

Development of Welding Technologies for Automotive Body

MATSUDA Hiroshi*¹ KITANI Yasushi*² MATSUSHITA Muneco*³ TANIGUCHI Koichi*⁴ SAWANISHI Chikaumi*⁵
IKEDA Rinsei*⁶

Abstract:

The new welding technologies developed by JFE Steel, which contribute to optimise automotive body structure with applying high strength steel sheets, are introduced. This paper includes Pulse SpotTM enhancing the weld joint strength of high strength steel sheets, J-MAC spotTM welding which enables short pitch welding by new adaptive control, Single-Side SpotTM welding which realises closed cross-section structure by controlling electrode force and welding current, and high speed and high efficiency remote laser welding.

1. Introduction

Severe requirements for reducing environmental impacts and improving passengers' safety promote development and application of higher strength steel sheets for automotive bodies. The welding technologies used in the automobile assembly process are critical for optimizing the structure of the automotive body while taking full advantage of the performance of these steel sheets. However, increase in strength and performance of steel sheets leads to high alloy compositions, which

tends to deteriorate the weldability. Moreover, in realizing high strength and high rigidity in automotive bodies, welding must be possible under more severe conditions than in the past. To fulfill these various needs, JFE Steel is actively engaged in research and development of welding technologies in addition to the development of new high strength steel sheets with excellent formability. This paper presents an outline of welding methods which JFE Steel has developed as new welding technologies for the automotive body assembly process. These include Pulse SpotTM welding, which enhances the strength of resistance spot welding joints of ultra high strength steel sheets, J-MAC SpotTM welding, which enables short pitch resistance spot welding to secure highly rigid automotive body, Single-Side SpotTM welding, which can be applied to the closed cross-section automotive parts, and remote laser welding to secure high joint strength in high speed welding.

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*¹ Dr. Eng.,
Senior Researcher General Manager,
Joining & Strength Research Dept.,
Steel Res. Lab.,
JFE Steel



*² Dr. Eng.,
Senior Researcher Deputy General Manager,
Joining & Strength Research Dept.,
Steel Res. Lab.,
JFE Steel



*³ Ph. D.,
Senior Researcher Deputy General Manager,
Joining & Strength Research Dept.,
Steel Res. Lab.,
JFE Steel



*⁴ Senior Researcher Deputy Manager,
Joining & Strength Research Dept.,
Steel Res. Lab.,
JFE Steel



*⁵ Senior Researcher Assistant Manager,
Joining & Strength Research Dept.,
Steel Res. Lab.,
JFE Steel



*⁶ Dr. Eng.,
General Manager,
Joining & Weldability Evaluation Center,
Structural Materials Solution Div.,
JFE Techno-Research

2. Pulse Spot™ Welding Technology

2.1 Issues of Cross Tension Strength of Ultra-High Strength Steel Sheets

In order to improve the crashworthiness of automotive bodies, securing the fracture strength of resistance spot welding joints is necessary and indispensable. However, in joints of ultra-high tensile strength materials, brittle fracture in nuggets under stress loading in the peeling direction and a resulting decrease of joint strength are concerns. As the cause of this problem, stress concentration in the nugget edge under stress loading, hardening and embrittlement due to quenching of the nuggets and decreased toughness due to segregation of P during solidification have been pointed out¹⁻³. To date, the in-process tempering treatment method was proposed; in this method, nuggets are tempered by post-heating by flowing a current after nugget formation⁴. However, the decreased shear strength of the joint due to softening of the nuggets, the necessity of an extended cooling time before applying a current, etc. were problems. Therefore, JFE Steel developed the “Pulse Spot™ welding”⁵⁻¹¹ resistance spot welding technology utilizing the heat generated by applying a short-time high current as a welding method that improves the peel strength of resistance spot welding joints welded in a shorter time than is possible with the conventional temper treatment, while also avoiding decreased shear strength.

2.2 Concept and Features of Pulse Spot Welding

Figure 1 shows the results of a numerical analysis of the temperature distribution and current density distribution in short-time, high-current post-heating (hereinafter, pulsed current)⁵. This figure shows the result when a nugget was formed at a weld current of 6 kA, an adequate cooling time of 100 cycles (2s) was set, and 1 cycle (0.02s) of a high current of 20 kA was flown in order to clarify the distinctive features of the pulsed current. In pulsed current, it can be understood that the current density distribution becomes remark-

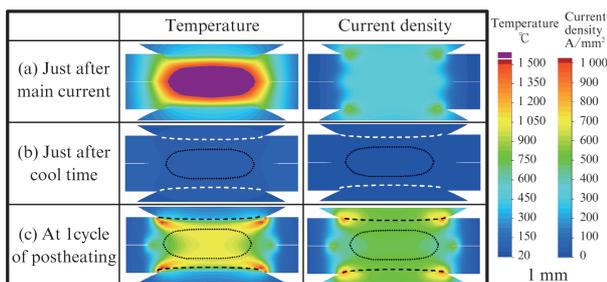


Fig. 1 Temperature distribution and current density distribution by short-time high-current post-heating⁵⁾

ably high in the vicinity of the electrode contact point, and periphery of the nugget near the electrode tends to be heated to a higher temperature than the interior of the nugget.

