Development of Non-short-circuit-type Wire Feed Control GMAW Process “AXELARC™”

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Abstract

While conventional short-circuit wire feed control processes are effective in achieving low spatter and low-heat-input welding, they present challenges when it comes to high-current ranges, medium-to-thick plates, and multi-layer multi-pass welding. To address this issue, the world's first non-short-circuit-type wire feed control process, AXELARC™, has been developed, in which the process leverages the inertia for droplet transfer by alternating the wire feed direction forward and backward. The applicability of the process to the field of medium-to-thick plates has been examined. The results confirm its ability to achieve low spatter and low fume welding in a wide range of conditions, from low to high currents. Additionally, it enables deep penetration, high deposition, and high-speed welding capabilities. The newly developed process is expected to make a significant contribution to improving welding quality and efficiency in the field of medium-to-thick plates.

Introduction

In the gas shielded metal arc welding process, the welding wire serves as the electrode. The electrode wire melts due to the Joule heat and the arc heat at the wire extension. As the droplet detaches from the wire tip, the arc length changes. In other words, the frequency of droplet transfer and the droplet size are factors that govern the arc stability, and droplets that cannot transfer smoothly may lead to spatter and fume emission. Therefore, in the arc-welding process, advanced technologies of droplet transfer control play significant roles in increasing efficiency, improving welding quality and pursuing further functional enhancement. Typical droplet transfer control technologies so far include the method of detecting necking of a droplet during the short circuit transfer process and controlling the current waveform,[1)] as well as the method of regularly detaching droplets by changing the welding current pulse-wise, as in pulsed MAG and MIG welding.[2)] These methods balance external forces acting on the droplet, such as surface tension, electromagnetic force, shear force caused by plasma stream, and arc pressure, through the operation of the welding current waveform. However, relying solely on the control of external force balance through the current waveform makes it challenging to expect significant progress in the arc welding process in the future.

Hence, Kobe Steel has developed the world's first wire feed control process, AXELARC™ [Note 1)], which utilizes “inertia” as a new droplet transfer control factor by changing the wire feed direction and speed over time and reversing the wire feed direction. This paper introduces an overview of AXELARC™ and provides an example of its effectiveness.

1. Overview of the newly developed non-short-circuit-type wire feed control process, AXELARC™

1.1 Outlines and issues of short-circuit wire feed control processes

In recent years, an extremely low-spatter and low-heat-input welding method has been gaining popularity, especially in the field of thin-plate welding. This method closely coordinates welding current waveform control with wire feed control by AC servo motors. Various welding processes have been introduced by welding equipment manufacturers in Japan and other countries.[3)~7)] The droplet transfer mode for these welding processes, using wire feed control, is consistently the short-circuit transfer mode. When the droplet at the tip of the welding wire short-circuits to the molten pool, the welding current is reduced, and reversing and retracting the welding wire opens the short circuit. The common feature is the significant reduction of spatter generation upon the re-establishment of the arc. These short-circuit wire feed control processes have the advantage of suppressing short-circuit currents, achieving lower heat input compared with conventional short-circuit welding processes, which is particularly beneficial for extremely thin plates, around 1.0 mm thick, reducing distortion and preventing burn-through.

However, this excellent low-spatter effect mainly relies on the stabilization of the short-

Note 1) AXELARC is a registered trademark (TM) of Kobe Steel.

circuit transfer phenomenon in the low current range, and maintaining a similar droplet transfer mode and its benefits in the high current range is generally challenging. Moreover, assuming short-circuit transfer as the basis results in shallow penetration and high weld reinforcement, often leading to a narrow convex bead shape. Increasing the welding current (wire melting rate) to enhance welding efficiency exacerbates this convex bead formation tendency. Consequently, the efficiency improvements sought in the medium-to-thick plate welding field, including high current and faster welding speeds, become less attainable. Additionally, when performing multi-layer, multi-path welding within a groove, issues like insufficient penetration and lack of fusion become more likely, presenting challenges for the application of short-circuit wire feed control processes in medium-to-thick plate welding. In contrast, AXELARC™ assumes no short-circuiting of the droplet at the wire tip with the molten pool. This means it's a process developed to overcome the challenges associated with the short-circuit wire feed control processes mentioned above. It holds the potential for application in medium-to-thick plate welding.

