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Recent Trend of Welding Technology Development and Applications†

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Abstract:

Resently, weight reduction of car bodies to reduce the environmental load substance and workability improvement to enhance the international competitiveness have made progress in the field of automotive materials. Under such circumstances, steel materials are required to have super high tensile strength and to be able to deal with complex structures of parts with high performance. In the field of thick plates and steel pipes, trend of mega-structural construction and high efficiency transportation leads to the strict demand of thick and high tensile strength steel products. To fully utilize such advanced steel products, the innovation of welding technologies are necessary and various welding technologies have been developed and applied with the progress of steel materials. This paper introduces the developments and the actual applications of state-of-the-art welding technologies in JFE Group.

1. Introduction

In application of steel materials, while development of steel materials is solely important, progress in welding technologies making good use of advanced steel materials is also necessary and indispensable. In recent years, high tensile strength steels have progressively replaced mild steel, as exemplified by increasing application of ultra-high strength steels and the tendency of this innovation has been conducted with managing compensated formability and weldability of selected materials[1]. Progress in welding technologies adopting these materials is strongly demanded in order to make the best use of these high tensile strength steels and establish a global position of technological superiority. The requirements in the automotive field are extremely stringent, in that the weldability of high tensile strength materials by various welding methods, such as resistance spot welding, arc welding, laser welding, etc., must be on the same level as that of mild steel, and at the same time, joint strength corresponding to the higher strength of the base metal must be secured, and corrosion resistance, crack resistance, and other properties must be satisfied in the same conventional process.

In the field of thick plates, high strength/heavy gauge steel products are increasingly adopted in response to the trends toward larger-scale container ships and taller high-rise buildings. Accompanying these trends, in the past several years, high efficiency welding technologies with high heat input have been developed for high strength, heavy gauge plates such as YP460 in the shipbuilding field and HBL™ 385 and HBL™ 440 in construction[2, 3]. Although thick materials of 80–100 mm in thickness have been demanded recently, it is still not possible to satisfy joint properties and weldability with the conventional 1-pass high heat input welding technology. Therefore, development of new, low heat-input welding technologies and development of high performance welding consumables is demanded.

With regard to the welded steel pipes (UOE steel pipes) improved welding efficiency in pipe manufacturing is strongly demanded in order to meet increased demand for heavy gauge, high strength steel pipes for the applications emerged with improvement of transportation efficiency, environmental countermeasures, and development of oil fields in deep waters, driven by the high level of activity in the energy field[4].

This paper presents an overview of recent developments in welding technology against the background outlined above. In the automotive field, the development of new welding technologies and improvement of weld-

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ability are discussed, and in the plate and steel pipe fields, narrow gap welding technology and new welding consumables for high heat input welding responding to the use of thick materials, and recent progress in multiple electrode submerged arc welding, which is a welding technology for UOE pipes, are introduced.

As important aspects of welding technology, techniques for improvement of fatigue strength, recent welding technologies and quality assurance technologies are also discussed, and the current status of main welding automation technologies which have been applied practically in JFE Engineering is reviewed.

2. Status of Technology Development in Automotive Field

In resistance spot welding in the automotive field, in addition to ensuring the nugget diameter and obtaining the targeted strength of the joint, the welding process must also be robust. With the trend toward high strength steel materials, the combinations of those sheets to are also increasingly diverse, and depending on the design, sheets to join may rather become thicker in some cases. In such cases, welding of a three-sheet lap joint consisting of thick structural members and an outer panel is required, and formation of stable nuggets becomes difficult. JFE Steel developed "Intelligent Spot™ welding," as shown in **Fig. 1**, to meet such requirements. Hitherto, spot welding has been performed at a constant electrode force and welding current. In contrast, "Intelligent Spot™ welding" is a technology in which stable nuggets are formed by changing the electrode force and welding current during welding. This technology is already in practical use[5].

Moreover, in welding of high tensile strength steels, it was difficult to secure the cross tensile strength of joints as the strength increased. JFE Steel developed the "Pulse Spot™" welding technology to satisfy stable joint properties by controlling the segregation and strength distribution of welded joints[6]. As a feature of this technology, a short-time, high-voltage pulsed current is applied after the main current. In conventional welding, a current pattern that utilizes the tempering effect of the high strength part by applying a temper current has long been used. In comparison with that method, the developed method makes it possible to obtain more stable weld properties in a short time. A typical Pulse Spot™ welding current pattern is shown in **Fig. 2**. Recently, in addition to new welding processes, JFE Steel has also explored an approach to improvement of joint properties by studying the controlling factors for their strength characteristics based on a fracture mechanics analysis of resistance spot welds of high tensile strength materials[7].

