JFE TECHNICAL REPORT
No. 20 (Mar. 2015)

Development of Next Generation Resistance Spot Welding Technologies Improving the Weld Properties of Advanced High Strength Steel Sheets†

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Abstract:

The new technologies of resistance spot welding, which has been widely used for auto body production, are significant to realize the high collision safety of car body. Pulse Spot^{TM} welding, utilizing the short-time high-current post-heating can improve the weld joint strength of high strength steel sheets. Intelligent Spot^{TM} welding, varying the force and welding current during welding, enables to mitigate the limitation of the three sheets lap welding which is more frequently performed with increased application of high strength steels.

1. Introduction

Application of various types of advanced high-strength steel sheets to auto bodies has been studied as a means of satisfying both weight reduction and improved vehicle crashworthiness. Since welding technologies for effective use of these steel sheets are critical, JFE Steel not only supplies a wide variety of advanced high-strength steel sheets, but is also actively engaged in research and development on welding technologies for use in a car manufacturing process with the aim of applying various high strength steel sheets to auto bodies. Although the main welding technologies used in welding of auto bodies are resistance welding, arc welding, and laser welding, the most widely used welding method is resistance spot welding. Because this welding technology has high weldability, it is also positioned a key welding technology for the future.

This paper describes Pulse Spot^{TM} welding technology[1–5] and Intelligent Spot^{TM} welding technology[6–9]. As resistance spot welding technologies developed by JFE Steel, both of these technologies are expected to contribute to further expansion of the application of advanced high strength steel sheets in the future.

2. Pulse Spot^{TM} Welding Technology

2.1 Issues in Welding of High Strength Steel Sheets

Securing the fracture strength of resistance spot welded joints is indispensable for improving the crashworthiness of the auto body. However, it has been pointed out that cross tension strength (CTS), which is index of fracture strength in the peeling direction, might be low when using high strength steel sheets. **Figure 1** shows tensile shear strength (TSS), CTS, and their failure modes with a nugget diameter of 5 mm in two sheet lap joints of steel sheets with tensile strengths from 590 MPa to 1 180 MPa (in all cases, sheet thickness: 1.6 mm). Although TSS tends to increase with tensile strength of the steel sheet, CTS tends to decrease when the tensile strength exceeds 980 MPa. Furthermore, in the cross tension test of sheets of 780 MPa class and

† Originally published in *JFE GIHO* No. 34 (Aug. 2014), p. 8–13
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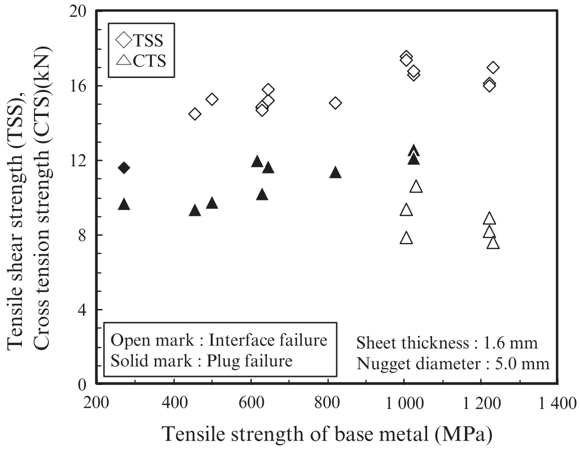


Fig. 1 Weld joint strength and failure mode of resistance spot weld in each tensile strength of base metal

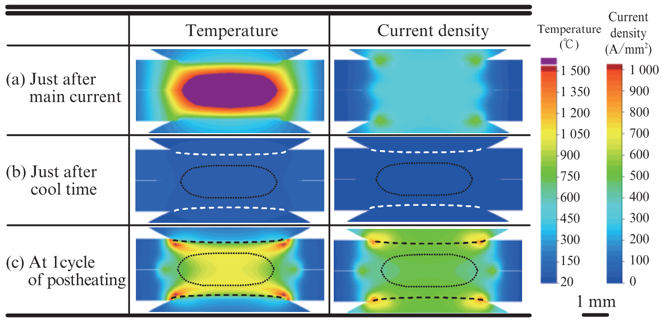


Fig. 2 Temperature distribution and current density distribution by short-time high-current post-heating[5)]

lower, the failure mode is plug failure, in which ductile fracture occurs and propagates in the base metal or the heat affected zone (HAZ), whereas a failure mode of steel sheets exceeding the 980 MPa class is interface failure, which is a type of brittle fracture through the nugget (fusion zone), and this reduces the CTS.