1.2 System configuration of AXELARC™

The configuration of the experimental apparatus for the AXELARC™ process is shown in **Fig. 1**. The feeding unit of this system comprises a push feeder that forwards the wire at a set speed, a pull feeder integrated into the welding torch, and a servo driver that controls the pull feeder. Furthermore, a wire buffer mechanism has been provided between the push feeder and the pull feeder to detect and correct errors in the amount of wire feeding. A mild-steel solid wire with a diameter of 1.2 mm, subjected to a special surface treatment, is used as the welding wire, and 100 % CO_2 is used for the shielding gas.

1.3 Droplet transfer mode for AXELARC™

Fig. 2 schematically illustrates the welding current waveform and wire feed speed waveform for AXELARC™ and presents images with examples of droplet transfer. The forward and backward feeding of the wire occurs repeatedly, and the current waveform is a pulse current waveform synchronized with the wire feed waveform's phase. As shown in Fig. 2(a) to (b), by forming droplets at the wire tip while advancing the wire, the droplets are accelerated in the direction of the molten pool. Consequently, as shown in Fig. 2(c), even after reversing the wire feed direction, the droplets at the wire tip attempt to move in the molten pool direction due to inertia. As a result, necking occurs at the top of the droplet (Fig. 2(d)), allowing the droplet to detach (free transfer) even without a short circuit (Fig. 2(e)). It should be noted that if the current is in a low current state, or the base current, at the time of droplet detachment, the generation of small particle spatter immediately after the droplet detachment is suppressed. Normally, in the high current range of CO_2 arc welding, a repulsion transfer mode occurs due to the upward force of the arc on the lower part of the droplet, leading to the generation of a significant amount of large-sized spatter. In contrast, the present process effectively utilizes inertia for the droplet detachment, and thus the detachment direction does not deviate greatly

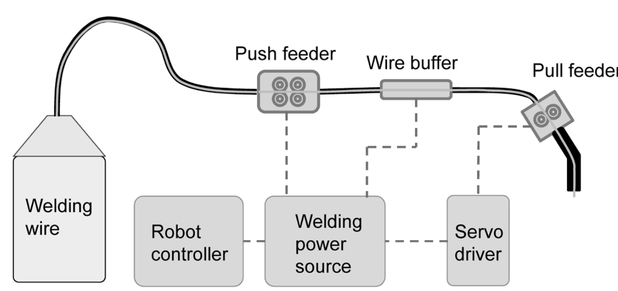


Fig. 1 Schematic diagram of the experimental system

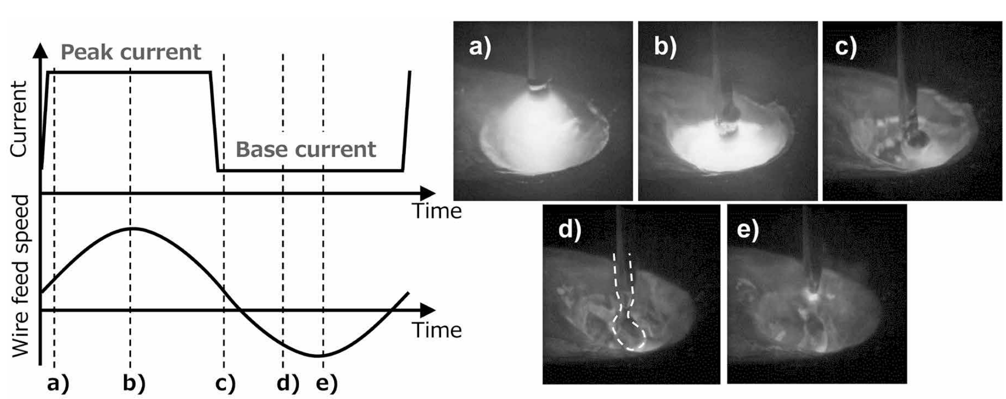


Fig. 2 Droplet transfer phenomenon using inertia

from the wire feed direction. Therefore, a regular droplet transfer synchronized with the wire feed speed waveform is achieved across a wide range of conditions, from low current to high current, with very little occurrence of large-sized spatter.

