JFE TECHNICAL REPORT
No. 20 (Mar. 2015)

Narrow Gap Gas Metal Arc (GMA) Welding Technologies†

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Abstract:

This paper describes the latest implementation status of the narrow gap welding process by the high speed rotating arc method developed by JFE Engineering in 1980s. In case of the engine crankcases, adaptive control function of the welding speed corresponding to the variation of the groove width has been newly developed. Tandem welding system by one operator without watching the two equipment has been also employed, shortening the welding lead-time to less than half that of the conventional method. Furthermore, for innovation of the narrow gap welding, another oscillation pattern of the welding torch by the circular weaving has been added to the conventional equipment. In case of the turbine members, application range has been expanded to be able to apply to the inclined narrow gap joints, and it was confirmed that the groove width could be decreased from the conventional 13 mm to about 8 mm.

1. Introduction

In welding of extra-heavy gauge plates with thicknesses exceeding 50 to 100 mm, use of an I-shaped narrow gap groove is effective, as this groove shape greatly reduces the cross-sectional area of the groove. Beginning in the 1980s, various narrow gap welding methods were developed and applied into practical uses. I-shaped narrow gap grooves are widely used in various types of large-scale structures because this groove shape not only significantly reducing the welding deposition volume, thereby shortening the welding time as the plate thickness increases, but also realizes low strain due to the reduced heat input and a fracture toughness improvement effect as a result of reheating. NKK (now JFE Engineering) also independently developed the “high speed rotating arc narrow gap welding method,” which it applied to its own products and sold to customers beginning the 1980s. Subsequently, with the aims of achieving higher efficiency and a higher level of automation, JFE Engineering also developed an adaptive control function of welding speed by use of an arc sensor, and promoted expanded application by adding new oscillation patterns.

This paper presents an outline of the high speed rotating arc narrow gap welding process and the recent condition of practical application, and also reports on the status of efforts to improve the penetration shape by addition of a circular weaving function, improve response to variations in groove width, expand application to inclined welded joints, etc., and to realize a narrower welding gap.

2. High Speed Rotating Arc Narrow Gap Welding Method

2.1 History and Types of Narrow Gap Welding

Narrow gap welding process was first developed in 1963 by Battelle Memorial Institute in the United States. Much research and development on this technology has been carried out in countries around the world, but where practical application is concerned, Japan was the most enthusiastic. It is generally said that there was a feeling that a variety of narrow gap welding methods flowered all at once in Japan in the 1980s. Various interpretations have also been given to the definition of nar-

† Originally published in *JFE GIHO* No. 34 (Aug. 2014), p. 98–103

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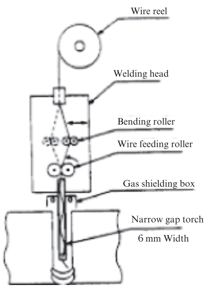
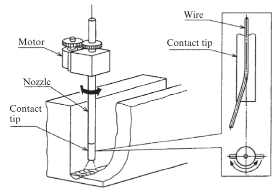
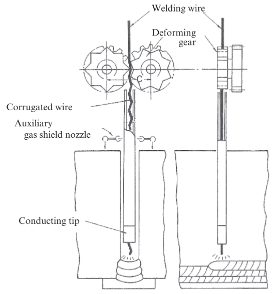
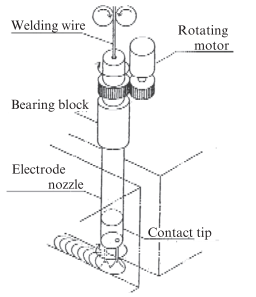
Table 1 Examples of narrow gap gas metal arc (GMA) welding equipments[3]