It has been pointed out that stress concentration at the nugget edge between sheets interface in the cross tension test and low toughness of the nugget edge against opening stress cause interface failure[10–12)]. Temper pattern has been proposed as a in-process post-heating current pattern to improve CTS[13)]. Although a nugget welded by resistance spot welding has hard martensite structure, in the temper pattern this martensitic structure is tempered by applying a long-time low-current post-heating (temper current). However, a number of issues related to weldability arise with the temper pattern. For example, the TSS of the joint decreases due to softening of the nugget and a cooling time of approximately 1 s is necessary before applying the post-heating current in order to obtain a sufficient tempering effect, and if the nugget diameter is reduced, the tempering effect can no longer be obtained because the temper current causes remelting of the nugget.

Therefore, as a post-heating method that increases CTS in a shorter time than the temper pattern, while also avoiding reduction of TSS, JFE Steel developed a resistance spot welding technology called Pulse Spot™ welding[1–5)], which utilizes the heating pattern of short-time high-current post-heating.

2.2 Weld Heating Pattern in Short-Time High-Current Post-Heating

Heating pattern in short-time high-current post-heating was studied by a numerical simulation of a two sheet lapped joint of 1 180 MPa class high strength steel sheets with a sheet thickness of 1.6 mm. A finite element software used in this study was SORPAS, which is a product of Swantec Software and Engineering ApS. The assumed welding conditions were main current to form a nugget: 6 kA, main current time: 16 cycles/50 Hz, cooling time: 100 cycles/50 Hz, post-heating current: 20 kA, post-heating current 1 cycle/50 Hz, and electrode force: 4.41 kN.

Figure 2 shows temperature distribution and current density distribution during the process. Immediately after the main current, temperature in the nugget is highest in the joint, and the current density is substantially uniform around the nugget. In contrast, after adequate cooling and a post-heating current of 20 kA × 1 cycle, the area in the vicinity of the electrode around the nugget was reheated to a higher temperature than the nugget itself, and the current density distribution was also highest around the area of electrode contact. In this condition, it is difficult to obtain the weld cooling effect of the water-cooled electrode in 1 cycle, and it is also thought that concentrated heat generation occurs in the vicinity of the electrode due to the extremely high current density.

2.3 Mechanism of Improved Welded Joint Strength by Pulse Spot™ Welding

The resistance spot welding technology, "Pulse Spot™ welding," was developed by utilizing the heat generation phenomenon in the area around the nugget in short-time high-current post-heating, as described in section 2.2. This technology makes it possible to obtain improved weld joint strength in a shorter time than with conventional temper pattern. **Figure 3** shows the current pattern of Pulse Spot™ welding. By adopting a pattern in which short-time cooling and short-time high-current post-heating (pulsed current) are repeated two times after the main current, which forms a nugget, it is possible to reheat the nugget obtained by the main current efficiently in a short time.

The effect of Pulse Spot™ welding was studied in lap welding joint of two sheets of 1 180 MPa class high

