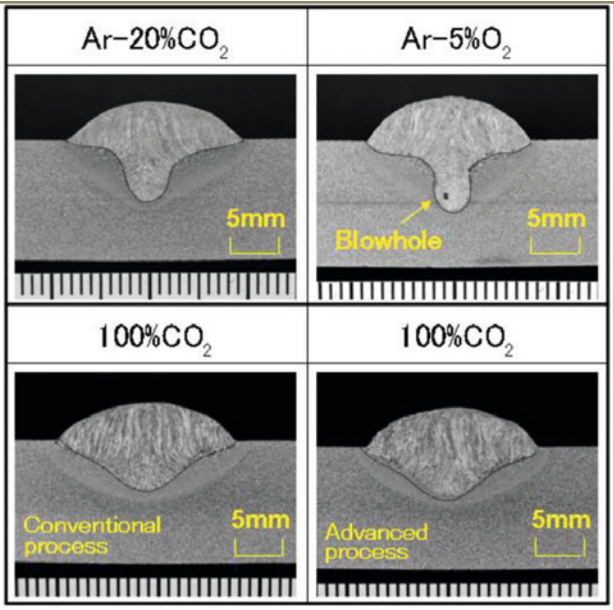


Figure 13 – Relationships between wire melting rate and heat input

3.5 Good penetration shape

The Ar-rich-gas-mixture shielded arc welding process is regarded as a low spatter welding process. With such a mixture, metal droplets are covered entirely by the arc and are transferred in a spray transfer mode; thus, spatter generation decreases compared with the conventional CO$_2$ gas-shielded arc welding process. However, the penetration contour tends to become "finger shaped," meaning relatively narrow with deep penetration at the bead centre immediately beneath the arc, which is caused by a strong plasma jet and high speed metal droplets plunging into the weld pool. Such a finger-shaped penetration tends to cause gas to be trapped at the bottom of the finger, producing blowholes, resulting in perhaps a lack of penetration and fusion in multi-pass groove welds. By contrast, in CO$_2$ gas-shielded arc welding, the weld penetration profile exhibits a bowl-shape form with broad and deep penetration, which is more resistant to weld defects. Figure 14 shows typical penetration profiles obtained with four different welding processes. Clearly, the advanced process produces a good penetration profile similar to that caused by the conventional CO$_2$ gas-shielded arc welding process, which as stated above is more resistant to weld defects.

Figure 15 compares penetration depths and cross-sectional area between the conventional and advanced processes. At the same mean current, a deeper weld penetration and larger area can be obtained in the latter process - Figures 15 a) and b). In contrast to this, at the same wire melting rate, the weld penetration in the advanced process tends to become slightly shallower as a lower mean current is required - Figure 15 c). As a result, the cross-sectional area decreases as well - Figure 15 d).



(Wire feeding rate: 13.2 m/min).

