TRENDS IN DEVELOPMENTS IN GAS SHIELDED ARC WELDING EQUIPMENT IN JAPAN

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In the welding field in Japan, new technologies and processes have been developed one after another in response to the improvement in materials and the changes in the market needs, which have remarkably been contributing to rationalization and cost reduction in various industries. Taking into account the abovementioned technological trends, this paper provides an overview of the present situation of technological developments in terms of gas shielded arc welding equipment. 16 Ref., 2 Tables, 10 Figures.

Keywords: *trends, technology, welding equipment development, MAG, MIG, TIG welding*

It has passed one century with the arc welding technology since 1904 when Oskar Kjellberg, a shipbuilding engineer in Sweden, developed and practiced the shielded metal arc welding process. The shielded metal arc welding process was introduced in shipyards in Japan about ten years later than that time, and in the 1920s, the first domestic DC arc-welding machine was born. Afterwards, the submerged arc welding process and the gas shielded arc welding processes such as TIG and MIG were developed and practiced one after another in Europe and the United States from the 1930s to 1940s. These welding processes were introduced in Japan, too, nearly ten years later after the employment in the Western countries.

In the early 1950s, the submerged arc welding machine was developed with the domestic technologies. Since then, the performance and quality of the domestic arc-welding equipment have earned a giant leap in tandem with the advancement of the heavy industries such mainly as shipbuilders and bridge fabricators. This became the trigger of shifting the main usage of the Western-made arc welding machines to the Japanese-made ones in fabrication sites. In the 1970s, the traditional major processes of submerged arc welding and shielded metal arc welding were superseded gradually by GMA welding, mainly CO_2 arc welding and MIG welding. This has urged the development of GMA welding equipment. The 1980s was special in that the articulated arc-welding robot became popular and the welding power source of the transistor-inverter controlled type was developed, and thereby the arc welding equipment was improved associated with the advancements in the power electronics; as a result, the technical development for higher efficiency and automatization in welding has been progressed until today.

This paper reports the performances and functions of the welding equipment developed in the last ten years aiming at the achievement of high-quality or high-efficiency in GMA welding.

The history of development of the GMA welding power source in Japan. *The trend and growth of the output control method for the GMA welding power source*. Figure 1 shows a summary of the trend and growth of the output control method for the welding power source for GMA welding in Japan for the last 30 years.

Though the step or slide-transform control type has decreased in the production quantity ratio, it is still used steadily at a ratio of about 5 %, mainly in the sheet-metal welding workshop. The thyristor control type, which was dominant for the output control method till the 1970s, is still used mainly in the fabrication sites for medium/thick plate welding constructions in shipbuilders and building constructors, with a volume ratio of around 20 %. Since the welding power source of the inverter control type with power transistor was developed in the early 1980s, the production volume ratio rapidly expanded by the early 1990s. In the latter half of the 1990s, developed was the digital inverter control type, which features the inverter for controlling the output and the software for controlling the welding current and voltage waveforms to govern the welding performance and function. This control type has earned a rapid growth of use since the 2000s, reaching a quantity ratio of nearly 70 % today.

Trends in the technology development for GMA welding power source. Figure 2 shows a

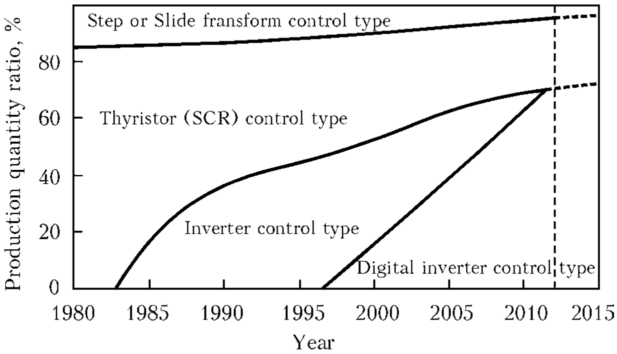


Figure 1. Change in spread of power source control type in Japan

summary of the recent trends in the development of the major control technologies for the arc welding power source [1]. The thyristor-controlled power source was developed in 1969, which led the development of the welding sequential control and the unified control for improved performance. The low-frequency pulse control and the medium-frequency pulse control with a fixed pulse frequency were also practiced.