1.4 Effect of droplet size and the maximum wire feed speed at wire tip on AXELARC™ droplet transfer phenomenon

In order to achieve stable droplet transfer in AXELARC™, various welding parameters related to the welding current waveform and wire feed speed waveform must be optimized. In this study, attention is focused on droplet size and the maximum speed of the wire tip to observe the droplet transfer phenomenon. It should be noted that, in AXELARC™, droplet transfer is based on one droplet detachment per one period of the forward-backward movement of the wire. The droplet size (V_{drop}) is determined using Equation (1):

$$V_{drop} = Wf_{avg} \times \frac{\pi d^2}{4} \times \frac{1}{f} \quad \cdots\cdots (1)$$

wherein, Wf_{avg} represents the average wire feed speed, d is the wire diameter, and f is the frequency of forward-backward feed.

Additionally, the maximum speed of the wire tip is determined using the highest acceleration rate (Wf_{max}) and is calculated with Equation (2):

$$Wf_{max} = L_m \times \pi \times f \quad \cdots\cdots (2)$$

wherein, L_m stands for the amplitude of wire feeding, and f is the frequency of the forward and backward feed.

Wf_{max} represents the speed added to the average wire feed speed when the wire tip reaches its maximum speed.

In the following experiment, the welding current waveform parameters were adjusted within the range of an average wire feed speed of 13 to 19 meters per minute. Specifically, the droplet size and the maximum wire feed speed of the wire tip were changed by manipulating the amplitude and frequency in the wire feeding parameters.

First, the following describes the case where the droplet size is kept constant, and the maximum wire feed speed is varied. **Fig. 3** shows the droplet transfer phenomenon at two different maximum wire feed speeds, 90 m/min and 70 m/min, at an average wire feed speed of 19 m/min with a droplet size of 3 mm^3. In Fig. 3(a), with the maximum wire feed speed at 90 m/min, the droplet transfer phenomenon can achieve free transfer, similar to that shown in Fig. 2. However, as shown in Fig. 3(b), when the maximum wire feed speed is 70 m/min, no necking occurs on the top of the droplet in the steps 3) to 4) in Fig. 3, and in step 5), the droplet does not detach. In AXELARC™, to utilize inertia for droplet transfer, it is necessary to configure wire feeding conditions to secure a predetermined average wire feed speed while setting an appropriate maximum wire feed speed depending on the droplet size.

Next, the following describes the case where the maximum wire feed speed is kept constant, and the droplet size is varied. **Fig. 4** shows the droplet transfer phenomenon with droplet sizes of 2 mm^3 and 3 mm^3 at an average wire feed speed of 13 m/min and the maximum wire feed speed of 70 m/min. In Fig. 4(a), with a droplet size of 3 mm^3, the droplet transfer phenomenon is similar to that shown in Fig. 2. However, in the case where the droplet size is 2 mm^3 as shown in Fig. 4(b), the droplet cannot detach in the steps 3) to 5) in Fig. 4. To realize droplet transfer in AXELARC™, the current waveform and wire feed speed waveform