Thus, by utilizing the phenomenon of preferential heat generation at the nugget periphery by the short-time high-current, Pulse Spot welding achieves ① enhanced joint toughness by alleviating P segregation in nuggets and ② improved joint strength by the effect of relaxing the stress concentration at the nugget edge by expanding the heat affected zone.

Next, the results of an evaluation of the improvement of the peel strength of joints by Pulse Spot™ welding will be presented. Using a 1 180 MPa class cold-rolled steel sheet with a thickness of 1.6 mm as the test material, cross tension strength (CTS) was evaluated by a cross tension test, which is a method for evaluating fracture strength in the peeling direction in a 2-sheet lap joint. Figure 2 shows the standard weld current pattern of Pulse Spot welding. In the current pattern used here, a nugget was formed by the main current, after which cooling and application of a short-time, high-current pulsed current were repeated twice.

Figure 3 shows the relationship between the current value of the pulsed current (I_p) and CTS. With conventional welding without the pulsed current, CTS=7 kN was obtained, but in contrast, CTS=12 kN was obtained at $I_p=8$ kA with Pulse Spot™ welding, con-

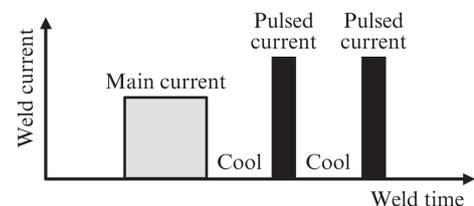


Fig. 2 Current pattern of Pulse Spot™ Welding

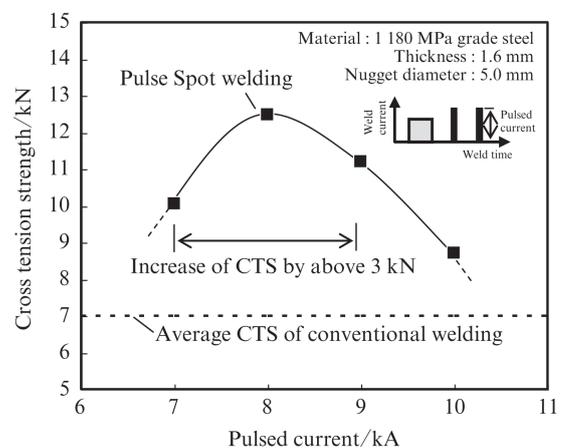


Fig. 3 Increase of cross tension strength by Pulse Spot™ welding and the effective conditions of pulsed current

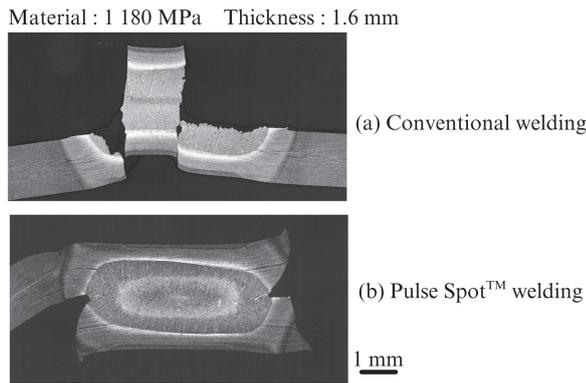


Photo 1 Cross-sectional macrostructures of fractured specimen after cross tension test⁵⁾

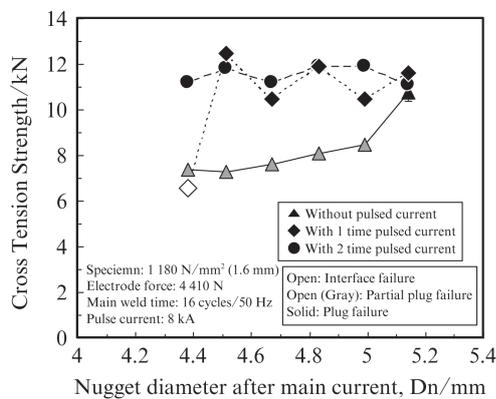


Fig. 4 Influence of Pulse Spot™ Welding on CTS and failure mode with nugget diameter variation¹²⁾

firming the remarkable CTS improvement effect of this technology. In addition, CTS was improved in a wide range from $I_p=7$ kA to 9 kA, confirming that weldability is also satisfactory. **Photo 1** shows the cross-sectional macrostructure after the cross tension test with $I_p=8$ kA. With conventional welding, a crack propagated in the nugget, leading to fracture. However, with Pulse Spot™ welding, propagation of the crack into the nugget was not observed, and the specimen displayed a satisfactory plug failure mode. It is considered that CTS was substantially improved owing to the effects of improvement of nugget toughness and relaxation of the stress concentration at the nugget edge.