In addition to development of unique resistance spot welding technologies for high tensile strength materials, JFE Steel is also engaged in technical development for improvement of welding efficiency. In particular, in order to perform resistance spot welding in the automobile assembly process, it is necessary to access the welds from both sides of the steel sheets by applying robots to welding, but for this, it was necessary to manage an access route and space to insert the welding guns from both sides. Therefore, JFE Steel developed a single-side spot resistance welding technology which enables welding by access from only one side. Although series type single-side spot welding methods by two electrodes have also been studied for many years, it was difficult to manage a stable current flow; instead JFE Steel developed the indirect type single-side spot welding method to solve this problem[8]. In this method, it is necessary to optimize the position of the grounding electrode depending on the component, but in addition to this, the electrode force and current are also controlled during welding, as illustrated in **Fig. 3**. Taking advantage of this feature, this is a welding technology with excellent robustness which makes it possible to suppress instabil-

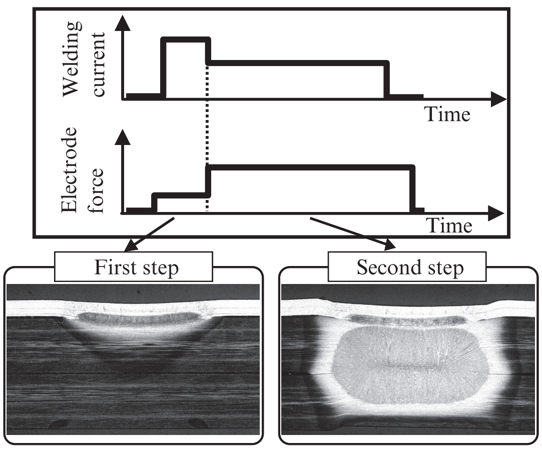


Fig. 1 Schematic illustration Intelligent Spot™ welding process for three-sheet-joint

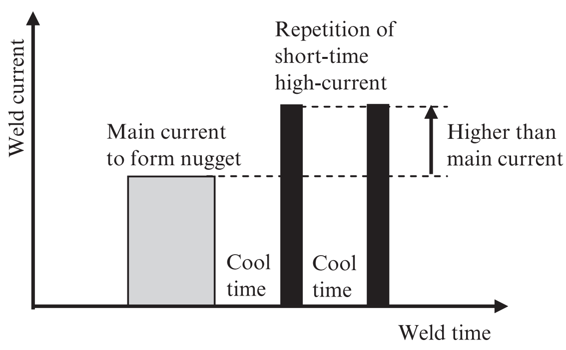


Fig. 2 Weld current pattern of Pulse Spot™ welding

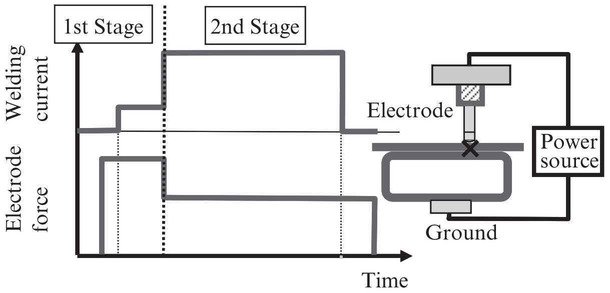


Fig. 3 Conditions of single-side spot welding

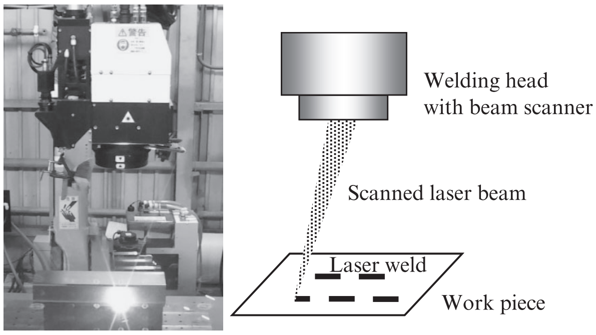


Fig. 4 Schematic diagram of remote laser welding

ity caused by shunting.