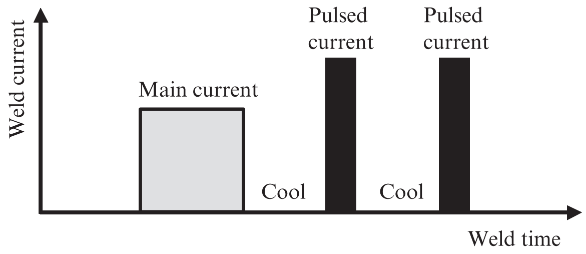


Fig. 3 Weld current pattern of Pulse Spot™ Welding

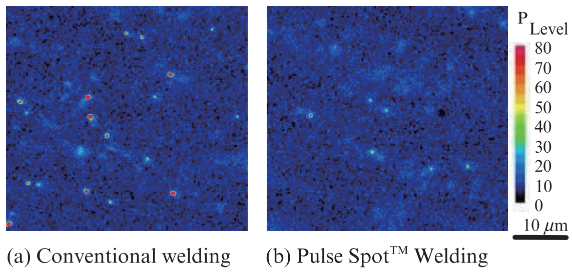


Fig. 4 Distribution of phosphorous at the edge of the nugget[5)]

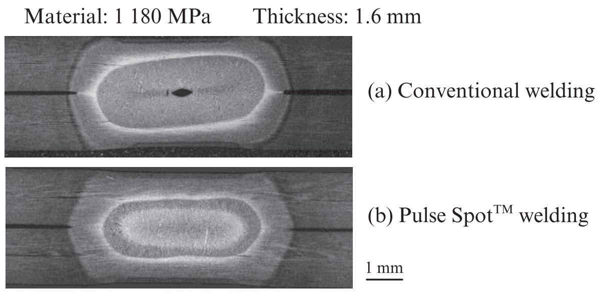


Photo 1 Cross-sectional macrostructures[5)]

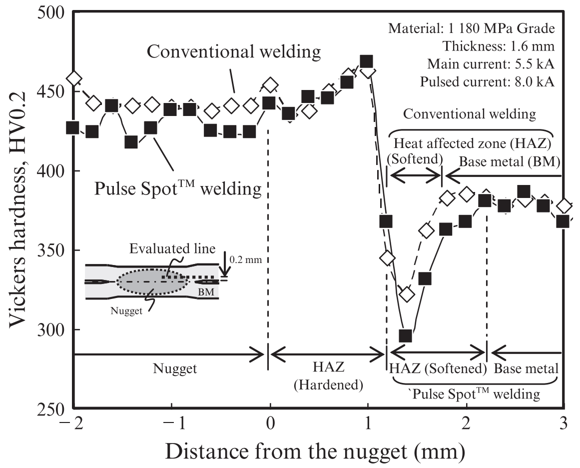


Fig. 5 Comparison of hardness distribution of weld joints

strength steel sheets with a sheet thickness of 1.6 mm. The welding conditions of the main current were a welding current of 5.5 kA and weld time of 14 cycles, the pulsed current conditions were a current of 9 kA and current time of 3 cycles, and the cooling time was 8 cycles. The electrode force was 3.5 kN. **Photo 1** shows the cross-sectional macrostructures of the welds obtained by conventional welding (only main current) and Pulse Spot™ welding. Etching was performed using a saturated solution of picric acid. In Pulse Spot™ welding, a ring pattern was observed by the contrast of the etching; this pattern did not appear in conventional welding.

Figure 4 shows the results of electron beam micro analysis (EPMA) mapping, which was performed to investigate segregation of P. It is considered that Pulse Spot™ welding reduces segregation of P in comparison with conventional welding, and this difference causes the difference in the degree of the etching. It is estimated that this occurs in Pulse Spot™ welding because P diffuses in the nugget due to reheating by the pulsed current.

Next, a comparison of the hardness distribution of the joints is shown in **Fig. 5**. The hardness distribution is similar with the two welding methods. However, in comparison with conventional welding, in Pulse Spot™ welding, a tendency could be seen in which the softened region expands in HAZ due to tempering of the martensitic structure of the base metal. In Pulse Spot™ welding, the softened region in HAZ is considered to be easily reheated. On the other hand, it was also found that there is virtually no decrease in nugget hardness.

Based on these results, with Pulse Spot™ welding, improved joint strength is expected as the result of two effects, that is, (1) improved nugget toughness due to reduced segregation of P in nuggets; and (2) alleviation of stress concentration at the nugget edge due to expansion of the width of the softened region in HAZ.