Method	(a) Wave-shaped wire	(b) Bent tip	(c) Curved tip	(d) High speed rotating arc
Principle of welding machine				
Groove width	Groove width : 9 mm (8–14) Torch : 6 mm *t*-35 mm *w*	16 (15–20) mm Nozzle : ϕ 8 mm	11–13 mm Torch : 8 mm *t*-65 mm *w*	12–18 mm Nozzle : ϕ 8 mm
Standard welding conditions	Wire diameter : 1.2 mm Arc current : 240 A, Pulsed Welding speed : 210 mm/min Shielding gas : 20% CO_2-Ar	1.2 mm 110–180 A, Pulsed 150–180 mm/min 20% CO_2-Ar	1.2 mm 260–270 A, Pulsed 210 mm/min 20% CO_2-Ar	1.2 mm 300–350 A 220–300 mm/min 20% CO_2-Ar
Weaving frequency	0.5–1.5 Hz Amplitude adjustment is easy.	0.2–0.6 Hz Amplitude adjustment is easy.	4–15 Hz Wire bending width: 2–4 mm	Max. 150 Hz Rotating diameter: 7.6 mm
Features	• Oscillates at low speed in straight lateral direction	• Reproduces the movement of experienced welders by detailed control	• Simple and high reproducibility oscillation mechanism	• Easy seam tracking by utilizing arc voltage

row gap welding, but the generally-accepted definition is that of an expert committee from that period, namely, “a technique to weld thick plates of more than 30 mm thickness either by mechanical or automatic arc welding process preparing a narrow gap groove compared with the plate thickness (gap is smaller than approximately 20 mm when plate thickness is under 200 mm and smaller than approximately 30 mm when plate thickness is over 200 mm).”[1]

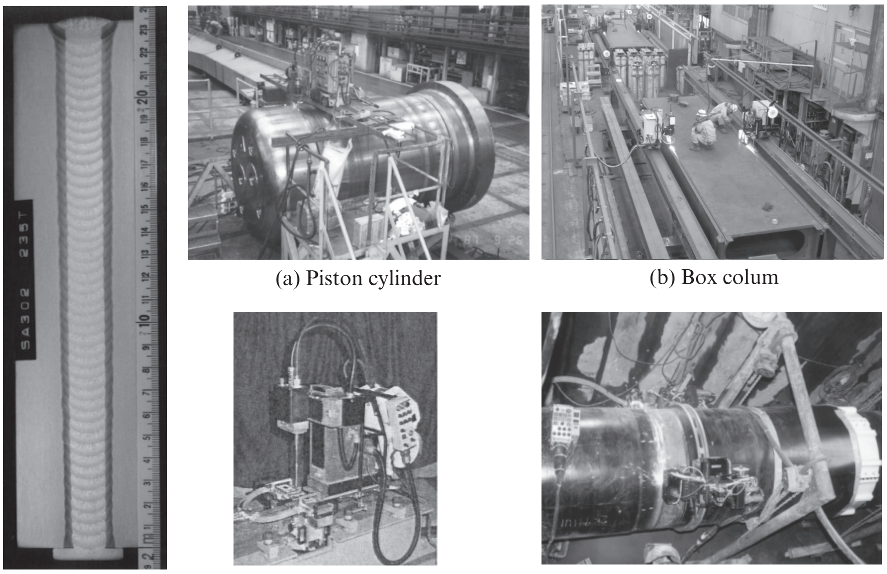
Narrow gap welding processes span a diverse range. In the original stage of development, gas metal arc welding (GMAW) was the main stream, but thereafter, development also progressed in various other welding processes such as submerged arc welding and gas tungsten arc welding. Although the main welding position in the earliest period was flat, several narrow gap welding processes for horizontal welding and vertical welding have also been developed[2].

Table 1 shows the main narrow gap welding methods (excerpted from the Journal of the Japan Welding Society, 1999). In both methods (a) and (c), the arc is oscillated in a narrow gap by forcibly bending the wire; however, due to differences in the wire bending machine, the oscillation frequency of (c) is higher. On the other hand, in both methods (b) and (d), the arc is oscillated by rotating the electrode, which is realized by applying eccentricity to the contact tip. The oscillation frequency is remarkably faster in method (d), and this technology has the advantage of an automatic seam tracking function using an arc sensor. Method (d) is the high speed rotating arc narrow gap welding method developed by JFE Engineering[4].

2.2 Features of the High Speed Rotating Arc Narrow Gap Welding Method

The principle of the rotating mechanism in this method will be explained using (d) in Table 1. The welding wire is supplied into the center of the electrode nozzle, and the required amount of eccentricity is given by the eccentric outlet hole of the contact tip. The electrode nozzle is supported by the bearing block, and rotated at high speed in the same direction by the rotating motor. Accordingly, the welding wire and the arc at its tip are rotated at high speed with a diameter corresponding to the eccentricity of the contact tip outlet hole. Because this high speed rotation of the arc disperses the heat input and the arc pressure, this is remarkably effective in improving the bead formation phenomena.