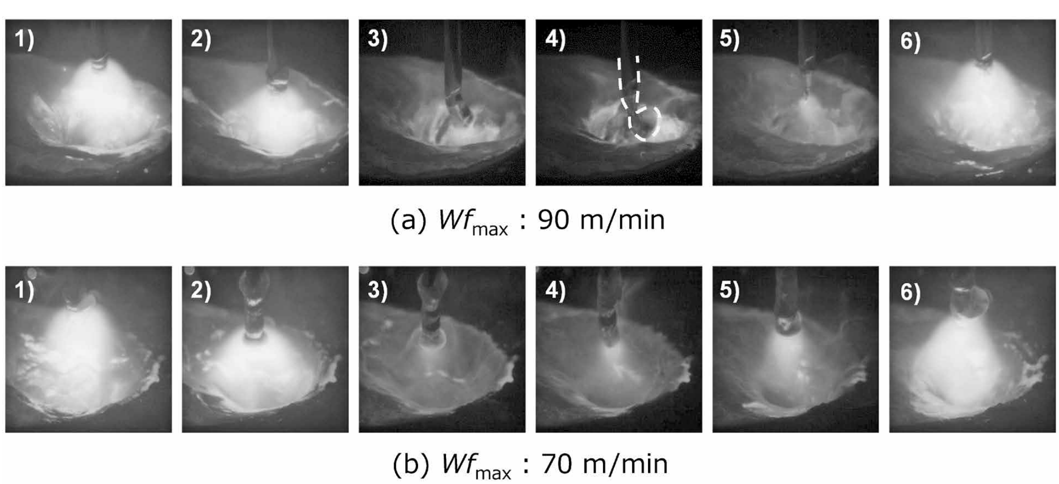


Fig. 3 Effect of maximum wire feed speed on droplet transfer phenomenon (Wf_{avg}: 19 m/min, V_{drop}: 3 mm^3)

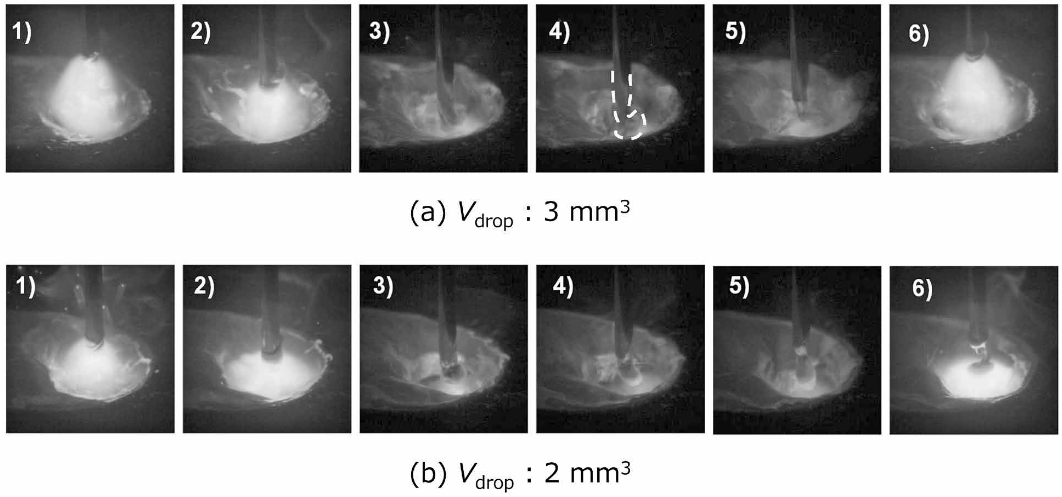


Fig. 4 Effect of droplet size on droplet transfer phenomenon (Wf_{avg}: 13 m/min, Wf_{max}: 70 m/min)

parameters must be set such that the droplet size becomes appropriate for the average wire feed speed.

The above experimental results indicate that the key factor determining the success of droplet detachment in AXELARC™ is the ability to accelerate the droplet to form necking on the top of the droplet through inertia. If a droplet reaches only an insufficient speed, the droplet is pulled back along with the wire without forming necking when the wire enters the backward movement. Consequently, in the subsequent wire melting period, the droplet enlarges, resulting in an unstable droplet transfer mode. On the other hand, when the droplet size and the maximum wire feed speed of the wire tip are properly configured, the formed droplet is synchronized with the wire and sufficiently accelerated towards the molten pool. If necking occurs on the top of the droplet due to inertia after the wire enters the backward movement, the droplet can detach during the backward movement. It should be noted that achieving this droplet transfer requires setting the parameters of the current waveform and wire feed speed waveform, and the optimal parameters may vary depending on the wire composition, wire diameter, shielding gas composition, and average wire feed speed.

2 Application effects of new wire feed control process, AXELARC™

2.1 Reduction in spatter and fume

Comparisons have been made between the conventional CO_2 arc welding process using constant voltage control and AXELARC™. **Fig. 5** compares