2.4 Improvement of Weld Joint Strength by Pulse Spot™ Welding

The effect of weld joint strength improvement by Pulse Spot™ welding was evaluated with lap joints of two sheets of 1 180 MPa high strength steel sheets with a thickness of 1.6 mm. **Figure 6** shows the relationship between CTS and the pulsed current in cases of a nugget diameter of 5.0 mm. Except the value of the pulsed current, all welding conditions were the same as in the previous section. The average CTS of the joint welded by conventional welding pattern was 7 kN, but in contrast, a CTS of 12 kN was obtained by Pulse Spot™ welding with the pulsed current of 8 kA. Thus, the results of this experiment confirmed a remarkable improvement effect on CTS by Pulse Spot™ welding. Moreover, CTS was also improved over a wide range of the pulsed current from 7 kA to 9 kA, demonstrating the excellent weldability of the developed technology.

Photo 2 shows cross-sectional macrostructures of fractured specimens after the cross tension tests. With

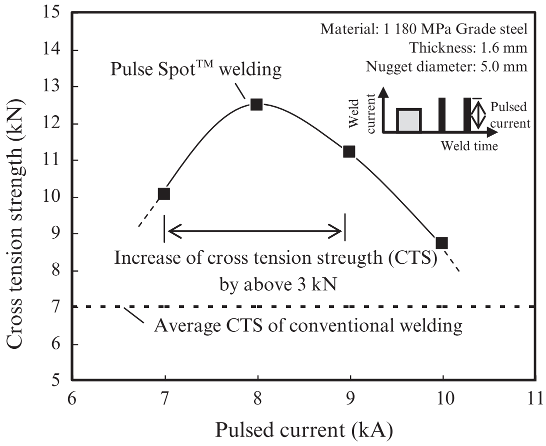


Fig. 6 Increase of cross tension strength by Pulse Spot™ welding and the effective conditions of pulsed current

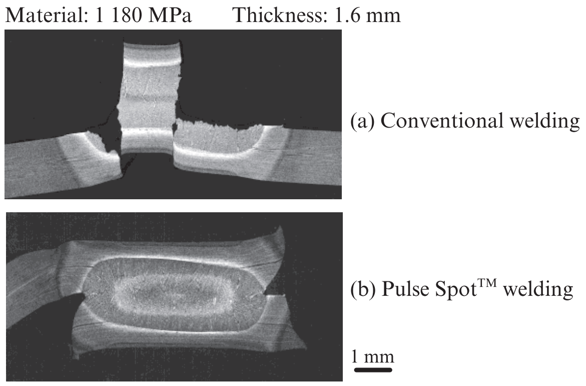


Photo 2 Cross-sectional macrostructures of fractured specimen after cross tension test[5)]

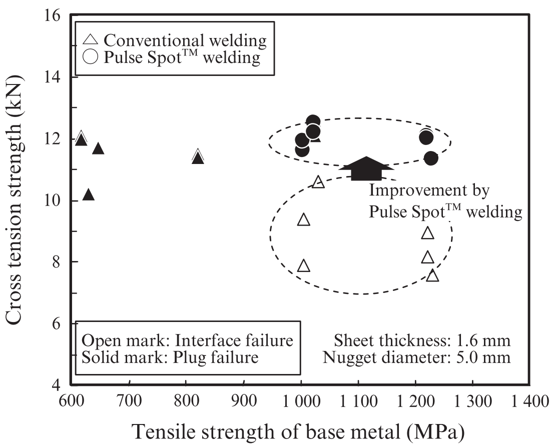


Fig. 7 Increase of cross tension strength of advanced high strength steel sheets by Pulse Spot™ welding

conventional welding, a crack propagated through the nugget, leading to partially interface failure, but with Pulse Spot™ welding, no cracks occurred in the nugget, and the specimen showed a plug failure. It is thought weld strength was greatly improved by the effects of improved nugget toughness and relaxation of stress concentration.