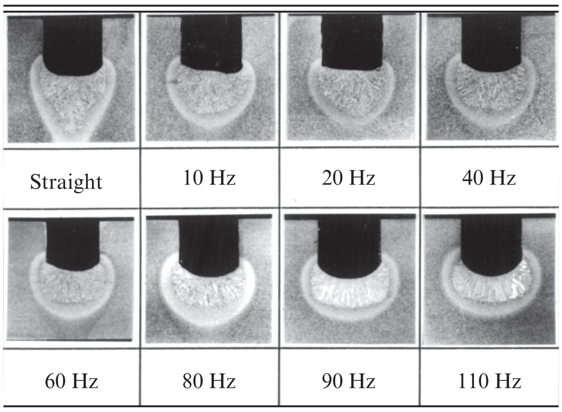
The influence of the rotating speed of the arc on the bead formation in narrow gap welding is shown in **Fig. 1**. The welding wire is a 1.2 mm solid wire, the shield gas is 20% CO_2-Ar, the welding current is 300 A, and the rotating diameter is 8 mm. Without rotation, penetration takes the form of concentrated and centralized penetration, which is peculiar to metal active gas (MAG) welding, whereas rotation of the arc results in a dispersed-type wide penetration shape and penetration at the side walls is increased. In addition, the concaved bead surface also becomes more suitable for multi-layer welding. Since the bead shape improvement effect by arc rotation becomes remarkable at 40 Hz and faster, 50 Hz has been adopted as the standard rotating speed.



(a) Piston cylinder (b) Box colum

(c) Railway rail (d) Gas pipeline

Photo 1 Applications of the High Speed Rotating Arc welding process



1.2 mm solid wire, 20% CO_2–Ar, Welding current: 300 A
Rotating diameter: 8 mm, Welding speed : 250 mm/min

Fig. 1 Influence of the rotating speed on the bead shape

Moreover, the arc sensing ability and its response have been improved remarkably, enabling satisfactory seam tracking control with a high speed rotating arc. Accordingly, the target position of the torch can be kept at the center of the groove at all times, and stable bilaterally-symmetrical penetration of the side walls can be obtained.

2.3 Application of High Speed Rotating Arc Narrow Gap Welding Method

Photo 1 shows the main applications of the high speed rotating arc narrow gap welding method and an example of the cross-sectional bead shape. The main objects of application by JFE Engineering are (a) heavy equipment parts, such as piston cylinders and (b) bridge and steel frame structure products such as steel frame BOX columns[5)]. The maximum plate thickness in products delivered by JFE Engineering is 275 mm. As special applications, JFE Engineering also has actual results of enclosed welding of railway rails[6)], as shown in (c), and girth welding of gas pipelines[7)], as shown in (d).

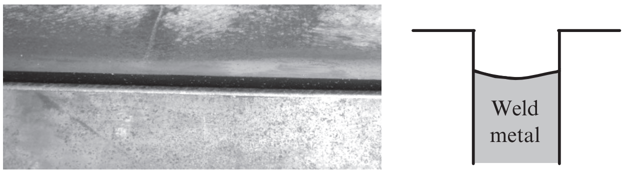
3. Recent Practical Applications

3.1 Adaptation to Groove Width Variations

When originally developed in the 1980s, an analog circuit board was used in the high speed rotating arc narrow gap welding machine, and arc sensor control was performed by an operational amplifier. Now, however, programable logic control is applied to all functions, and setting of the welding conditions and control parameters has also evolved from a control knob method to a touch panel system. Accompanying this, improvements in the welding automation function and the operability of the welding machine have also been realized. As an example of this, the present section presents an outline of the adaptive control function for welding speed (deposition rate) by using the arc sensor.