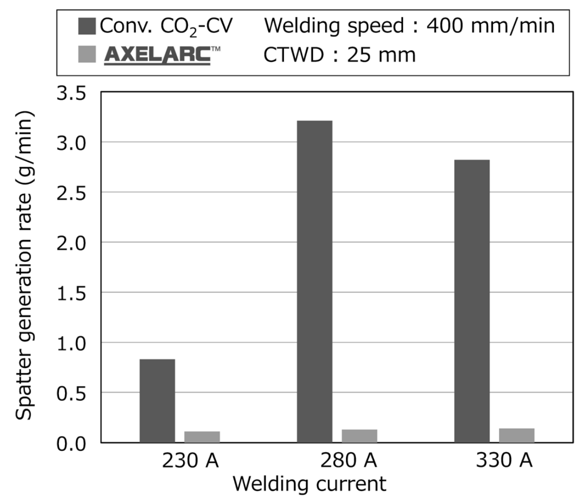


Fig. 5 Comparison of spatter generation rate

the spatter generation rate, and **Fig. 6** compares the scattering of spatter during welding. In Fig. 5, the comparison was made on the spatter generation rate when welding at currents ranging from 230 to 330 A, with the wire feed speed and the contact-to-work distance (CTWD) held constant. In the conventional CO_2 arc welding process, a significant portion of the spatter consists of spatter due to arc re-ignition after short circuit and large-sized spatter caused by droplets that rotate themselves and scatter due to repulsion and detachment. On the other hand, in AXELARC™, the droplet transfer process generates minimal short circuits, and thanks to the utilization of inertia, the detachment direction of the droplet remains aligned with the wire feed direction. As a result, the spatter generation rate is significantly reduced even under CO_2 arc welding process gas shield. Compared with the conventional CO_2 arc welding process, the spatter generation rate for AXELARC™ is generally less than 1/10 in a wide

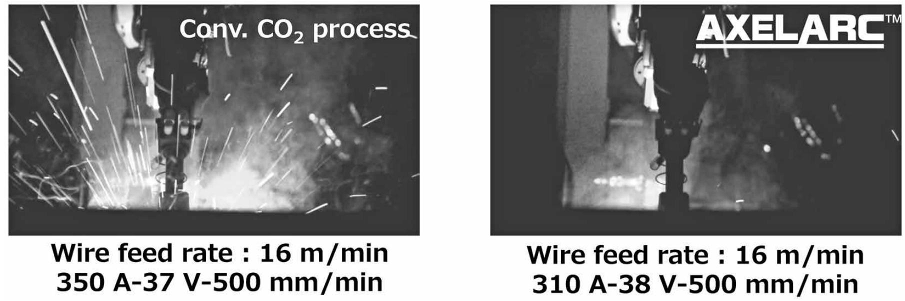


Fig. 6 Comparison of spatter scattering

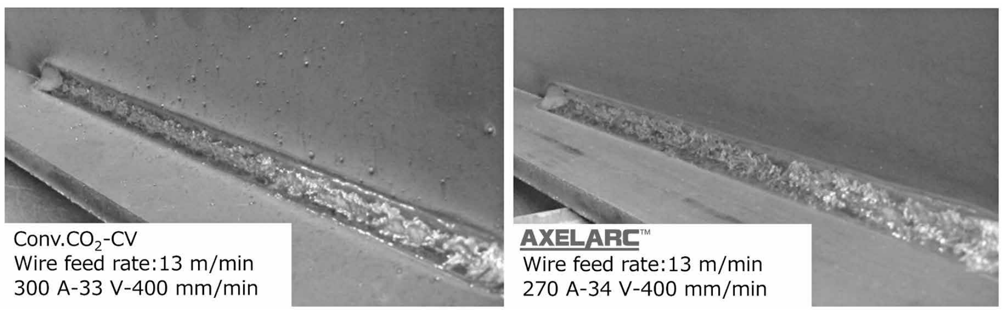


Fig. 7 Comparison of bead appearance in flat fillet welding

range of current conditions form low to high. As shown in **Fig. 7**, the amount of spatter adhering to the vicinity of the welding bead is also minimal.

Next, the fume emission rates for the conventional CO_2 arc welding process and for AXELARC™ were compared, and the results are shown in **Fig. 8**. Compared with the conventional CO_2 arc welding process, the fume emission rate for AXELARC™ is consistently lower under various wire feed speed conditions, and especially under high-speed wire feeding (high current) conditions, for which the fume emission rate using AXELARC™ is 40% or less that of the conventional method. Welding fume originates mainly from metal vapor emitted from droplet surfaces overheated by the arc. It diffuses through the repeated contraction and expansion of the surrounding gas during short circuits and re-arcing.[8)] The reduction in fume emission with AXELARC™ is attributed to the minimal occurrence of short circuits and the reduced heating time of the droplet thanks to the shorter droplet transfer period.