Pulse Spot™ welding was performed with steel sheets of 980–1 180 MPa class (thickness: 1.6 mm) whose CTS was evaluated in Fig. 1. **Figure 7** shows a comparison of CTS of those joints and joints prepared by conventional welding. The results showed that CTS is improved in joints welded by Pulse Spot™ welding, even with materials which displayed reduced CTS in conventional welding. Furthermore, the failure mode changed to plug failure, even in cases where interface failure occurred with conventional welding.

2.5 Progress of Pulse Spot™ Welding

Pulse Spot™ welding is a technology which makes it possible to improve CTS and failure mode of joints of advanced high strength steel sheets. In comparison with temper pattern, which was the conventional method for improving joint strength, Pulse Spot™ welding makes it possible to shorten process time and also has a wide pulsed current range in which high CTS can be obtained. Considering these advantages, it can be considered a resistance spot welding method with high weldability.

Study with automobile companies has already begun, aiming at application to auto body welding assembly lines, and the technology has received an excellent evaluation. Considering expanded application of high strength steel sheets for auto body weight reduction, it is expected to become an extremely effective welding technology in the future.

3. Intelligent Spot™ Welding Technology

Chapter 2 introduced the Pulse Spot™ welding technology as a technology that improves CTS of resistance spot welded joints of high strength steel sheets. However, because steel sheets with diverse strengths, including high strength steel sheets, sheet thicknesses, and coating conditions are used in auto bodies, adequate consideration is necessary for setting their resistance spot welding conditions. For example, in case of center pillar, it is necessary to weld a three sheet joint with a large sheet thickness ratio ((total thickness of sheet joint)/(thickness of the thin sheet positioned on the outer side of the joint)), comprising an outer panel (mild steel sheet with thickness of 0.8 mm or less; referred to as “thin sheet” in the following), a reinforcement member (high strength steel sheet with thickness of 1.0 mm or more; hereinafter, thick sheet), and an inner panel (thick sheet). In resistance spot welding of joints with high sheet thickness ratios, the sheet thickness ratio is generally limited to 4–5 or less due to the difficulty of forming a fusion zone between the thin sheet and the thick sheet.

To solve this problem, JFE Steel developed the

"Intelligent Spot™ welding technology"[6–9] as a new resistance spot welding technology which makes it possible to relax the sheet thickness ratio limit.

3.1 Mechanism of Intelligent Spot™ Welding

Intelligent Spot™ welding is a technology in which the position of heat generation is controlled by multi-step control of the electrode force and welding current, enabling resistance spot welding of joints with high sheet thickness ratios. The electrode force/welding current pattern and fusion zone formation process are shown schematically in **Fig. 8**. The welding process is divided into two steps. In the first step, adequate heat generation is secured between the thin sheet and the thick sheet by low electrode force, short weld time, high current welding. Then, in the second step, nuggets of the necessary diameters are formed between the thin sheet and thick sheet and the two thick sheets, respectively, by applying high electrode force and long weld time conditions.

In the first step, applying short weld time, high welding current conditions with the low electrode force makes heat generation and thermal expansion between the thin sheet and the thick sheet. This induces sheet separation at the thin sheet-thick sheet interface. Because the contact area is reduced at the thin sheet-thick sheet interface, the current density increases, and as a result, heat generation between the thin sheet and thick sheet is accelerated. In the second step, when the electrode force is increased, the current pass area increases and the current density decreases, and as a result, a fusion zone is formed at the center between the two electrodes by the heat balance between resistance heating (Joule heat) and electrode cooling, and it grows to both sheet interfaces. By using this welding technology based on the mechanism described above, it is possible to obtain the necessary nugget diameter between each of the pairs of sheets.