In actual products, the width of the narrow gap groove is not constant. This is due not only to errors in groove preparation and assembly, but also to variations in the amount of shrinkage depending on the location, which occur because the intensity of restraint of the joint is not uniform over the full length of the weld line. **Photo 2** shows an example of the appearance of the weld bead in an engine frame with a plate thickness of 140 mm and a total length of approximately 5 m. Because the deposited bead height varied by more than 15 mm at maximum, complicated excess metal adjustment work was necessary after automatic welding.

(a) Small groove in width



(b) Large groove in width

Photo 2 Weld bead variation without the welding speed control

Photo 3 Adaptive control of the welding speed

Therefore, based on the results of torch height control by the arc sensor, a function which detects variations in the weld bead height and automatically adjusts the welding speed in-process so as to achieve a uniform bead height was added. **Photo 3** shows the bead appearance before the final pass welding. It can be confirmed that the bead height is substantially uniform over the full length of the weld line. The system is designed so that the results of detection of the weld bead height can be checked from the touch panel. The results confirm that the bead height variation before the final pass was kept within±1 mm. As a result of the addition of this adaptive control function of the welding speed, that is, a function for adaptation to variations in the groove width, complicated excess metal height adjustment work after final welding is no longer necessary, and stable weld quality has been achieved.

3.2 Tandem 1-Operator/2-Welder System

Because the welding system performs automatic seam tracking control and adaptive control of the welding speed by the arc sensor, the operator only needs to check the arc immediately after the start of welding, and after which welding is basically performed without operator' s monitoring. Therefore, during welding of one working object, a tandem welding method was adopted, in which one operator is responsible for the operation of two narrow gap welders. **Photo 4** shows an example of tandem welding. The leading machine and trailing machine travel in the same direction with a short distance between the two machines, and after slag removal work, the welding direction is reversed, and tandem welding of the next pass is performed in the opposite order. Adoption of tandem welding has improved the number of layer passes per unit of time by approximately 1.75 times, achieving a large improvement in welding efficiency.

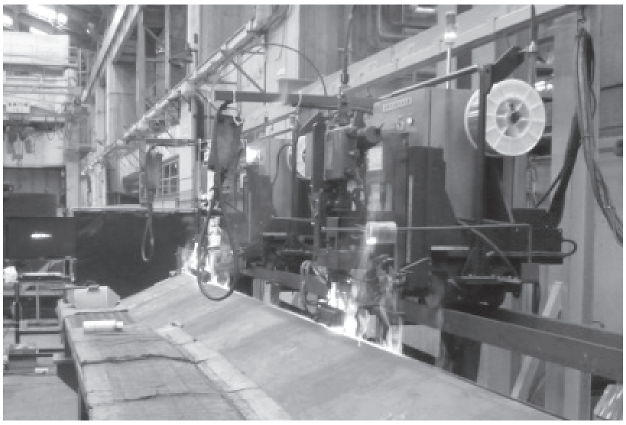


Photo 4 Tandem narrow gap welding of the engine crankcase

3.3 Demand for further Reduction of the Groove Width

The lead time for welding of one engine frame member was shortened to less than half of the conventional time as a result of the above-mentioned improvement of operability by adoption of digital control equipment, elimination of the need for excess metal adjustment welding by adaptive control of the welding speed, and improved efficiency by adoption of the tandem welding method. Because these improvements also prevented

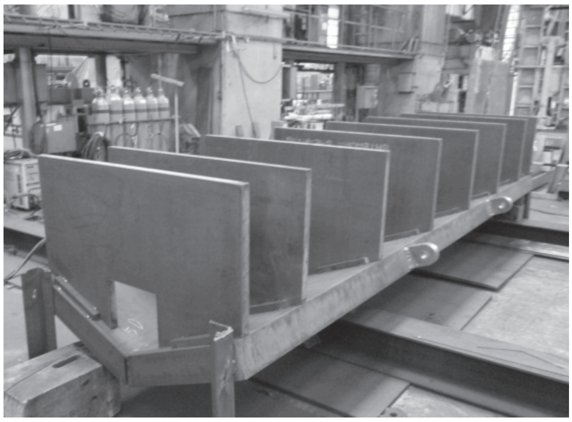


Photo 5 Distortion restrained members of the narrow gap joint

welding defects, there were no strong calls from the production site for further increase in efficiency. However, reduction of welding distortion remained as a deeply-rooted need. **Photo 5** shows the appearance of a deformation-constrained member of an engine frame. As many as eight constrained members are attached in order to constrain the angular deformation caused by more than 30 passes of narrow gap welding, and the man-hours required to attach and remove these members exceed the man-hours necessary for the welding. Thus, a further reduction of the groove width, which is currently 13 mm, is demanded from the viewpoint of preventing welding distortion.