The weldability of Pulse Spot welding was evaluated by a test simulating the variation of the nugget diameter assumed in the actual automotive body assembly process¹²⁻¹³⁾. The diameter of the nuggets formed before pulsed current in a two-sheet lap joint of a 1 180 MPa class cold-rolled steel sheet with a thickness of 1.6 mm was varied by changing the weld current of the main current, while maintaining a constant current value of the pulsed current. **Figure 4** shows the relationship between CTS and the nugget diameter (D_n) at each number of pulsed currents (N_p). When only the

main current was applied ($N_p=0$), a CTS of 10.7 kN with plug failure was obtained with $D_n=5.2$ mm. However, as D_n became smaller, partial plug failure occurred and CTS decreased. In the range of $D_n=4.5$ mm to 5.2 mm, plug failure also occurred with both $N_p=1$ and 2, and CTS improved to 10 kN or more. In contrast to this, when D_n was reduced to 4.4 mm, CTS at $N_p=1$ decreased to the same level as with $N_p=0$, but it was possible to suppress this decrease in CTS by using $N_p=2$. From these results, CTS can be improved over a wide range of nugget diameters by using repeated Pulse Spot™ welding, and stable joint strength can be secured easily even in case of the nugget diameter variations assumed in the actual automotive body assembly process.

2.3 Development of Pulse Spot Welding Technology

Practical application of this technology in the assembly welding process of high strength steel sheets at automotive body assembly lines is already being promoted through joint research and development with auto makers. With expansion of the applications of high strength steel sheets and optimization of automotive body structures for further automotive body weight reduction, this is expected to be an extremely effective welding technology in the future.

3. J-MAC Spot™ Welding Technology

3.1 Issues of Reduction of Weld Spacing and Concept of J-MAC Spot Welding Technology

In recent years, reduction of the weld spacing in resistance spot welding in the welding assembly process has been studied with the aim of enhancing the collision strength and rigidity of the automotive body. However, when the weld spacing is reduced, shunting to existing welds has a large influence on nugget formation at the target welding position. As a result, it is necessary to set the proper welding current at each welding point so as to secure the assumed nugget diameter at the respective welding positions. However, this gives rise to other issues, such as the excessive work time required in selecting the welding conditions. As a technique for suppressing variations in nugget diameter due to this kind of shunting, etc., a resistance spot welding method employing adaptive control was studied^{14,15)}. Unlike conventional constant current control, in the adaptive control method, the heat quantity is calculated by monitoring the current and voltage between the electrodes during welding, and the welding current is changed successively so as to coincide with a preset target heat quantity during welding. However, the effect

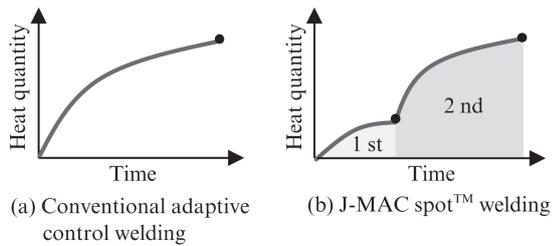


Fig. 5 Schematic diagram of target heat quantity in adaptive control

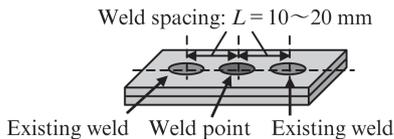


Fig. 6 Schematic illustration of experimental set up

of that technique was inadequate under conditions where shunting to existing welds was remarkable, for example, when the weld spacing was 10 mm or less. In addition, little progress was made in elucidating the mechanism of the shunting, which changes depending on the strength of the steel sheets and other factors. The J-MAC Spot welding technology¹⁶⁻¹⁹⁾ is a welding technology which makes it possible to secure a uniform nugget diameter independent of the shunting condition and strength of the steel sheets by dividing the adaptive control period and controlling the heat quantity to the optimized multi-stage current pattern.