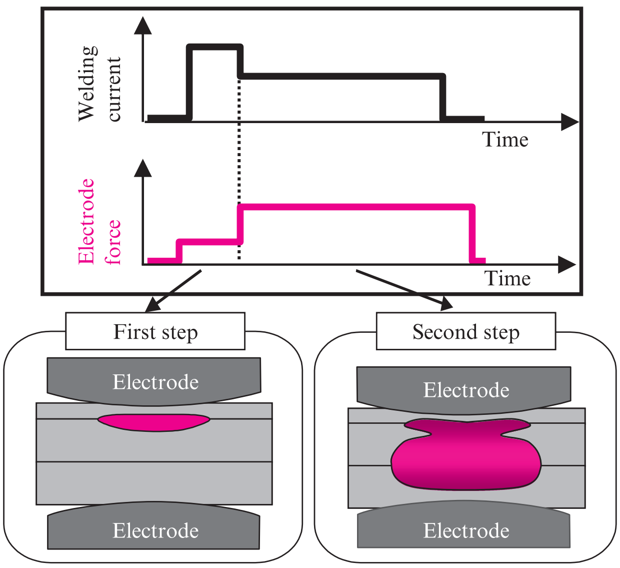


Fig. 8 Schematic illustration of Intelligent Spot™ welding process for three-sheet-joint with higher sheet thickness ratio

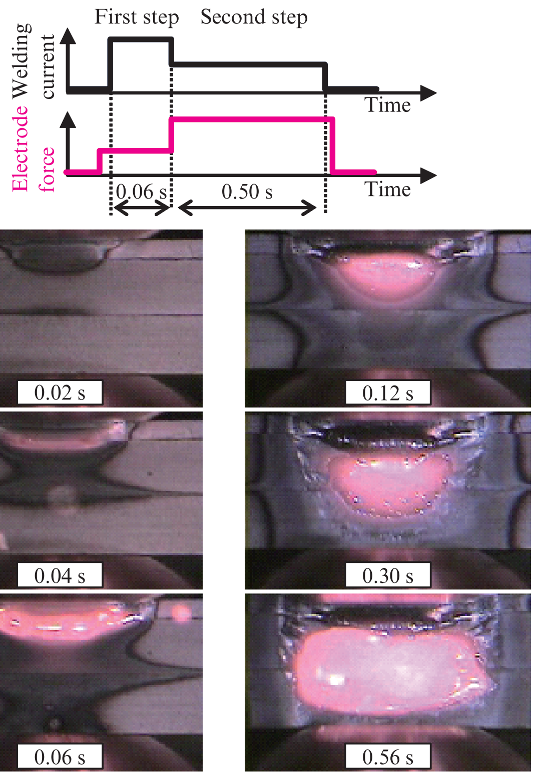
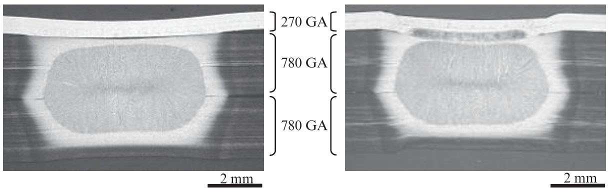


Photo 3 Nugget formation process in Intelligent Spot™ welding observed by high speed video camera

Photo 3 shows the results of direct observation by a high speed video camera of the nugget formation process in Intelligent Spot™ welding, in welding of the edge parts of the steel sheets in a three sheet lap joint (sheet thickness ratio: 7.6) comprising sheets with thicknesses of 0.7 mm, 2.3 mm, and 2.3 mm. The sheets used here were a 0.7 mm thick 270 MPa class galvannealed steel sheet (270GA) and two 2.3 mm thick 780 MPa class galvannealed steel sheets (780GA). As can be clearly observed from the photographs, in the low electrode force first stage, heat generation between the thin sheet and the thick sheet is accelerated, and in the second stage, when the electrode force is increased, a fusion zone is formed between the two thick sheets.