4. Study of Innovative Technologies in Narrow Gap GMA Welding Method

4.1 Outline of Circular Weaving Method

In the existing high speed rotating arc narrow gap welding method, the tolerance with respect to variations in the groove width is small, which gives rise to various problems. For example, because the arc rotating diameter cannot be changed during welding, if the groove width becomes smaller than the specified value, the arc will climb up the side walls, resulting in unstable welding. Moreover, since the rotating speed was the only substantial weaving parameter, it was not possible to control the heat input distribution in the groove width direction. Therefore, it has been attempted to control the heat input distribution in the groove width direction by changing the torch weaving pattern from unidirectional continuous rotation to reciprocating circular weaving.

Figure 2 shows an example of the weaving conditions and torch trajectory in circular weaving. In this weaving condition, priority is given to securing penetration at the corner parts of the narrow gap. Therefore, the heat input to the groove corner parts was increased by setting the weaving conditions so that the weaving center was the front in the welding direction, the weaving angle was±120 degrees, the end stopping time was 0.2 seconds at each end, and the weaving frequency was 1.2 Hz (weaving speed: 1 080 degrees per second).

Figure 3 shows a comparison of the penetration shape in the first pass welding between the conventional method and the newly-developed circular weaving method. Although penetration at the corner parts is small in conventional method, it can be confirmed that the penetration depth at the groove corner parts increases when circular weaving is applied, and the penetration displays a twin-peak shape. The penetration shape of the horizontal cross section at the bottom of the groove is shown in **Fig. 4**; here, it can be seen that penetration in the groove width direction varies slightly with a wave-shaped form having the same period as weaving, corresponding to the trajectory of the torch. As lack of fusion might occur between weaving pitches if the weaving period was too long, the weaving pitch (traveling distance in one weaving period) in circular weaving is set to a condition of 5 mm or less.