The pulse power source with the synergic pulse process on board was developed in 1980 and was marketed as the welding power source equipped with the world's first, general-purpose, low-priced transistor for the output control by the transistor chopper. This type of power source became the prototype of the present pulse MAG/MIG welding power source. However, in 1983 after three years, the practice of the inverter-controlled welding power source highly expanded, resulting in the development of the pulse MAG/MIG welding power source of the inverter control type that featured high-speed output control. This development caused the pulse MAG/MIG welding power source of the transistor-chopper control type to become disused shortly.

Afterwards, all the advancements in the welding power source were based on the inverter control type. In 1990, the high-function/performance welding power source that was combined with the microcomputer control was developed [2, 3]. In 1992, the intelligent welding power source with the fuzzy control on board was developed [4, 5].

At the end of the 20th century, it was started to apply highly the digital control to the welding power source, with the background of advancement in the digital control technology; i.e., the majority of the control circuits were engineered to change the analog control to the digital control to improve the reproducibility of welding conditions [6]. Recently, it has actively been promoted to increase the output control speed by using the high-speed control element; as a result, the high-performance welding power source, that can control the welding and arc phenomena in almost the ideal modes, has also been marketed [7].

Table 1 shows a summary of the performances of the microprocessors applied to the welding power sources of the digital inverter-control type. In 1996, the digital control (with software) was employed for all the controls of the welding current and voltage waveforms to regulate the arc welding process [8]. At that time, 16-bit microprocessor was used to enable a single-chip micro-

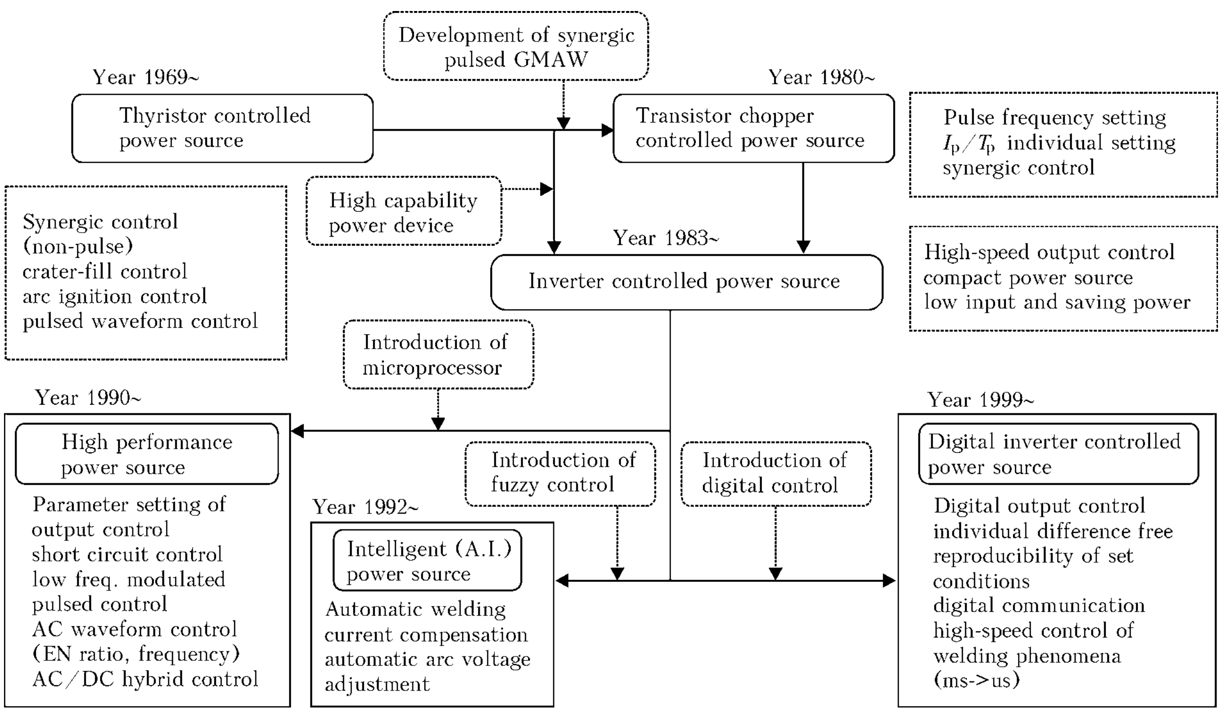
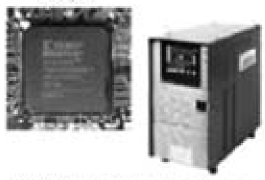


Figure 2. Trends in developments of main control technology for arc welding power source