As a welding technology which accesses the weld from one side, laser welding is also an important candidate technology. Recently, a high efficiency welding technology called remote laser welding (**Fig. 4**) was developed thanks to progress in laser oscillators and peripheral hardware such as optical systems, and the technology has been applied widely, both in Japan and other countries[9]. While many issues for laser welding technology remain to be solved, such as the cost of the equipment, safety countermeasures, etc., it is expected to be possible to satisfy both improved stiffness and reduced sheet thickness by application of high tensile strength materials by a changeover from point welding in resistance spot welding to continuous/linear welding[10]. Moreover, expanded application of laser welding is also expected in the future by selection of laser welding methods suited to respective parts, for example, application of laser arc hybrid welding to auto chassis parts, remote laser welding to the door area, etc.

3. Status of Technical Development in Plate and Steel Pipe Fields

Due to the increasing scale of structures in the shipbuilding and construction fields in recent years, adoption of high strength and heavy thickness in the steel materials used in those structures is progressing. In the shipbuilding field, upscaling of container ships has progressed to 18 000 TEU, considering efficiency in transportation of long distance cargos (TEU: Twenty-feet equivalent unit; Container capacity converted to 20-foot container unit) . Similarly, there is an orientation toward designs reaching 80–100 mm in thickness of high strength steels. Therefore, two-electrode electrogas welding (EGW) is now applied to the hatch side coamings and similar parts of ships that had been welded in one pass by conventional large heat input welding[11], and the low heat input multi-layer welding by CO_2 arc welding is inevitably used welding of longitudinal stiffeners. However, two-electrode EGW requires an increased heat input and advanced welding technology. On the other hand, various problems also arise in multi-layer CO_2 arc welding, including increased welding time and cost. To solve these problems, the development of narrow gap welding technology which makes it possible to reduce the heat input and improve welding efficiency has been promoted. J-STAR™ Welding[12], which is a type of CO_2 arc welding, is one such effort. However, J-STAR™ Welding realizes droplet transfer in a spray form, enabling deep penetration welding with minimal spatter, and thus is an optimal method for narrow gap welding. **Figure 5** shows the setup for J-STAR™ Welding. In contrast to electrode positive (EP) welding, which has been used until now, the opposite polarity, electrode negative (EN), is adopted in J-STAR™ Welding. A wire with a trace amount of rare earth metal (REM) as an arc stabilizer is used. Because J-STAR™ Welding utilizes a conventional welding power source and enables narrow gap welding simply by selection of the proper welding wire, low cost, high efficiency welding is possible. Moreover, due to the smaller number of welding passes and decrease in the amount of welding, application to heavy gauge plates is considered possible in the sectors of building and bridge construction.

Electroslag welding (ESW) is used in welding of diaphragms of box columns, which is considered necessary in the sector of building construction. Low heat input, multi-layer welding is difficult to apply to this work, but

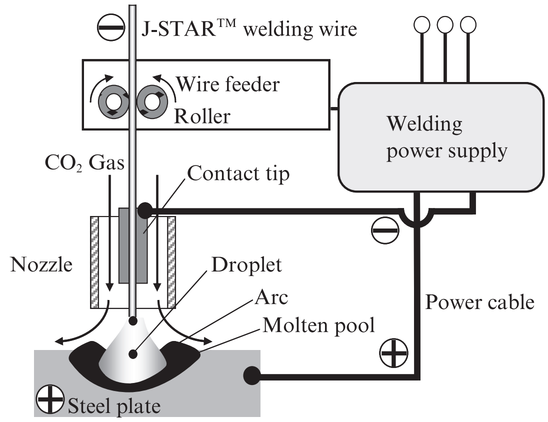


Fig. 5 Illustration of setup for J-STAR™ Welding

as plate thickness increases, ultra-large heat input welding becomes unavoidable. As a result, it is difficult to obtain stable weld metal properties. Since dilution of the base metal is large, it is important to adjust the composition of the welding wire and flux corresponding to conditions, but composition adjustment of solid wires requires time and increases costs. Given this situation, technical development was carried out to enable quick, low cost composition adjustment corresponding to welding conditions by using an ESW wire as a metal cored wire (MCW) design[13]. Elements that cannot be added stably in solid wires can be added easily by this MCW design, and stabilization of the properties of the weld metal of ESW is possible with extra thick materials. Ministerial approval has already been obtained for these wires, and final tests have been carried out aiming at the practical application stage.