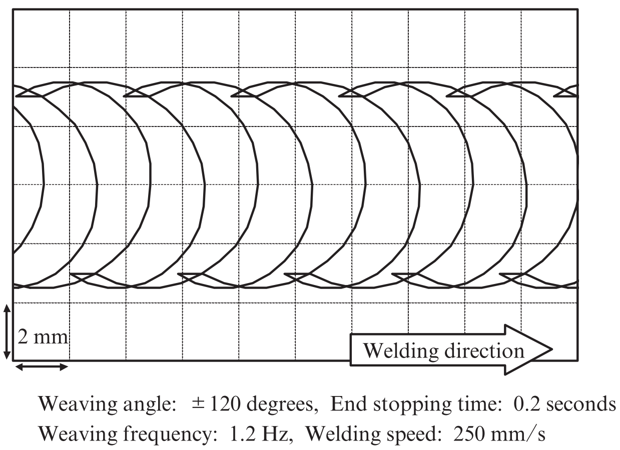


Fig. 2 Example of the trajectory in the circular weaving

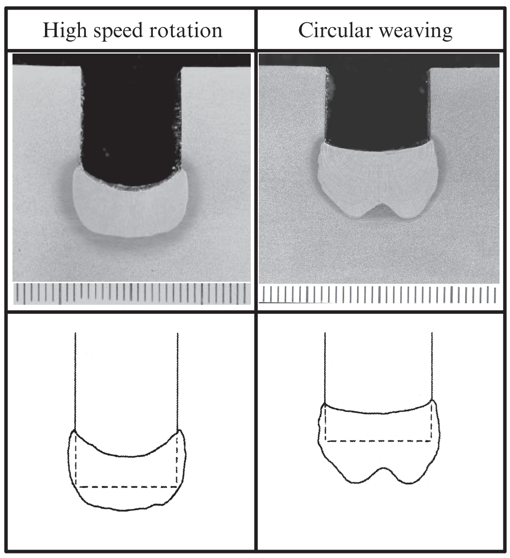


Fig. 3 Comparison of the bead shape by torch weaving method

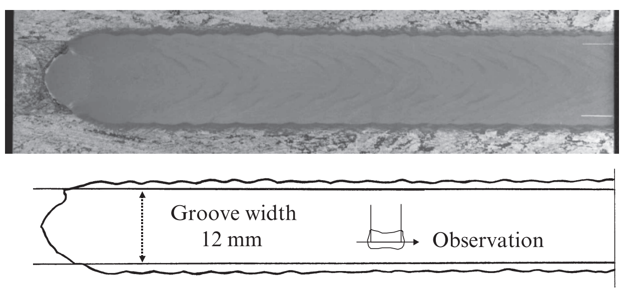


Fig. 4 Observation of the penetration width

4.2 Application to Inclined Joints

Because the weaving parameters can be set with asymmetrically in circular weaving, adaptability to inclined joints and other types by bilaterally-asymmetrical joints is also improved. **Photo 6** shows the condition of application to a 15 degrees-inclined narrow gap joint of a turbine diaphragm. In case of the conventional method, penetration was shallow at the groove corner part on the lower side of the inclined joint, and lack of fusion easily occurred. However, with the circular weaving method, it has been confirmed that stable weld quality can be obtained in actual welding as a result of improvement of the penetration shape by adopting bilaterally-asymmetrical weaving conditions.

4.3 Efforts to Achieve further Reduction of the Groove Width

In the narrow gap joint of the turbine diaphragm mentioned above, one plate was an extra-heavy carbon steel plate, while the other was a thin stainless steel plate with a thickness of about 6 mm. Accordingly, even in I-groove narrow gap welding, the welding distortion of the thin stainless steel plate was large, and an even smaller heat input had been required. Therefore, reduction of the existing 13 mm groove width was studied. In gas tungsten arc welding, an ultra-narrow gap welding method with a gap of 5–6 mm has been developed by using a small-width tungsten electrode, but because the contact tip in gas metal arc welding is a consumable, the target groove width was set at 8 mm, as this seemed to be the insertion limit with commercial small-diameter tips.

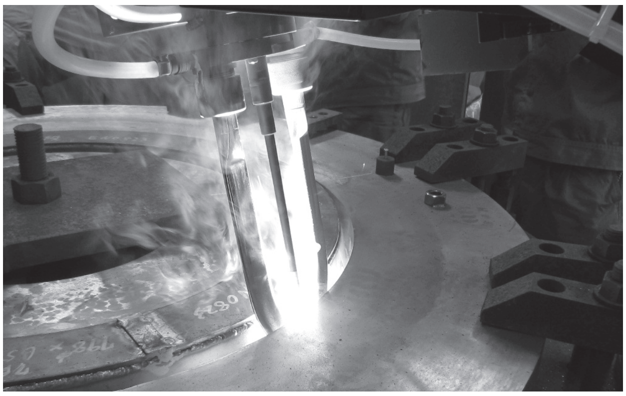


Photo 6 Application to the inclined narrow gap joints

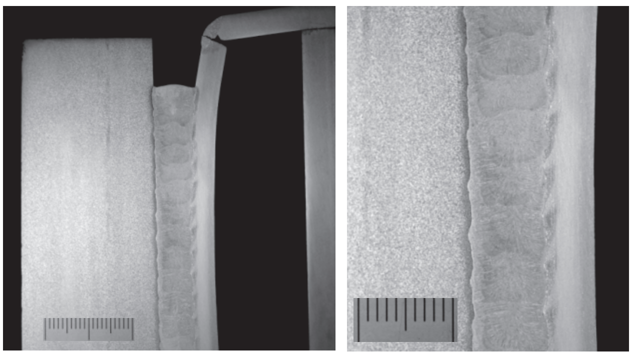


Photo 7 An example of 8 mm narrow gap welding

Photo 7 shows an example of the result of 8 mm narrow gap welding. Satisfactory results were obtained by applying the circular weaving method. Differ from actual products, the constraint of this test specimen was weak, and as a result, welding shrinkage caused the side plate to deform in an arched shape. For this reason, the groove width of narrow gap joints changes with progress of the welding pass. In the conventional high speed rotating arc method, the weaving width (i.e., rotating diameter) is fixed, but in the circular weaving method, it is possible to make fine adjustments in the weaving width corresponding to changes in the groove width, which expands the allowable range of groove width variation. It may be noted that two methods of fine weaving width adjustment are used together; namely, when the weaving width is reduced, the weaving angle of circular weaving is decreased, and when the width is increased, linear reciprocal weaving of the welding head traverse axis is performed simultaneously with circular weaving.