Table 1. Change in micro processor and welding power source

	The first generation 1996-2000	The second generation 2001-	The third generation 2008-	The fourth generation 2010-
Power source			FPGA  FPGA: all-purpose LSI, in which plural DSP and CPU are assembled in 1 chip.	ASIC   ASIC: LSI optimum for welding control, in which plural DSP, CPU and analog circuit are assembled in 1 chip.
Micro processor	16 bit	32 bit/DSP	FPGA	ASIC
Processing cycle	100 ms	25 ms	1ms	20 ns
Processing capability	1	4	16	64

DSP: Digital signal processor
FPGA: Field progrfmmable gate array
ASIC: Application specific integrated circuit

computer to execute multiple controls, including the optimizing control of pulse parameters and the fuzzy control for automatic adjustment of welding current and voltage, thereby eliminating the need of individual logic circuits. In 2000, 32-bit microprocessor, which features the two times or higher control frequency and 4–8 times capacity as compared to the conventional type, began to be applied. With respect to the control speed, the digital signal processor (DSP) that enables the direct control with software has provided the fast-acting output control by inverter [9]. Lately, the field programmable gate array (FPGA) with a highly-integrated circuit that unifies 32-bit microcomputer and DSP has been employed in the welding power source, and thereby the control speed and program capacity have been improved by 1- or 2-digit magnitude as compared to those used in ten years ago. These microprocessors used in the welding power source are commercial ones. In order to realize a high-dimensional welding control, the authors have developed the special welding-control microprocessor called welding best electronic engine (Welbee), the single-purpose LSI for the welding control, which is the unique fourth-generation engine dedicated to the welding and inverter controls [10]. By using the Welbee, the operation processing rate can be increased from a conventional micro-order level to a nano-order level, and thereby the control performance of the welding power source can be improved by 64 times higher than that of the first-generation welding power source. This high performance has enabled to sample the welding current and voltage at a super-high speed and thus to monitor/control the complex arc phenomena that could not necessarily be controlled by conventional power sources due to insufficient operation-processing rates.

Digital control methods for the welding current waveform and their performances. *Development of spatter reduction GMA welding process*. The several methods for reducing spatter, typically the controlled bridge transfer (CBT) method [11] that feature less spattering in the short-circuiting current range (up to around 150–180 A) in CO_2 arc welding have been suggested and realized for the low-spatter welding process. On the other hand, from the viewpoint of higher welding efficiency, the low-spatter performance is required also in the globular-transfer current range where the metal transfer is prone to become irregular and unstable. However, the spatter performance of the conventional welding power sources was not enough in the globular-transfer current range (over 200 A).

As shown in Figure 3, in the use of the welding power source equipped with the dedicated welding microprocessor of Welbee, the superimposed pulse current waveform, which consists of periodical changes, is applied immediately after the re-arcing from short-circuiting to regulate the metal transfer. Additionally, the welding current is controlled to be nearly tens of amperes at the moment of shifting from short-circuiting to arcing by means of the high-speed operation processing of the algorithm for detecting the weld pool condition in the last stage of the short-circuiting. The development of this technology for

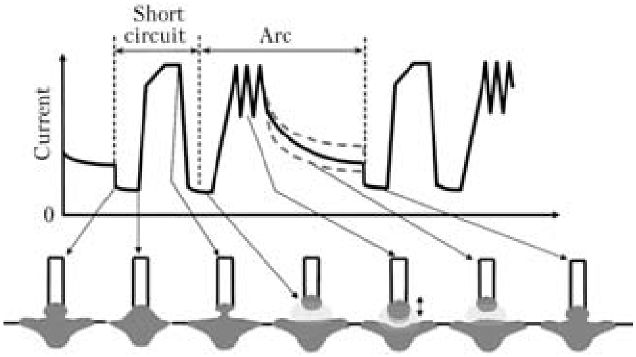


Figure 3. Controlled bridge transfer expanded (CBT expanded) process

controlling the welding current waveform has enabled to reduce spatter even in the current range over 200 A.

Figure 4 shows a comparison of the amounts of spatter in CO_2 arc welding with a Welbee-installed welding power source and a conventional welding power source. The right part of the figure shows typical spattering views and the relative amounts of spatter. In the condition where the amount of spatter is 0.5 g/min or less, only minute particles of spatter are observed. In the condition where the amount of spatter is 1.0 g/min or larger, a mixture of coarse and minute particles of spatter can be observed.