Figure 5 shows a schematic diagram of the target heat quantity patterns in conventional adaptive control spot welding and J-MAC Spot welding. In conventional adaptive control spot welding, in which only the final target heat quantity is set, but in J-MAC Spot welding, the adaptive control period is divided and target quantities are set for each section. Here, current flowing at the object welding position is stabilized by expanding the current-flow diameter between the two sheets by dividing the control period into two stages and setting the target heat quantity low in the 1st stage, and a uniform nugget diameter is then secured by increasing the heat quantity in the 2nd stage.

3.2 Effect of Application of J-MAC Spot Welding Technology

In order to verify the effect of application of J-MAC Spot welding, welding by the respective control methods of constant current control, conventional adaptive control and J-MAC Spot welding was performed between two existing weld points with different weld point spacings, as shown in **Fig. 6**, and the nugget diameters were measured and compared.

Figure 7 shows the relationship between the nugget

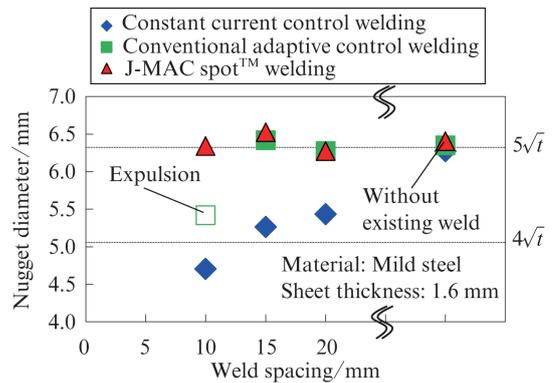


Fig. 7 Relationship between nugget diameter and weld spacing in the joint of mild steel sheets

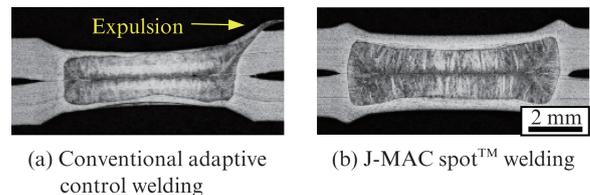


Photo 2 Cross-sectional macrostructure of welds with 10 mm pitch¹⁹⁾

diameter and the weld spacing in two-sheet welding of mild steel sheets with a sheet thickness of 1.6 mm. **Photo 2** shows photographs of the cross-sectional macrostructures obtained by conventional adaptive control welding and J-MAC Spot welding with a 10 mm spot welding spacing. In the case of constant current control, the nugget diameter decreased due to the large shunting accompanying reduction of the weld spacing, and the results fell below $4\sqrt{t}$ at a weld spacing of 10 mm. With conventional adaptive control, the current at the weld point decreased due to shunting until the weld spacing of 15 mm, but appropriate compensation of this current was possible, and a nugget diameter of approximately $5\sqrt{t}$ was obtained. However, expulsion occurred at the weld spacing of 10 mm, and the nugget diameter decreased. In the initial stage of current flowing, the current-flow diameter between the sheets at the weld point decreases, and shunting to the existing weld occurs easily. Therefore, with the weld spacing of 10 mm, the welding current is increased rapidly in the initial period of current flowing in order to compensate for the reduction in the heat quantity due to shunting, but it is thought that expulsion occurs as a result of excessive heat generation as a result of the high current density around the steel sheet surface in the area where the electrode is in contact with the sheet. On the other hand, with J-MAC Spot welding, a nugget diameter of approximately $5\sqrt{t}$ was obtained even with the weld spacing of 10 mm. It can be understood that increasing the contact diameter in the 1st stage of current flowing,

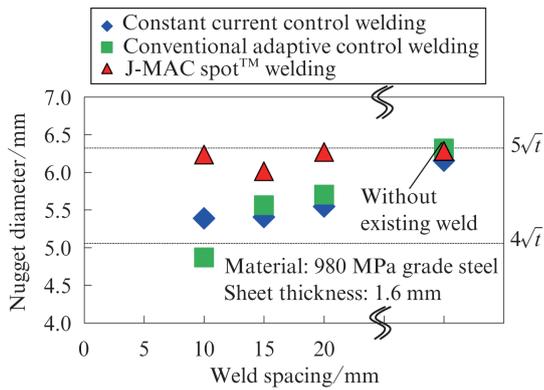


Fig. 8 Relationship between nugget diameter and weld spacing in the joint of high strength steel sheets

and then forming the nugget by concentrating the current between the sheets in the 2nd stage of current flowing enables welding without a sudden increase in the welding current, even when shunting is large, and as a result, the occurrence of expulsion is suppressed and stable welding becomes possible.