Figure 14 – Comparison of penetration profiles

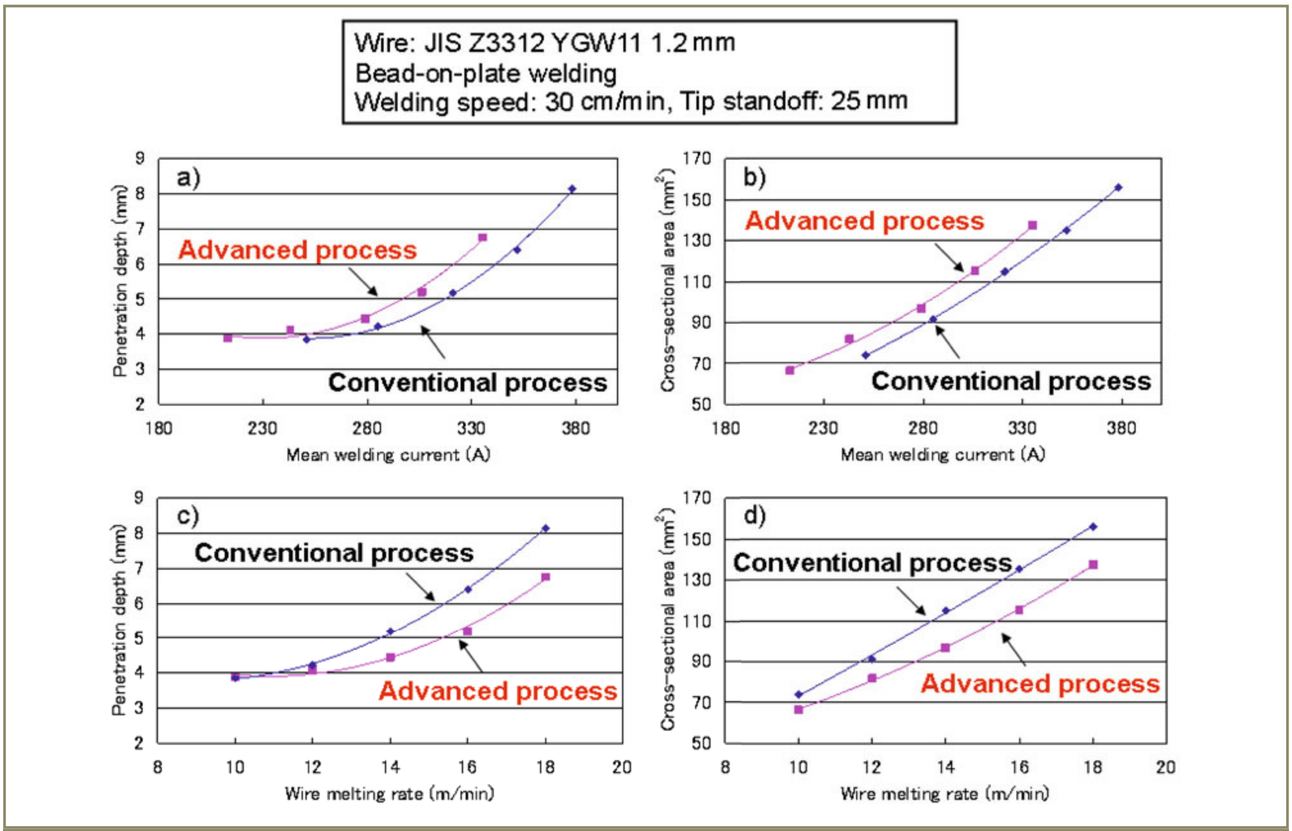


Figure 15 – Comparison of penetration depth and cross-sectional area

4 Application of the advanced process in the robot system for welding steel frames

Since the Hanshin-Awaji big earthquake of 1995 in Kobe, Japan, the construction and steel frame industries have been more strictly required to secure the mechanical properties of weld metal under the regulation of controlling heat input and interpass temperature [9]. These industries have also been required to improve their welding efficiency, while, at the same time, suffering from a shortage of skilled workers. In such a situation, welding robot systems for steel frames have increasingly become popular over the last few years in Japan. The CO$_2$ gas-shielded arc welding process is used extensively in these construction and steel frame industries, though, as mentioned above, it tends to generate a large amount of spatter. If the welding process uses a shielding gas nozzle, which becomes clogged with a large amount of spatter, it may cause insufficient shielding (nitrogen contamination), which may ultimately degrade the mechanical properties of the weld metal and hence, cause weld defects such as blowholes. To prevent these problems occurring during continuous operations over a long period of time, automatic nozzle cleaning or replacement is carried out. However, when this procedure is repeated frequently, the arcing-time ratio decreases in robotic welding employed to improve welding efficiency. Spatter particles adhered on the base metal also cause a decrease in welding efficiency because of a longer post-weld cleaning time required to remove them.

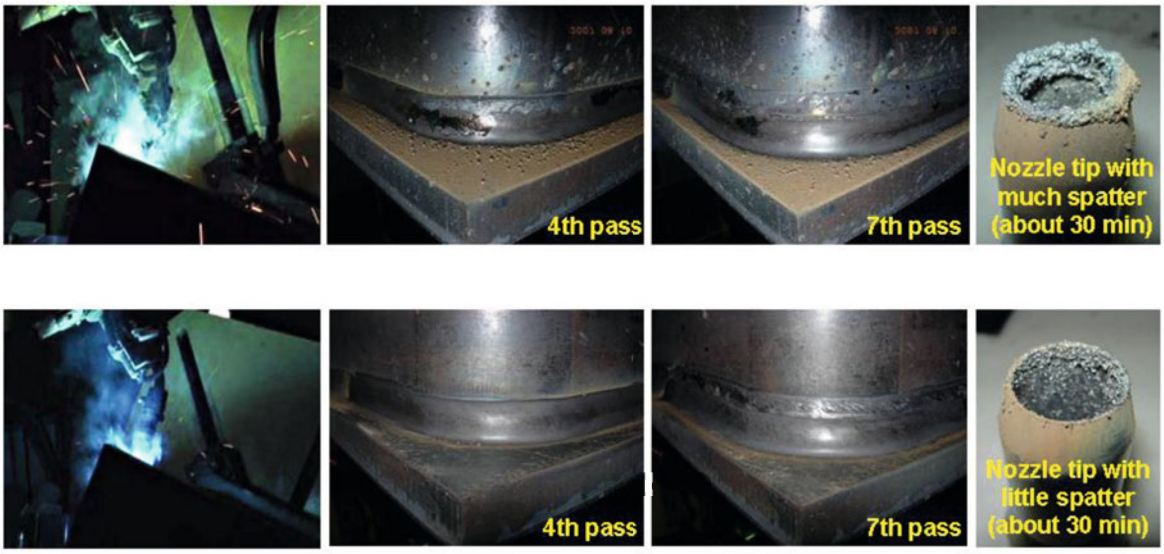
To improve this situation with the pure CO$_2$ gas-shielded arc welding process, the author has developed a new robot system equipped with an advanced process for welding steel frames for buildings. The typical welding performances with this new robotic system are discussed below. Table 1 shows an example of operating conditions by both the conventional and advanced processes for welding steel frames.