Control for stabilizing the metal transfer in pulsed GMA welding. Table 2 shows examples of the welding-current-waveform control in pulsed GMA welding that have recently been developed by applying the digital control technology [12].

In the pulsed GMA welding of mild steel, the common shielding gas used is an Ar–CO_2 mixture with 20 % CO_2. On the other hand, the CO_2 ratio in the shielding gas mixture often changes depending on the mixing mechanism and the performance of the mixer in cases where the shielding gas is supplied to the welding process line via a concentrated piping system in the workshop. It is known that the metal transfer becomes unstable when the CO_2 ratio exceeds 20 % in the shielding gas, and thereby the one-droplet per pulse transfer becomes impossible to achieve.

With the newly developed pulse-current waveform control, the initial value of a pulsed current is set to be higher than the proper value for 80 % Ar + 20 % CO_2, in order to enhance the constriction of a droplet for detaching from the wire tip even when the CO_2 mixing ratio becomes higher up to 30 %. This control method also features the two-step pulse waveform, which reduces the pulse current to prevent the droplet from becoming larger excessively while maintaining the electromagnetic pinching force to detach the molten droplet formed at the initial stage of the process. In the process of lowering the pulse current to the base current, it is reduced exponentially, not linearly, in order to maintain the electromagnetic pinching force immediately before detaching the molten droplet. Consequently, this process assures a steady metal transfer while preventing the generation of minute particles of spatter that is caused by the residue of molten droplet flown apart from the wire tip as the result of an excessive energy accompanied by the detachment of the droplet.

In the pulsed GMA welding, stainless steel requires the shielding gas with a higher ratio of Ar as compared with mild steel; in general, oxidized gas (O_2 or CO_2) is added at several percent to improve the arc stability. However, even if an Ar-rich shielding gas is used, a stable metal-transfer arc may not be obtained in the pulsed GMA welding of stainless steel because the high viscosity or surface tension of the molten droplet makes it difficult to detach the droplet from the wire tip. With the newly-developed current waveform control, the initial rising rate of a pulsed current is designed to be high so that the electromagnetic pinch force can firmly work on the molten droplet at the initial rise of pulsed current. Additionally, to cope with a lack of electromagnetic pinch force while a pulse current is applied, the pulse current is designed to increase

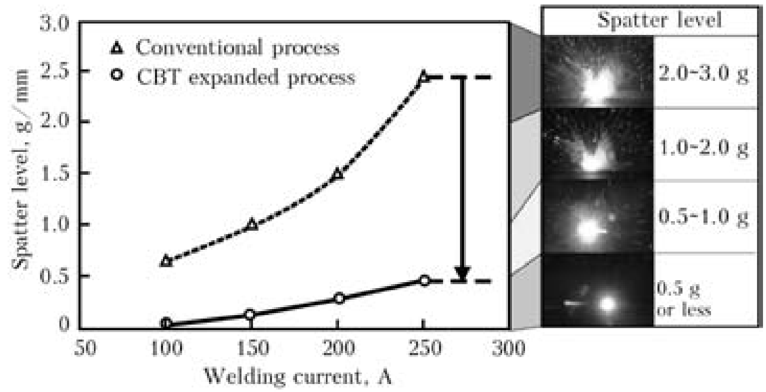
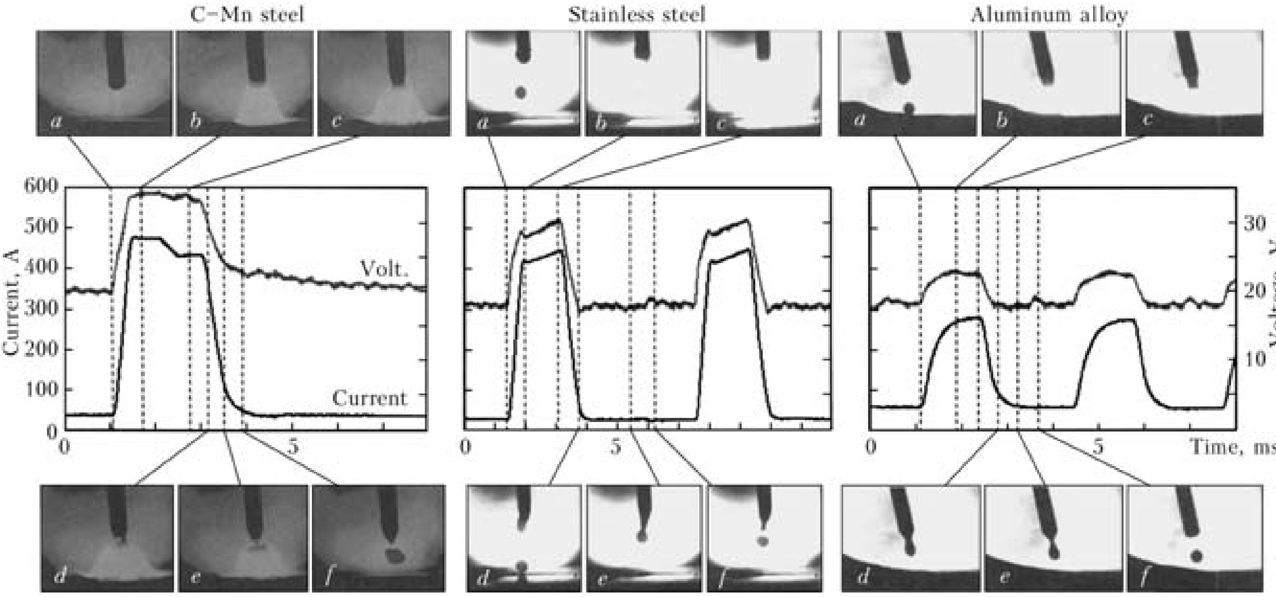