Figure 8 shows the relationship between the nugget diameter and the weld spacing in two-sheet welding of 980 MPa class high strength steel sheets with a sheet thickness of 1.6 mm. The nugget diameter decreases as the weld spacing is reduced, not only in constant current welding, but also in conventional adaptive control welding. This is due to the influence of sheet separation, which occurs when the existing weld point is formed. When welding high strength steel sheets, the reduction in the contact diameter between the sheets at the object welding position due to the sheet gap becomes remarkable as the weld spacing is reduced, and as a result, the resistance between the electrodes increases. Therefore, it is thought that the system misrecognizes the quantity of heat generation as excessive and reduces the welding current, and this results in a decrease in the nugget diameter. On the other hand, in the case of J-MAC Spot welding, a nugget diameter of approximately $5\sqrt{t}$ was obtained irrespective of the weld spacing. Stable nugget formation is possible by eliminating the sheet gap by current flowing in the 1st stage, when the resistance between the electrodes tends to increase, and sufficiently enlarging the contact diameter between the sheets, and then controlling the weld current to the value which is essentially necessary for nugget formation by current flowing in the 2nd stage of current flowing.

As described above, although the welding phenomena that occur when the weld spacing is reduced differ depending on the strength of the steel sheets, J-MAC Spot welding is effective for stably securing the required nugget diameter independent of the strength of steel sheets.

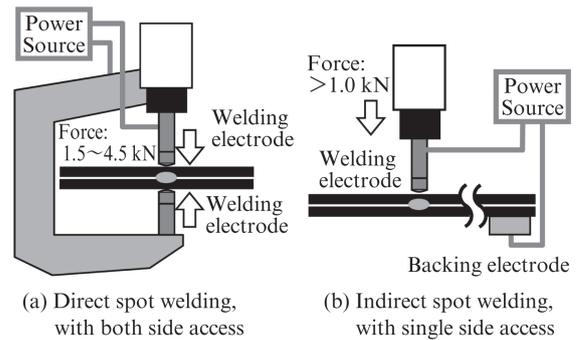


Fig. 9 Schematics of resistance welding processes

4. Single-Side Spot™ Welding Process

4.1 Issues of Single-Side Access Resistance Spot Welding

Recently, there has been an increasing number of requests for a welding method that enables lap welding with access from only one side of members with the aims of enhancing freedom in the design of automotive bodies, improving productivity and achieving light weight and high rigidity in auto bodies. The resistance spot welding process shown in Fig. 9(a) is mainly used in the current automotive body assembly process, but single-side welding is not possible because electrode access from both sides is necessary. Therefore, the indirect process^{20,21)} shown in Fig. 9(b) was developed as a resistance spot welding method that enables welding with single side access. The indirect process is a method in which one electrode is pressed against a lapped sheet member from one side, and welding is performed by attaching a backing electrode (earth electrode) at a remote position on the other member and flowing a current between the two electrodes. Because a current flows across the members at the weld point, it is comparatively easy to obtain a fusion zone (nugget) by Joule heat generation. However, because the shunting current that flows in locations other than the weld point changes depending on the thickness of the member and the existence of previous weld points, those changes have a large influence on the diameter of the formed nuggets²⁰⁻²³⁾.

To overcome these problems, the Single-Side Spot Welding technology²⁴⁻²⁷⁾ was developed to enable stable nugget formation in spite of changes in the shunting ratio by two-step control of the current and electrode force in the indirect single-side spot welding process.

4.2 Analysis of Welding Phenomena by Numerical Simulation

Using the general-purpose welding phenomena analysis software SORPAS™ (SWANTEC Software

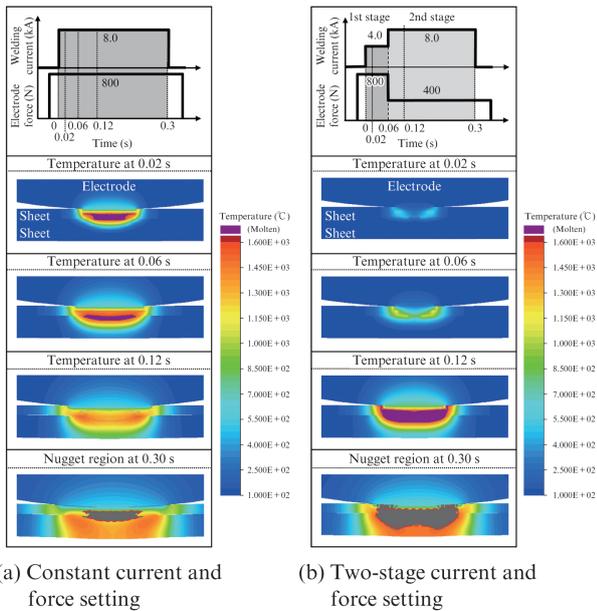


Fig. 10 Temperature distribution during welding predicted by numerical simulation

and Engineering ApS), the nugget formation stabilization effect of two-stage electrode force and current control was verified by a numerical simulation by the thermo-elastic-plastic finite element method. The sheet combination was a 270 MPa class cold-rolled steel sheet (thickness: 0.7 mm) as the top sheet and a 980 MPa class cold-rolled sheet (thickness: 1.6 mm) as the bottom sheet.