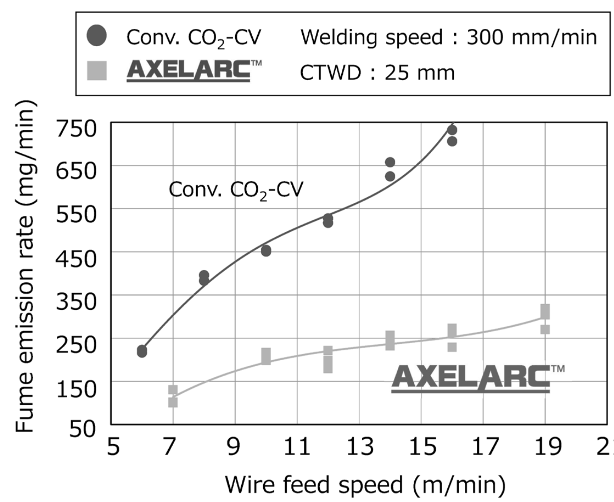


Fig. 8 Comparison of fume emission rate

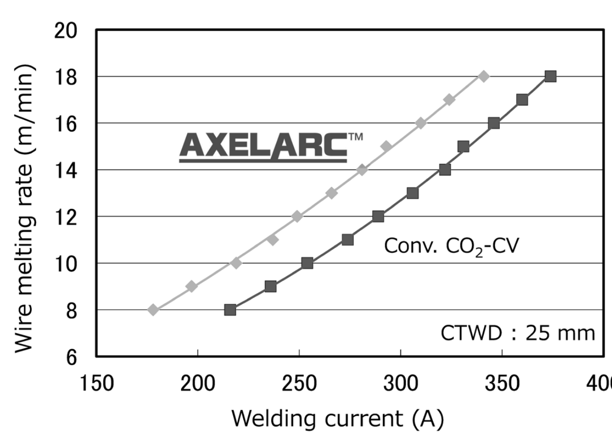


Fig. 9 Comparison of wire melting rate

2.2 Melting characteristics of wires

Fig. 9 shows the relationship between the welding current and wire melting rate for the conventional CO_2 arc welding process and AXELARC™. The wire melting rate with AXELARC™ is approximately 15-20% higher for the same average current. Therefore, under the same average current conditions, an increase in deposition is expected, which leads to improved welding efficiency. This difference is believed to be primarily the result of the pulse current used in AXELARC™, resulting in a higher Joule heating rate in the wire extension part, unlike the conventional CO_2 arc welding process, which experiences relatively small current variations.

2.3 Deep penetration performance

Fig.10 shows the penetration depths for various welding processes when bead-on-plate welding is performed by varying the welding speed, using a common wire feed speed of 16 m/min and a contact-to-work distance of 25 mm. AXELARC™ exhibits deeper penetration compared with conventional short-circuit wire feed control processes and pulsed MAG welding process, achieving penetration depths equivalent to those of the conventional CO_2 arc welding process. **Fig.11** shows the penetration depth in flat fillet welding. In a wide range of wire feed speed conditions, AXELARC™ exhibits deeper penetration, achieving depths equivalent to or greater than those of the conventional CO_2 arc welding process. In addition, it advantageously yields a flatter bead shape compared with conventional short-circuit wire feed control processes. **Fig.12** compares penetration shapes in flat fillet welding by various welding processes. AXELARC™ exhibits a flat bead shape even at a wire feed speed of 7 m/min, which is in contrast to the conventional CO_2 arc welding process. This improvement in bead shape is attributed to AXELARC™'s ability to minimize short circuit occurrences and promote free droplet transfer, while conventional CO_2 arc welding is based on short-circuit transfer. The above experiments indicate the possibility that AXELARC™ will improve defect tolerance and has the potential to contribute to the