Figure 4. Comparison of spatter level

Table 2. Pulsed wave form type and their metal transfer



gradually after reaching the pulse current, thereby ensuring the sufficient electromagnetic pinch force in accord with the timing of detaching the molten droplet. The process of reducing the pulse current to the base current is the same as the pulse waveform for the pulsed GMA welding of mild steel; i.e., the pulse current is decreased exponentially to prevent the generation of minute-particle spatter caused by the residue of molten droplet flown apart from the wire tip, thereby achieving a steady metal transfer.

In the pulsed GMA welding of aluminum and its alloys, the pulsed-current waveform control must be executed in consideration of the properties that the melting point, viscosity and surface tension of the wire are lower than those of steel wire. Especially, if an excessive pulse peak current is energized to the wire, minute particles of spatter may be generated when the molten droplet detaches from the wire. To solve this problem, the lately-developed current waveform control features the exponentially ascending or descending curves for the rising or falling current waveform between the peak current and the base current. This technology prevents the generation of minute-particle spatter when the molten droplet detaches, thereby obtaining a stable one-pulse one-droplet transfer.

Pulsed GMA welding process with superimposed low-frequency pulse. In 1990, the pulsed GMA welding process with superimposed low-frequency pulse was developed for aluminum and its alloys [13]. In this process, the arc condition is changed cyclically by controlling the output current and voltage with the welding current waveform that features the low-frequency pulse superimposed, for reflecting the vibration of the weld pool, on the medium frequency pulse that controls the metal transfer under a constant wire feed rate.

With this advanced technology, the authors have made suggestions for realizing the GMA weld beads with the regular ripple pattern like TIG weld beads, and for using the weld pool vibration to refine crystal grains and to reduce the susceptibility to solidification cracking [14] as well as to prevent blowholes [15].

However, with mild steel and stainless steel whose melting points are higher, the change in the arc phenomena is not as cyclical as observed with aluminum alloys; thus, the above-mentioned effects could not be achieved.

To overcome this problem, the new pulsed MAG/MIG welding process with superimposed low-frequency pulse has been developed, with which the wire feed speed can be synchronized with the current waveform control, as shown in Figure 5. With this advanced process, the output can dynamically be changed at a low frequency of 5 Hz max for mild steel and stainless steel, and thereby it has become possible to change significantly the arc pressure and wire melting rate.

With this advanced process, a molten pool can cyclically be vibrated. This function enables to remove zinc vapor from the molten pool in the welding of galvanized steel plates, thereby reducing the occurrence of blowholes and pits in the weld metal.

Development of AC-pulsed GMA welding process. Depending on the type of welding structure, some of the welding joints, may be difficult to weld because the root gap is required to be