Figure 10 shows the calculation results. In (a) Constant current and force setting pattern, heat generation occurred between the electrode and the top sheet immediately after the start of current flowing, after which the temperature dropped to below the melting point even during current flowing. As a result, the fused nugget during welding was extremely limited (area shown in gray in the distribution of the peak temperature during a current-flow time of 0.30 s). With (b) Two-stage current and force setting pattern, heat generation between the top sheet and the bottom sheet continued during welding, and the nugget expanded remarkably in comparison with (a).

From the results presented above, it is thought that the nugget formation promotion effect in the two-stage current and force setting pattern is obtained by the following mechanism. Initially, the sheets are preheated while applying an adequate electrode force by applying high force and low current conditions, and a tight contact face is formed between the top sheet and the bottom sheet, securing a stable conduction path. After this, low force and high current conditions are applied, preventing an increase in the tight contact face by avoiding sinking of the electrode into the steel sheet, which is caused by the electrode force, while nugget

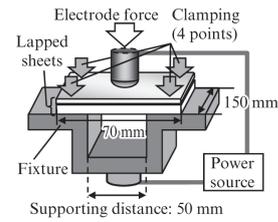


Fig. 11 Experimental setup of Single-side spot welding

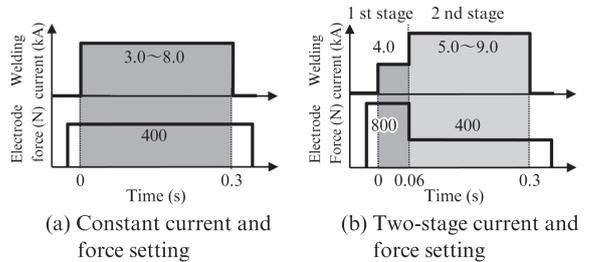


Fig. 12 Welding parameters

formation is promoted by the preferential flow of the increased welding current via the local conduction path formed in first stage, thereby enabling stable nugget formation.

4.3 Verification of Nugget Formation Promotion Effect by Welding Experiment

As in the numerical simulation, the sheet combination in this experiment was a 270 MPa class cold-rolled steel sheet with a thickness of 0.7 mm as the top sheet and a 980 MPa class cold-rolled sheet with a thickness of 1.6 mm as the bottom sheet, and indirect single-side spot welding was performed using the experimental setup shown in **Fig. 11**. To intentionally increase shunting, welding was performed under a condition of tight contact between the sheets by clamping the lapped sheets. In welding, an R type electrode with a tip curvature radius of 40 mm was used. Welding was evaluated with two current patterns, (a) Constant current and force setting and (b) Two-stage current and force setting, as shown in **Fig. 12**.

Figure 13 shows the results of the weldability test. With the constant current and force pattern, the appropriate welding current range for obtaining a nugget diameter of $4\sqrt{t}$ or more without expulsion was 1 kA or less, but with the two-stage current and force pattern, appropriate welding current range was expanded remarkably. **Photo 3** shows the cross-sectional macrostructures of the welds with the constant current and force and the two-stage current and force patterns. A satisfactory nugget formation condition can be confirmed with the two-stage current and force pattern.

The results of the experiment described above that confirmed the developed two-stage current and force

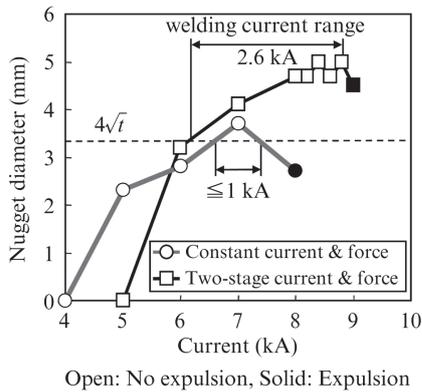


Fig. 13 Welding current range testing results

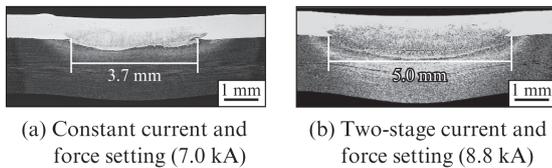


Photo 3 Cross-sectional macrostructures of the welds

pattern is effective in stable formation of nuggets, even in single-side spot welding with large shunting.