Figure 16 shows spatter generation during welding and spatter adhesion on the work and the nozzle in the welding of a steel core. Obviously, the new robotic system with this advanced process markedly decreases the spatter scattered in the surrounding area when compared to that used in the conventional process. The spatter adhering around the weld bead also decreased; thus, post-weld cleaning is expected to be reduced. Furthermore, in comparison to the shielding gas nozzles after welding (for about 30 min of arc time), the advanced process results in less spatter adhesion in the nozzle. This can decrease the risk of degrading the weld metal mechanical properties and the occurrence of such weld defects as blowholes caused by a lack of shielding (nitrogen contamination). Also, the frequency of cleaning or replacing the nozzle can be reduced,

Table 1 – Example of operating conditions for welding steel frames by the Welding Robot System

Pass N°	Wire feed rate [m/min]	Welding speed [cm/min]	Conventional process		Advanced process	
			Current [A]	Voltage [V]	Current [A]	Voltage [V]
1	14.0	30	310	34.5	283	34.5
2	16.0	25	345	37.0	310	35.7
3	16.0	25	345	37.0	310	35.7
4	16.0	25	345	37.0	310	35.7
5	14.5	32	320	35.0	287	35.1
6	12.8	27	295	32.8	266	33.6
7	12.2	30	280	31.8	250	32.6

(BCP325, 22 mm thickness × 350 square, 35° single bevel groove, 7 mm gap).

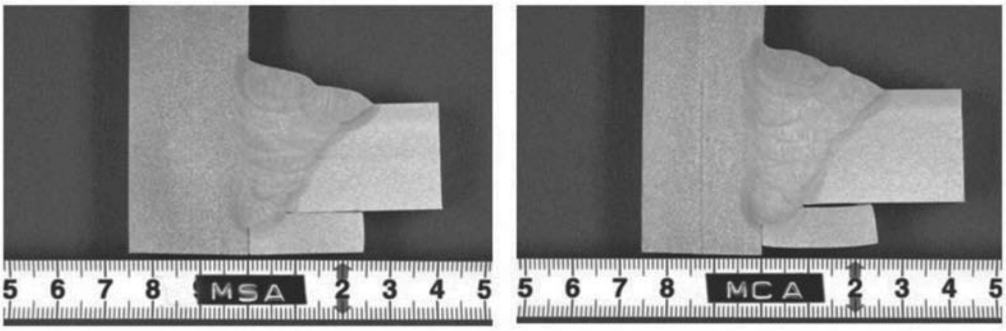


b) Advanced process

(BCP325, 22 mm thickness × 350 square, 35° single bevel groove, 7 mm gap)

Figure 16 – Views of spatter during and after welding by the welding robot system for welding steel frames

thereby shortening the operation time. For example, in the welding of a column of 22 mm thickness × 400 mm square, the operation time can decrease by about 10 %, due to the shortening of the arc time and nozzle cleaning time. In addition, consistent joint penetration can be obtained as shown in Figure 17. Typical mechanical properties of the weld metal by the advanced process are shown in Table 2.



a) Straight weld

b) Corner weld

Figure 17 – Cross-sectional macrostructures of core welds by the Welding Robot System with the advanced process for welding steel frames

Table 2 – Typical mechanical properties of weld metal

0.2 % proof strength [MPa]	Tensile strength [MPa]	Elongation [%]	Reduction in area [%]	Impact absorbed energy, vE0°C [J]
534	635	31	73	150,149,148 Average 149

- Welding process: the advanced process.
- Welding groove: 35° single bevel with a gap of 7 mm; - Plate thickness: 25 mm.
- Pass sequence: 5 layers with 6 passes; - Heat input: 30 kJ/cm; - Interpass temperature.: 250°C.

5 Conclusion

The authors have optimized the pulse current for each timing of droplet formation (2nd pulse unit parameter) and detachment (1st pulse unit parameter). Consequently, it has been clarified that the metal droplet can be controlled so as to transfer regularly with a constant size in a globular mode, thereby preventing its short-circuiting and deformation. As a result, the advanced process can provide lower spatter and fume, higher welding efficiency and better weld quality in the robotic welding of mid to thick plates. Also, it can contribute to cost-saving by using a cheaper CO_2 shielding gas instead of expensive Ar-rich gas mixtures. However, at the same wire melting rate, the weld penetration in the advanced process tends to become slightly shallower.

By optimizing the chemical composition of welding wires (mild steel and high tensile steel), and power source waveform control, the authors will be engaged in further research with respect to effect of pulse parameter on globular transfer behaviour, and development of higher weld quality, lower production costs, and less spatter and fume for better welding work environments, so that the advanced process can be used in wider applications in the future.

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