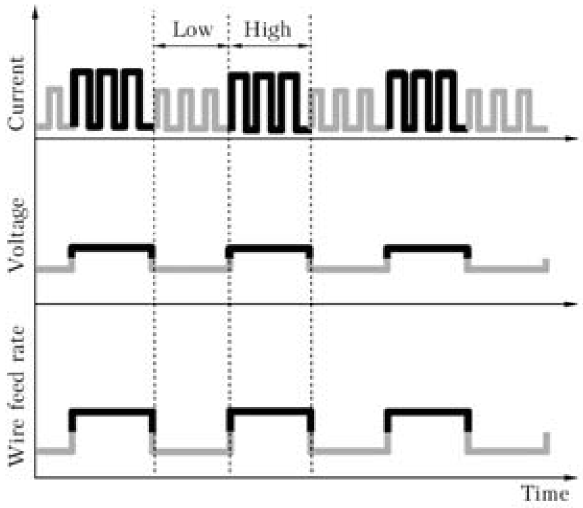


Figure 5. Low-frequency modulated pulsed GMA process

filled with deposited metal even though the base metal's thermal capacity is small. In the automatic welding of such particular joints, the use of low welding current can prevent burn-through that is caused by excessive heat input; however, it will become difficult to bridge the root gap with deposited metal. Conversely, if the welding current is increased to fill the root gap with deposited metal, excessive heat input may cause burn-through. This problem can be attributed to the nature of the common DC GMA welding process in which the welding current is related directly to the wire melting rate. Therefore, it is significantly difficult to set the proper welding condition in the welding by robots and automatic machines. Even if the proper condition could be set up, it would become difficult to maintain/control that condition due to less robustness.

The AC-pulsed GMA welding process is one of the processes that can solve such welding problems.

Figure 6 shows a welding current waveform in AC-pulsed GMA welding.

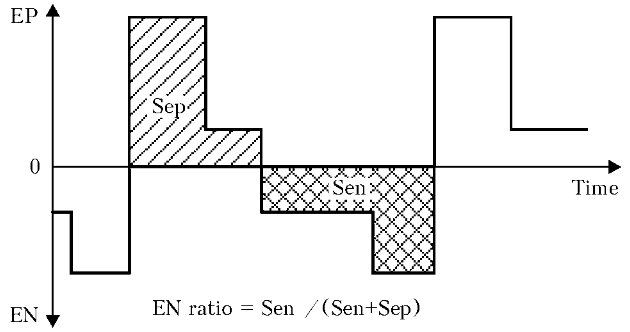


Figure 6. AC pulsed GMA waveform

In AC-pulsed GMA welding, the ratio of EN polarity current to the average welding current in one pulse cycle is called the EN ratio [16] which can be defined by the equation shown in the figure: EN ratio = Sen/(Sen + Sep).

Figure 7 shows the relation between welding current and wire feed speed as a function of the EN ratio in the use of Al–Mg alloy wire and mild steel wire with a wire diameter of 1.2 mm. As shown in these figures, setting an EN ratio can determine the melting characteristic curve for a particular wire in relation to the melting rate vs. welding current in AC-pulsed GMA welding. Specifically, when comparing the EN ratios at the same welding current, the wire melting rate becomes faster with a higher EN ratio, and slower with a lower EN ratio.

When the wire melting rate is kept constant, a change in the EN ratio affects the welding current; i.e., the welding current decreases with a higher EN ratio, and increases with a lower EN ratio.

Due to these characteristics, changing the EN ratio affects the cross-sectional contour of a weld bead in AC-pulsed GMA welding as shown in Figure 8; i.e., with an increase in the EN ratio, the bead width and penetration decrease, and weld reinforcement increases. This specific feature of the AC-pulsed GMA welding process is