Regarding technical development in the field of steel pipes, the following introduces a multiple electrode submerged arc welding (SAW) method that can be applied to welding of the longitudinal seam of welded pipes, as performed in the UOE pipe manufacturing process. In recent years, there has been a high need for heavy wall thickness, high strength steel pipes. As a result, the welding process has become the rate-determining step in the manufacturing process, and decreased toughness of the heat affected zone (HAZ) due to excessive heat input and other negative effects have become a concern. Hitherto, the compositions of the base metal and the weld metal have been designed to be suitable for large heat input welding, and study centered on large heat input, high speed welding by multiple electrode SAW. However, as shown schematically in **Fig. 6**, it is possible to increase penetration depth and deposition efficiency, even with the same welding current, by using a small diameter wire, which had not been studied in the past. Based on this, a heat input-saving SAW technology which enables efficient welding was developed by increasing the degree of freedom in control of the penetration shape of the weld[14]. As a result, it became possible to give the ideal welding bead, and the ideal high speed welding technology for heavy thickness materials, which can also suppress the occurrence of welding defects, could be developed.

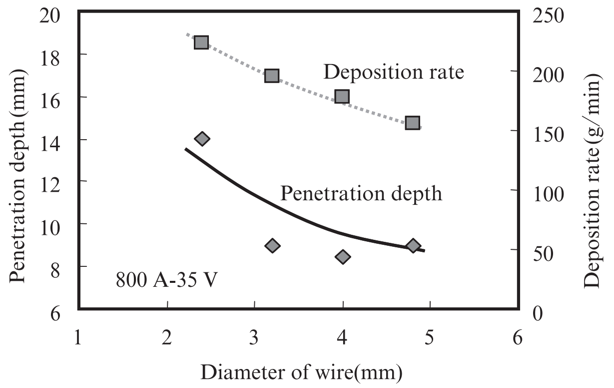


Fig. 6 Effect of wire diameter on penetration depth and deposition rate

4. Current Status of Basic Technology Development

Since the 1970s, much research has been devoted to microstructural control of weld metal. Microstructural control in a Ti-B system by an acicular ferrite microstructure was considered optimal and has been widely applied in order to achieve high toughness. However, the formation mechanism of that microstructure has still not been clarified, and it is currently applied by empirical phenomenology. Although various studies have been carried out up to now, new knowledge continues to be obtained by utilizing state-of-the-art observation techniques, for example, techniques for identifying the inclusions that acicular ferrite forms by direct observation of the acicular ferrite formation process by the high temperature laser scanning confocal microscope, and detailed analysis of their structures, and detailed analysis of the crystal orientation relationship of inclusions and ferrite and ferrite and austenite[15].

This kind of basic study and other important studies related to welded joints are reviewed in the following. As particular issues, techniques for improving fracture and fatigue properties of stress concentration at the weld toe are important, and a variety of studies have examined this issue. Up to the present, improvement of HAZ properties by composition design of the steel material has been used as a technique for improving the fracture properties of welds. However, NBFW™ (Non-Brittle Facture Welding) method[16] was developed as a technique for improving performance from the welding process. In the NBFW™ method, the toughness of the HAZ around the weld toe is improved by applying ingenuity to the pass sequence and the heat input in the final layer of multi-layer welds.

Where the fatigue characteristics of welds are concerned, due to tensile residual stress and stress concentration in the weld toe, it was not possible to improve the fatigue strength of joints even if the strength of the base metal was increased, and this was a large barrier to the use of high strength materials. What was studied in response to this problem was a method for controlling the smooth bead shape so as to mitigate stress concentration in the weld toe by a new welding technology, and peening treatment to smoothen the bead shape after welding and give compressive residual stress to parts where tensile residual stress was present.

A hybrid welding technology of plasma welding and

J-STAR™ welding may be mentioned as an example of the former. Conventionally, the polarities of the plasma electrode and the CO_2 arc welding electrode were opposite, and it was difficult to control the bead shape due to the repulsion between the plasma and the arc. However, by use in combination with electrode-negative J-STAR™ welding, a smooth weld bead toe shape is easily obtained, and it is possible to improve fatigue characteristics[17].