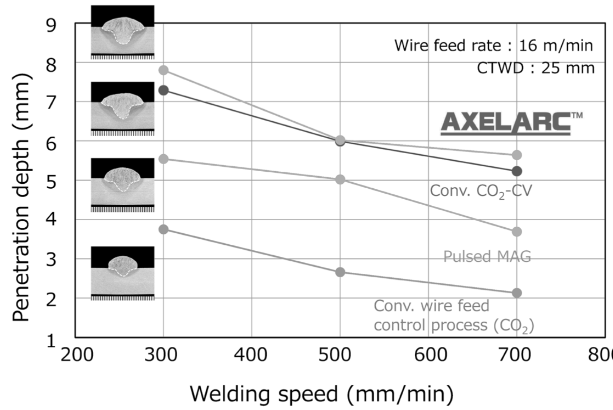


Fig.10 Comparison of penetration depth in Bead-on-plate welding

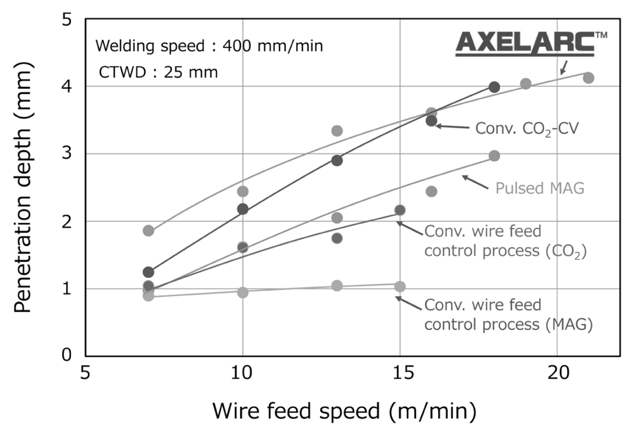


Fig.11 Comparison of penetration depth in flat fillet welding

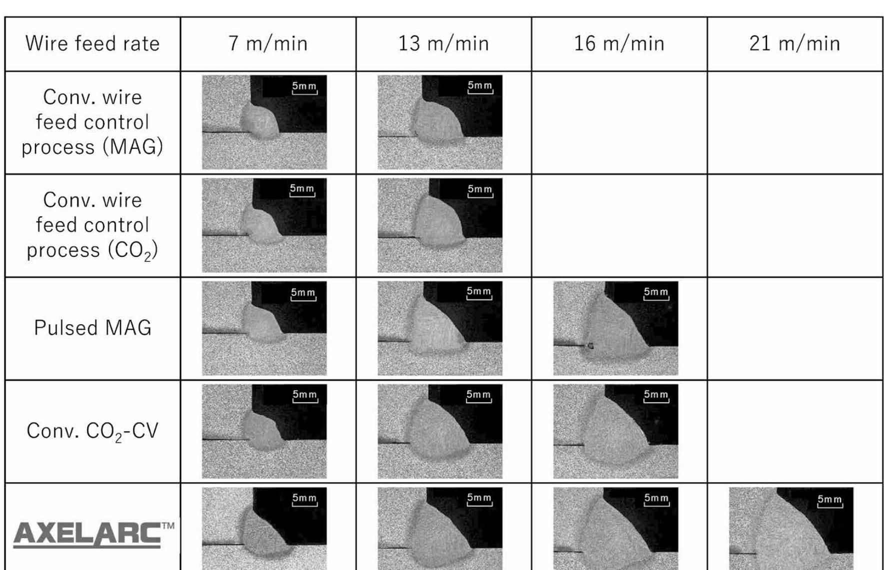


Fig.12 Comparison of cross-sectional profile in flat fillet welding (CTWD: 25 mm, Welding speed: 400 mm/min)

high-quality welding of medium to thick plates.

2.4 Improved welding efficiency for medium-to-thick plates

Fig.13 shows examples of welding conditions, bead appearance, and macroscopic cross-sectional photos in flat fillet welding. AXELARC™ increases the deposition rate compared with pulsed MAG welding, allowing for an approximately 20% faster welding speed while maintaining an equivalent leg length. It also results in a pronounced, deep penetration with a bowl-shaped appearance. In flat fillet welding, conventional pulsed MAG welding requires 3-4 passes to achieve a leg length of 18 mm, whereas AXELARC™ achieves the same leg length in a single pass, as shown in **Fig.14**. This fact demonstrates the potential of AXELARC™ for higher speed and a greater deposition rate in flat fillet welding. **Fig.15** shows examples of horizontal fillet welding by pulsed MAG welding and AXELARC™, aiming at a leg length of 9 mm. AXELARC™ allows for an approximately 30% faster welding speed, while achieving an excellent bead appearance and a deep penetration shape. This feature is distinct from pulsed MAG welding, which exhibits small undercut on the vertical plate side. Thus, AXELARC™ contributes to improved quality and efficiency in welding medium-to-thick plates.