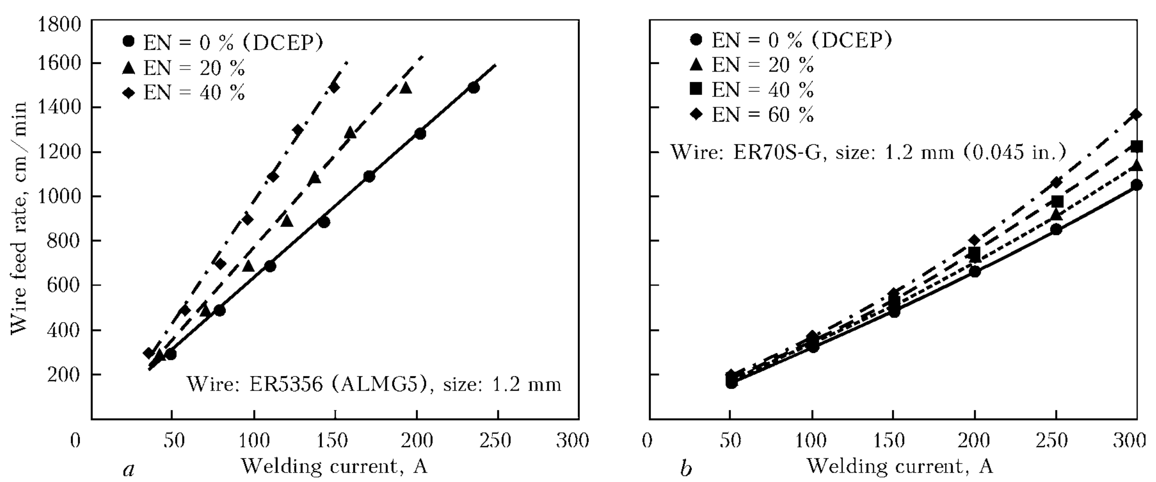


Figure 7. Wire melting characteristic: *a* — aluminium alloy wire; *b* — mild steel wire

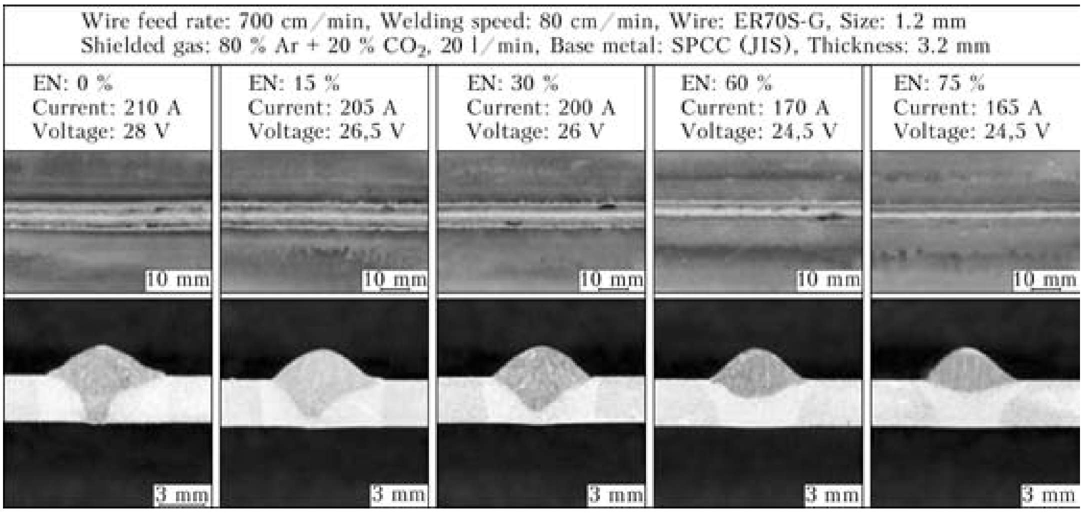


Figure 8. Effect of EN ratio on bead formation

useful in the welding of a welding joint having an excessive gap.

Cold tandem GMA welding. Figure 9 shows the principles of the cold tandem GMA welding process. Specifically, a couple of wires are aligned in tandem along the welding line, and while the leading wire generates a pulse arc, the trailing wire that is not energized is fed into the molten metal produced by the leading arc. In the cold-filler tandem GMA welding process, the filler wire is fed at 5 mm away backwards from the leading arc in the molten pool, unlike the TIG filler welding process in which the filler wire is fed into the molten pool immediately beneath the arc. With this process, the solidification rate of the molten pool becomes faster and thus the prevention of undercut and humped bead can be expected. Because the filler wire is fed into the rear part of the molten pool, the heat capacity of the arc is never drawn by melting the filler wire. This is why the penetration shape is almost not affected by the filler wire fed. In addition, since the preceding arc is kept in perfect spray without short-circuiting, similarly to the conventional pulsed MAG welding process, the generation of spatter is extremely low.

In recent years, thick-plate fabricators tend to use narrow groove joints to get higher welding efficiency. However, the use of a high-efficient welding process in a narrow groove joint may cause the occurrence of a hot crack in the penetrated weld center depending upon the penetration shape. The hot cracking can occur if molten metal does not fill the shrinkage cavity that is formed at the interface (the finally solidified zone) of the columnar structures near the center of a weld during the solidification and shrinkage process. With the cold-filler tandem GMA welding process, the cold filler wire is fed into the molten pool formed by a high-current arc, and hence it can be expected that the molten-metal filling action into the molten pool can be enhanced, thereby preventing the hot cracking.