On the other hand, if it is possible to control the toe shape only in hammer peening, the work load in welding is similar to that in grinder treatment, and for that reason alone, no large merit can be obtained. However, hammer peening also has the effect of introducing residual compressive stress. The technique of hammer peening on base metal (**Fig. 7**) was developed, making maximum use of the effect of introducing residual compressive stress, and application to actual bridges has begun[18].

In quality assurance of welds, visualization technology was applied to electric resistance welded pipes, and a study was carried out by the phased array ultrasonic testing method. In visualization technology, direct observation of the molten pool has been performed by using the high speed camera, which has been widely used in observation of welding phenomena in recent years, and the reliability of welds has been improved by optimization of welding conditions based on the results of that observation. Moreover, a quality assurance technology for welds has been established by utilizing the phased array technology, which makes it possible to apply online inspection technology with sensitivity more than 10 times higher than in the past[19]. Since these technologies are applicable to arc welds, laser welds, and other types of welds, further development can be expected in the future.

Friction stir welding (FSW) appears as a recent technology. As welding technologies, fusion welding employing arc, laser, and other methods has been investigated in research hitherto, and much technical development has been carried out. However, many problems arise when applying the complex phenomena that occur accompanying melting and damage at the HAZ to joining of high tensile strength steels and dissimilar materials. Therefore, FSW, which is a non-fusion joining method, has attracted attention as a new technology[20].

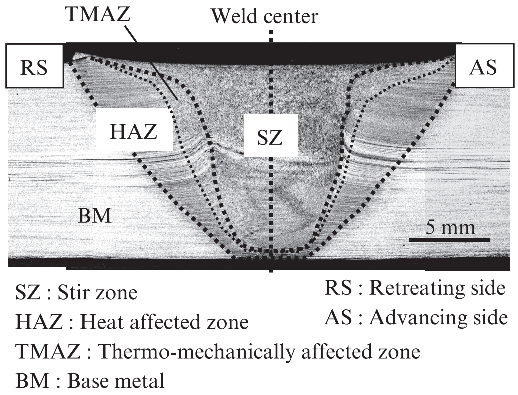


Photo 1 Macrostructure of friction stir welding

Because tool durability is a problem in this joining technology, to date, practical application had centered on low melting point metals such as Al and the like. However, with progress in tool development, research has now advanced also to steel materials. In particular, studies have been carried out on application of FSW to high tensile strength steel sheets for automotive applications, and expansion of the range of joining conditions under which strength can be obtained stably can be seen. On the other hand, in the field of thick plates, study of application to the girth-welded joints of UOE pipes has begun. Butt-welded joints have been fabricated with the plate thickness of 12 mm, as shown in **Photo 1**, and detailed study of the microstructure, toughness evaluation, etc. is underway. Since FSW is a non-fusion method, it has large merits from the viewpoint of weldability, in that defects such as blowholes, residual stress, and welding distortion, etc. are suppressed, and the welding process does not generate spatter, fumes, or slag. High expectations are placed on future practical application in joining of dissimilar materials, including suppression of the formation of intermetallic compounds, which have a large negative effect that can be seen at the bonded interface.

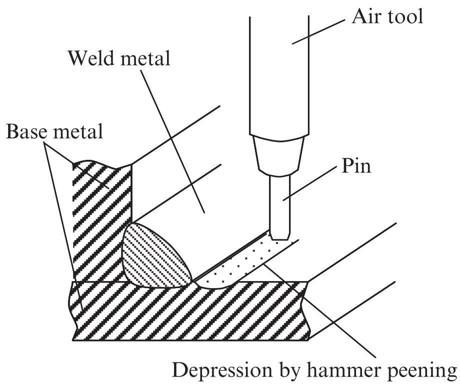


Fig. 7 Schematic diagram of hammer peening on base metal

5. Trends in Welding Automation Technologies in Actual Fabrication

JFE Engineering produces a wide range of welded structure products, including industrial machinery such as engines, turbines, shield drilling machines, and cranes and social infrastructure products such as bridges, coastal structures, and water pipes. Field welding has also become a key technology for laying pipelines and railway rails and construction of various types of plants.

This chapter introduces four welding automation technologies developed by JFE Engineering, an unmanned robot welding system, narrow gap welding for extra thick steel plates, field welding for pipelines, and rail welding, and reviews the transition of technologies and recent trends.