4.4 Development of Single-Side Spot Welding Technology

The developed Single-Side Spot™ welding process enables a large increase in the degree of freedom in the design of automotive bodies in comparison with conventional resistance spot welding. For example, in order to realize edge, attractive automotive body exterior designs, JFE Steel verified the applicability of the Single-Side Spot™ welding process to parts where welding had been impossible by conventional resistance spot welding due to interference between the members and the welding gun, and confirmed that welding is amply possible²⁷⁾. Since the developed technology is also considered to be effective for reduction of both automotive body weight and manufacturing costs, expanded application is expected in the future.

5. Remote Laser Welding Technology

5.1 Issues of Laser Welding Technology in Body-in-White Welding

Although laser welding has attracted attention as an alternative body-in-white assembly welding technology to resistance spot welding, it has not been widely used due to various restrictions, including strict requirements for accuracy in the assembly of the parts to be welded and the high equipment cost in comparison with spot welding. However, in recent years, remote

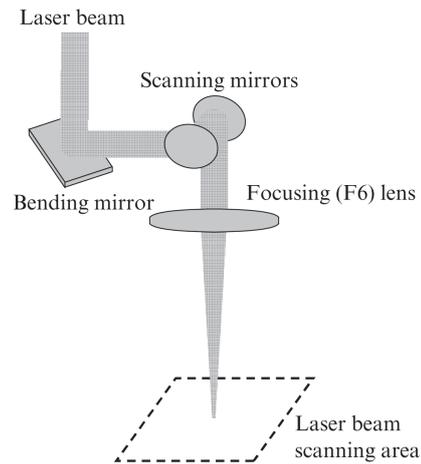


Fig. 14 Schematic illustration of remote laser welding process

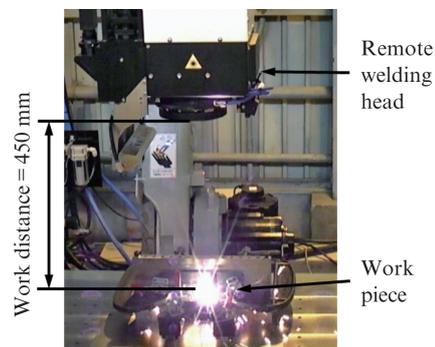


Photo 4 Example of robotic remote laser welding system

laser welding with beam scanning optics such as a galvano scanner, etc. has been put into practical use and applied to welding of automotive body parts²⁸⁾.

Remote laser welding, as shown in **Fig. 14** and **Photo 4**, is a technology which enables free irradiation of the laser beam on arbitrary locations within a certain scanning region by combining a mechanism such as the galvano mirrors, etc. that scan the laser beam and a long focal length focusing lens, and greatly shortens the movement time between welding locations by coupling with the operation of a robot. This has resulted in heightened interest in this technology, as dramatically higher welding efficiency is possible in comparison with conventional laser welding, and a sufficient cost benefit can be obtained even when using expensive laser welding equipment.

Moreover, the benefits of improved strength and rigidity of members by laser welding in linear continuous welding in comparison with spot welding by resistance spot welding had been recognized previously. In contrast, remote laser welding has the advantage of welding with a freely-shaped weld line by utilizing the laser beam scanning mechanism. Until now, however, the influence of the laser weld line shape on the joint strength of high strength steel sheets had not received

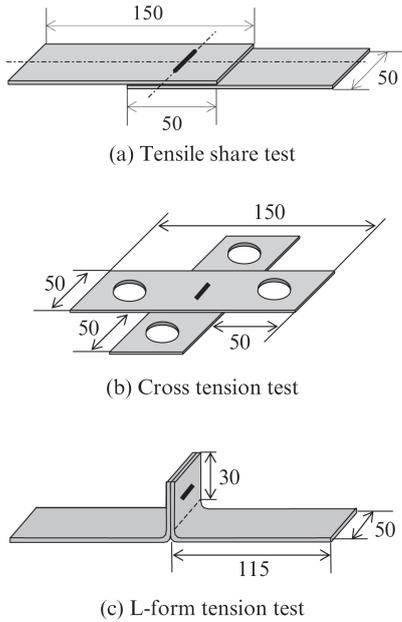


Fig. 15 Dimensions of tensile test specimens for remote laser welding

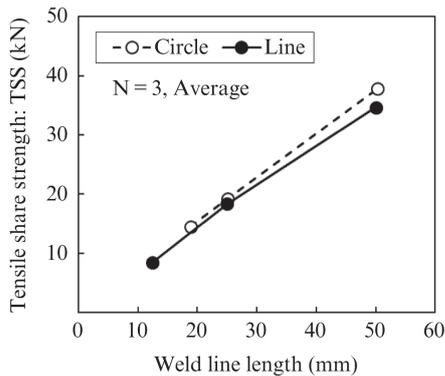


Fig. 16 Tensile share test results of remote laser welded joints of 1 180 MPa grade steel sheet

adequate study. The following introduces the strength of laser welded joints by various tensile test methods.