4.4 Combination with J-STAR™ Welding

Since spatter easily occurs in conventional narrow gap welding with a CO_2 gas shield, MAG gas (20% CO_2-Ar) welding, in which droplet transfer takes the spray type, had been adopted, as shown in Table 1. J-STAR™ welding[8)], which was developed by JFE Steel, has the advantage of minimizing spatter because spray transfer occurs even with a CO_2 gas shield.

Therefore, weldability in narrow gap welding with the J-STAR™ wire was investigated. With the conventional high speed rotating arc method, no significant difference was observed in penetration to the both side walls when the J-STAR™ wire was used, but an increase in the penetration depth was confirmed with the circular weaving method.

Photo 8 shows a comparison of the penetration shape in circular weaving method with an 8 mm groove width when using the conventional wire and the J-STAR™ wire. The welding heat input decreases because it is necessary to increase the welding speed when the groove width is decreased, assuming a constant welding current and welding bead height. Therefore, although penetration of the groove corner parts was barely adequate with conventional MAG welding, it can be seen that satisfac-

"J-STAR" is registered trademark in Japan.

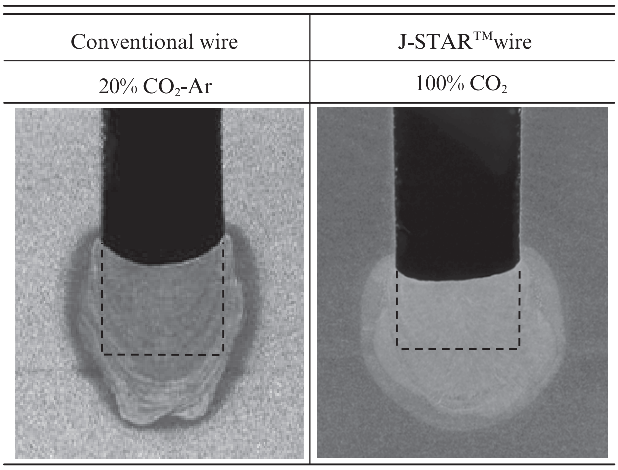


Photo 8　Comparison of the penetration shapes

tory penetration can be obtained with J-STAR™ CO_2 welding. This appears to be an effect of the strong convection flow of the weld pool, which is a distinctive feature of J-STAR™ welding, and the heat of dissociation of the CO_2 gas. Moreover, in explaining this difference, it is also conjectured that the high oscillation speed of the arc in the high speed rotating arc method prevents the formation of a depression in the weld pool directly under the arc, but with the circular weaving method, in which the weaving frequency is several hertz, a depression is formed in the weld pool and as a result, the penetration improvement effect of J-STAR™ was achieved to a remarkable degree.

5. Conclusion

The features of the high speed rotating arc welding method, which is a unique narrow gap welding method developed by JFE Engineering, and examples of its application were presented, and the condition of application of a newly-developed adaptive control function for welding speed corresponding to variations in the groove width and a tandem welding method in which one operator is responsible for two welding machines was introduced. The status of a study of the circular weaving method, which is being developed with the aim of realizing innovations in narrow gap welding, such as a further reduction of the groove width and welding of inclined joints, was also reported. The main points are enumerated below.

(1) In order to respond to variations in groove width, an adaptive control function for the welding speed by using the arc sensor was developed. This has eliminated the need for complicated excess metal height adjustment work after production welding and contributed to stabilizing weld quality.

(2) A one operator/two welding machine tandem welding method was adopted, shortening the lead time in welding of engine frame members to less than one-half of the conventional time.

(3) A circular weaving function was newly added to the existing narrow gap welding machine, expanding the range of application to bilaterally-asymmetrical joints such as 15 degrees-inclined joints. The potential of this technology for reducing the current 13 mm groove width to approximately 8 mm was confirmed.

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