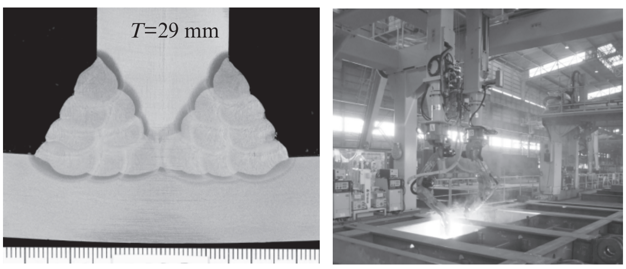
5.1 Unmanned Robot Welding System

Tsu Works, JFE Engineering introduced a full-scale unmanned robot welding system by multi-articulated robots in 1992 as part of a changeover to line production of bridges and coastal structures[21]. The high speed rotating arc welding process, which was developed independently by JFE Engineering, was applied in these robots, and a large improvement in productivity and quality stabilization were achieved thanks to its outstanding high current, high speed weldability and arc sensor.

At the time of introduction, the object was only one pass horizontal fillet weld joints. However, as a result of subsequent technical development, its range of application was expanded to vertical and inclined joints and further, to multi-layer full penetration joints. As a result of a review of the robot axis configuration, development of a compact rotating torch, development of a simple teaching function, and other improvements, its range of application was expanded from simple flat welded panels to complex 3-dimensional structures. As recent examples of actual application, **Photo 2** shows a gouging-less full penetration weld joint and robot welding of a breakwater panel.

5.2 Narrow Gap Welding of Heavy Plates

Commercial portable rectangular coordinate robots are applied to welding of grooved multi-pass weld joints of thick plates. However, in the case of extra thick plates with thicknesses exceeding 100 mm, the amount of deposited metal becomes extremely large, and decreased toughness is a problem in high strength steels. Narrow gap welding with a square parallel groove is an effective solution to these problems. JFE Engineering developed the narrow gap welding process with high speed rotating arc in the 1980s, and has applied this technology to extra thick plate products such as steel frames, bridges, parts for heavy machinery, etc.[22].



(a) Full penetration weld joint (b) Breakwater panel

Photo 2 Recent applications of unmanned robot welding

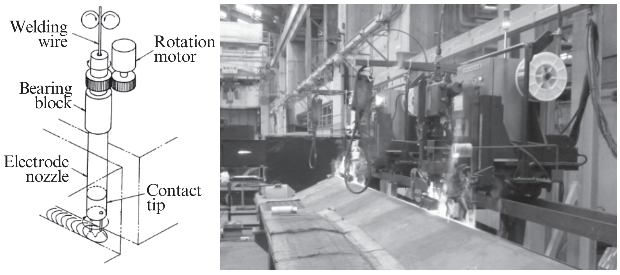


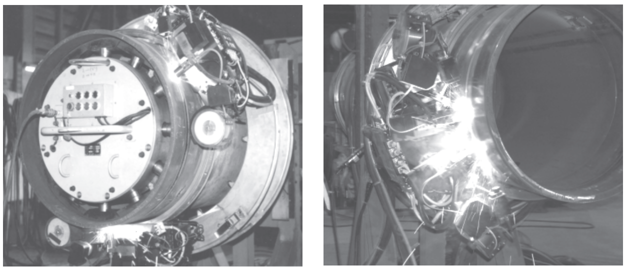
Fig. 8 Principle and application of the narrow gap welding

The principle of this welding process and an example of application are shown in **Fig. 8**. Welding efficiency and quality have improved greatly in comparison with the conventional technology as a result of application of the tandem unmonitored welding method and development of an adaptive control function for welding speed responding to changes in groove width. A circular weaving function was also added, thereby expanding the range of application to inclined and other asymmetrical joints, and efforts to reduce the groove width from 13 mm to around 8 mm and minimize welding distortion are now underway.