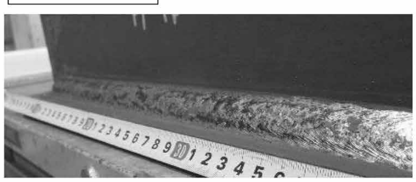
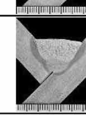
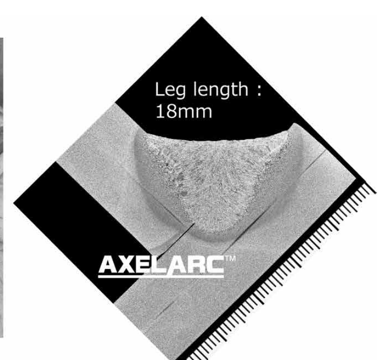
Process / Bead appearance	Leg length (mm)	Welding current (A)	Welding speed (mm/min)	Cross section
Pulsed MAG 	8	380	420	
	10	380	300	
	14	380	1st 420 2nd 260	
AXELARC™ 	8	390	500	
	10	390	360	
	14	390	1st 500 2nd 310	

Fig.13 Welding conditions and results for flat fillet joint



Wire feed rate : 19 m/min
380 A-43 V-150 mm/min

Fig.14 Bead appearance and cross-sectional profile in flat fillet welding with a large leg length

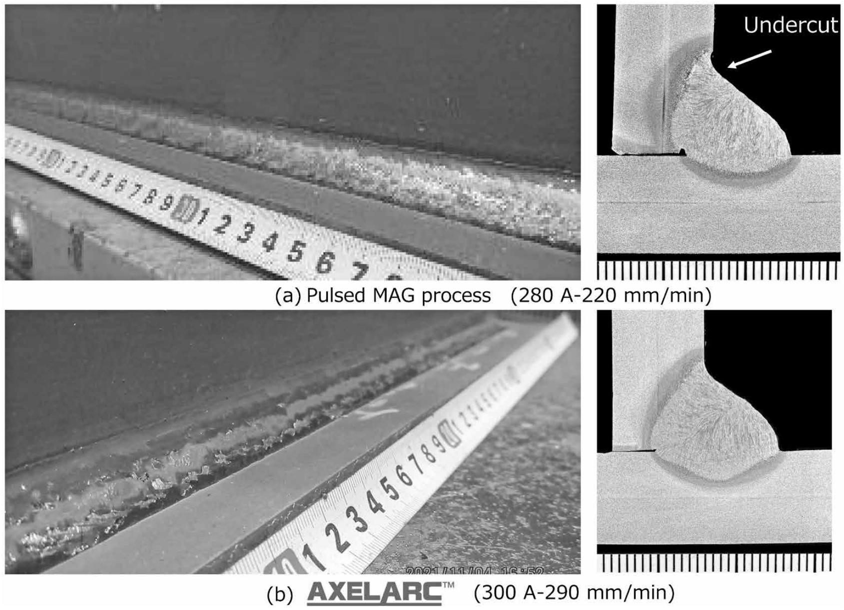


Fig.15 Bead appearance and cross-sectional profile in horizontal fillet welding aiming for a 9 mm leg length

Conclusions

Kobe Steel has developed a new wire feed control process, AXELARC™, which utilizes droplet acceleration and the formation of necking as a result of inertia, eliminating the need for short-circuit transfer. This process enables low-spatter and low-fume welding over a wide range of current conditions while maintaining deep penetration, allowing for high deposition rates and increased welding speed. As a result, AXELARC™ is poised to significantly contribute to improving the quality and efficiency of welding in the medium-to-thick plate field. Kobe Steel will strive to utilize AXELARC™ and aim to create new welding solutions that go beyond the constraints of wire types, shielding gas compositions, and welding condition ranges that have been inherently limiting in conventional welding processes.

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