Figure 10 shows the welding results of the pipe-flange joint of machinery structure steel. In this experiment, welding was started with the pulsed GMA welding process, which was followed in the mid-course by cold-filler tandem GMA welding with the trailing filler wire fed, in order to compare the effect of the filler wire. Consequently, solidification cracking occurred near the center of the bead from the weld start when only pulsed GMA welding was used; by contrast, right after switching to cold-filler tandem GMA welding, the crack propagation was arrested, and thereby the expected effect of the cold filler wire has been confirmed.

Closings and outlooks. The authors have introduced the trends in the development of the GMA welding equipment observed in Japan for the last ten years. The GMA welding equipment has remarkably been improved in tandem with the developments in the power electronics con-

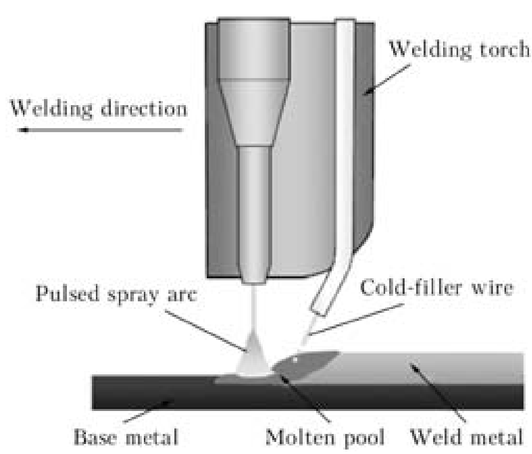


Figure 9. Principle of cold tandem pulsed GMA process

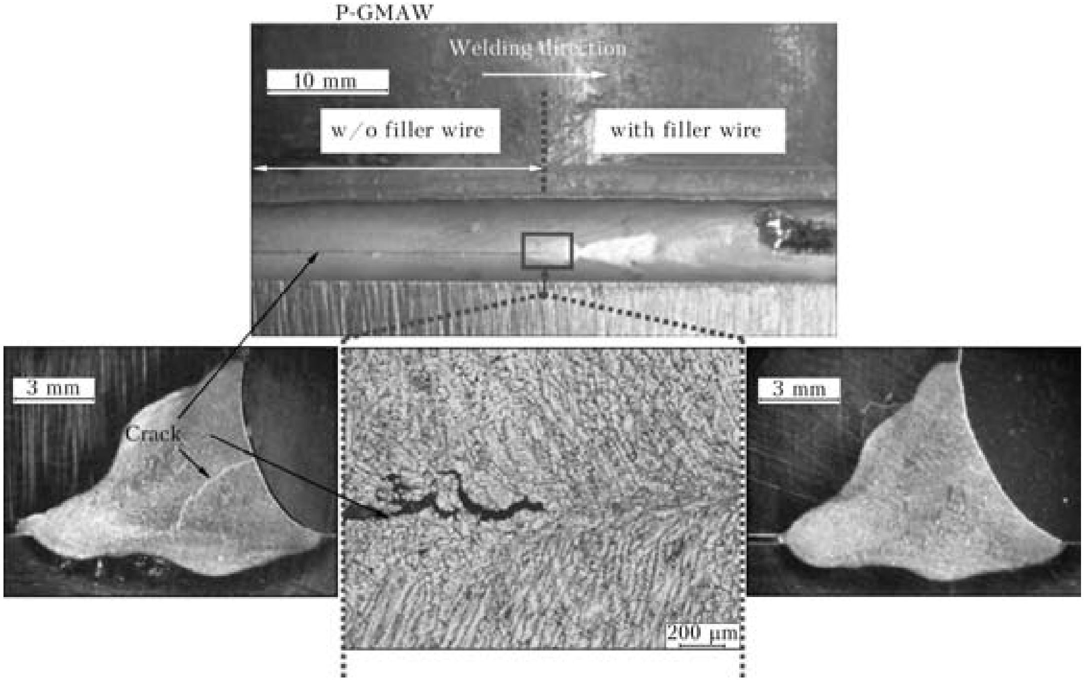


Figure 10. Inhibiting effect of solidification crack propagation by cold tandem pulsed GMAW

trols and elements together with the advancements in various control methodologies. Today, the capacity of microprocessors is also advanced considerably; thus, particular output controls that were hard to realize are becoming possible to practice.

On the other hand, for the fusion welding process like the arc welding process, it is required to handle the phenomena in which solid, liquid and vapor phases can change for a short time. Therefore, in order to accomplish the further advancement/development of the welding equipment, better understanding the physical phenomena centered on the arc phenomena in the welding process will become more vital for the technological step-up in the future.

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