5.2 Influence of Weld Line Shape on Strength of Laser Welded Joints

Although it is considered particularly difficult to secure joint strength by resistance spot welding of ultra-high tensile strength materials of 980 MPa class and higher, improvement of the strength of welded joints of these materials can be expected by applying welding of various shapes by remote laser welding. **Figure 15** shows the dimensions of three types of tensile test specimens prepared by remote laser welding of 1 180 MPa class cold-rolled steel sheets (Japan Iron and Steel Federation Standard (JFS) JSC1180 YNN) with a sheet thickness of 1.6 mm. The results showed that joint strength differed with the circular and linear shapes, even with the same weld line length, and that tendency changed depending on the test specimen

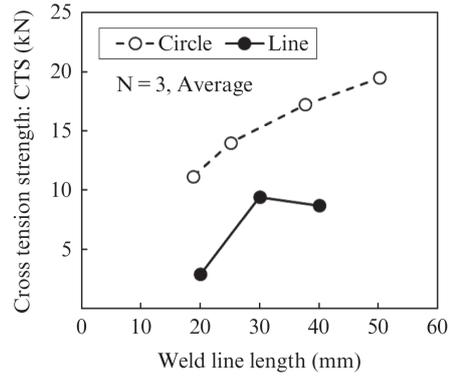


Fig. 17 Cross tension test results of remote laser welded joints of 1 180 MPa grade steel sheet

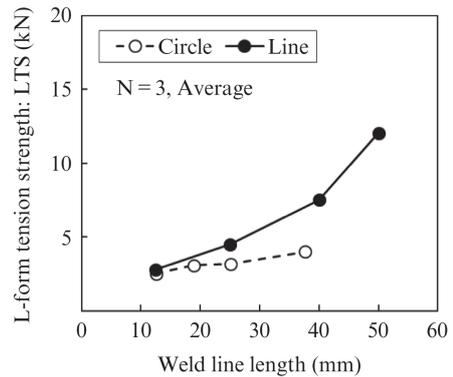


Fig. 18 L-form tension test results of remote laser welded joints of 1 180 MPa grade steelsheet

geometry^{29,30}. In the tensile shear test in **Fig. 16**, tensile shear strength (TSS) showed approximately the same values with the circular and linear weld line shapes when the weld line length was the same, and TSS was proportional to the weld line length. In the cross tension test in **Fig. 17**, with the same weld line length, the cross tension strength (CTS) with the circular weld line shape was higher than that of the linear weld line shape, and with the linear shape, CTS did not necessarily increase when the weld line length was longer. In the L-form tension test in **Fig. 18**, the increase in L-form tension strength (LTS) as the length of the line was extended was larger with the linear weld line shape than with the circular weld line shape, and in particular, a high LTS was obtained by linear welding with a weld line length of 50 mm, which was welded across the full width of the test specimen. The behavior of changes in joint strength depending on differences in these specimen shapes and weld line shapes is considered to be influenced by the stress and strain distribution states acting on the welds in the tensile tests. Therefore, the mechanisms were estimated by a finite element analysis (FEA) of the stress and strain distribution during the tests with the respective test specimen shapes³¹.

These results demonstrated the possibility of solving the problem of securing welded joint strength with

ultra-high strength steel sheets, which are expected to enlarge utilization, by applying remote laser welding to assembly welding of automotive bodies and selecting a joint shape or a weld line shape that considers the stress and strain distribution acting on the joint. As future body-in white welding technologies for use with ultra-high tensile strength steel sheets, high expectations are placed on technical development of remote laser welding, together with technical development of resistance spot welding.

6. Conclusion

This paper has presented an outline of various welding technologies developed by JFE Steel in order to support expanded application of steel sheets so as to realize higher performance in automotive bodies. In view of the heightened requirements for further reductions in environmental impacts in the auto industry, for example, by acceleration of the trend toward electric vehicles (EV), continuing progress is expected in the development of steel sheets that can contribute to enhancing automotive body performance while also securing collision safety, and in needs for the application of those products. JFE Steel intends to promote the practical application of the technologies developed to date, as well as the development of new welding technologies which respond to additional needs.

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