5.3 Field Girth Welding of Gas Pipelines

In comparison with the shop welding described above, field welding of gas pipelines is performed in a severe work environment and also has high quality requirements, and for these reasons, acceptance of automatic welders in the field was delayed. However, in the 1990s, the reliability of automatic welders improved, compact designs were developed, and large diameter, heavy thickness pipes were adopted in gas pipelines. Accompanying these changes, the number of joints in which automatic welders were used increased rapidly, by more than four times in approximately 5 years, and the automation rate of high pressure main pipelines exceeded 80%. At present, the automation rate is nearly 100%. In response to the trend toward large diameter, heavy wall thickness pipelines, all companies involved in welding work have taken on the challenge of high efficiency by simultaneous inside-outside welding and the square groove narrow gap welding methods, but due to the field workability of these methods and the complexity of groove preparation work, they did not become established in field welding. Accordingly, later efforts focused on improvement of existing machines[23].

Photo 3 shows an example of application of a high efficiency welding method using two torches. Photo 3(a) shows a two head method in which two welding carriages move in parallel in the same direction on the same rail. However, because the interval between the car-



(a) Two head method (b) Dual torch method

Photo 3 Highly-efficient welding methods by two torches

riages is changed by changing their speed depending on the welding position, application of this method is limited to large diameter pipes of a certain size. On the other hand, (b) shows a dual torch method which was developed recently. The range of application has been extended to smaller diameter pipes, and operation and monitoring have been simplified, making this an extremely practical technology for field welding.

5.4 Rail Welding Technologies

JFE Engineering's rail welding technologies have an extensive track record, which includes Japan's *shinkansen* superexpress, conventional lines operated by JR (Japan Railway Company), subways, and private rail lines. Rail welding consists of three welding operations, namely, primary welding, in which short rails are made up in the shop into long rails with lengths of 100–200 m, secondary welding, in which the length of the rails is extended to approximately 1 km in the field, and tertiary welding, in which final laying or rail exchange is performed at the site. Primary welding is performed by flash welding, and secondary welding is done by gas pressure welding. The main techniques for tertiary welding are enclosed arc welding and thermit welding. JFE Rail Link not only performs secondary and tertiary welding as a welding contractor, but also sells flash welding machines to railway companies. This technology offers high welding efficiency, with a flash welding time of about 1.5–4 minutes, which is shorter than that by other joining methods, and is also excellent in terms of quality stability and welding management[24].

The principle of flash welding and a rail welding machine are shown in **Fig. 9**. This machine is a lightweight, portable machine designed for use at field bases. In the construction of the Hokuriku *shinkansen* line in preparation for the Winter Olympic Games in Nagano, this technology supported the rapid pitch of field work of 30 or more rails/day. Recently, a new low cost, compact, lightweight type was developed in the renewal of fixed type machines at the rail center; this technology offers a combination of high efficiency and power saving thanks to a unique control system and is demonstrating its effectiveness in welding of long rails.

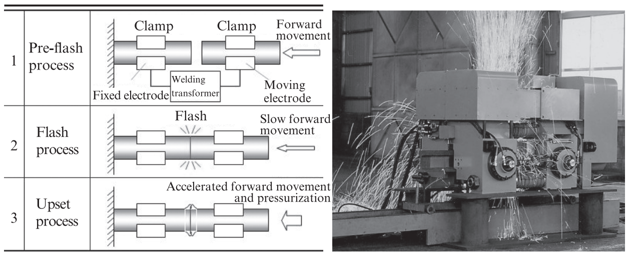


Fig. 9 Principle and portable machine of the flash welding

6. Conclusion

This paper has presented an overview of recent trends in the development of welding technologies in the JFE Group by reviewing typical technologies in the automotive material field and the plate and steel pipe fields. Trends in basic research on the microstructure of the weld metal, which has continued from an early date, technical progress by welding methods which are being promoted from the viewpoint of fatigue and fracture of welds, and recent quality control technologies for welds and joining technologies were also introduced. These technologies have already reached the level of practical application, and their application is necessary and indispensable presence as major key technologies when responding to the strict requirements placed on steel materials. JFE Steel is engaged in technical development on a daily basis in order to supply advanced steel products and state-of-the-art use technologies to customers.

JFE Engineering is endeavoring to achieve higher efficiency in welding and to secure stable quality in a diverse range of steel structure products. This paper introduced four examples of welding automation technologies which were developed independently by JFE Engineering. Because welding is a critical technology which holds the key to the safety of social infrastructure, industrial machinery, and energy-related products, the company is putting great effort into technical development in order to create the foundation for a safe and secure life.

The JFE Group is confident that progress in the development of these welding and joining technologies, use technologies, and automation technologies in the group will enhance global technological competitiveness while also contributing to society.

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