3.2 Application to Welding of High Sheet Thickness Ratio Joints

Photo 4 shows cross section macros of welds by conventional resistance spot welding and Intelligent Spot™ welding in case of the above-mentioned joint (270GA: 0.7 mm-780GA: 2.3 mm-780GA: 2.3 mm). In both cases, these are cross sections with welding conditions in which the thick sheet-thick sheet nugget diame-



(a) Conventional resistance spot welding (b) Intelligent Spot™ Welding

270GA: 270 MPa Grade galvannealed steel sheet
780GA: 780 MPa Grade galvannealed steel sheet

Photo 4 Comparison of cross section macros of three sheets joint with high sheet thickness ratio[7)]

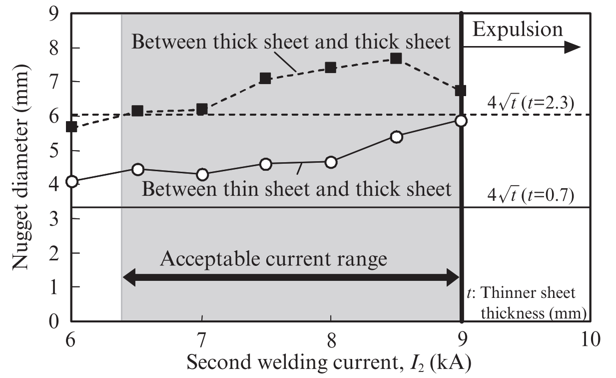


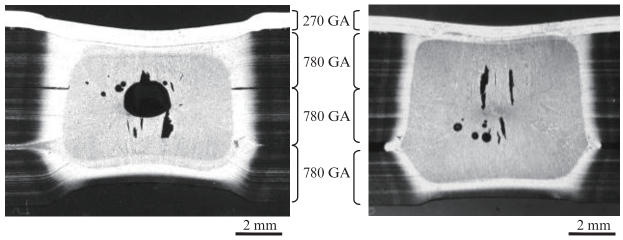
Fig. 9 Acceptable current range of Intelligent Spot™ welding

ter is $4\sqrt{t}$ (t: sheet thickness). However, nugget formation between the thin sheet and thick sheet was observed only in the case of Intelligent Spot™ welding.

The results of an investigation of the acceptable current range of Intelligent Spot™ welding of this joint are shown in **Fig. 9**. With conventional resistance spot welding, it is difficult to obtain a nugget, whose diameter is over $4\sqrt{t}$, between the thin sheet and the thick sheet with this joint without expulsion. On the other hand, a wide acceptable current range of approximately 2.5 kA was obtained with Intelligent Spot™ welding.

Next, the following presents an example of the case of a four sheet lap joint in which a 2.3 mm thick 780 MPa class galvannealed steel sheet is added to the above-mentioned three-sheet lap joint. In this case, the sheet thickness ratio is 10.9. **Photo 5** shows cross section macros of the welded joints. Here, (a) is the case of conventional resistance spot welding, whose electrode force is constant, and (b) is the case of Intelligent Spot™ welding. In (a), a nugget was not formed between the thin sheet and the thick sheet, even though the welding current was increased to a level where expulsion occurred. On the other hand, as in the case of the three-sheet joint, formation of a nugget between the thin sheet and thick sheet was observed with Intelligent Spot™ welding, as shown in (b).

However, for practical application of four sheet lap joints, study of various issues related to weldability and



(a) Conventional resistance spot welding (b) Intelligent Spot™ Welding

270 GA: 270 MPa Grade galvannealed steel sheet
780 GA: 780 MPa Grade galvannealed steel sheet

Photo 5 Comparison of cross section macros of four sheets joint with high sheet thickness ratio[8)]

the welding equipment is considered necessary, including control of the gap tolerance between the lapped sheets and application of a high electrode force welding machine to obtain nuggets between thick sheets.

3.3 Effects of Intelligent Spot™ Welding

Due to the problem of nugget formation between the thin sheet and the thick sheet in joints with high sheet thickness ratio, auto makers have implemented countermeasures such as limiting the sheet thickness ratio in welding of three sheet lap joints to approximately 4–5, and performing welding of two sheets at a time by zigzag processing, but as a result, productivity and design freedom were sometimes sacrificed. Moreover, even within the limit range of sheet thickness ratio, makers tended to set excess welding currents in order to secure the nugget diameter between the thin sheet and thick sheet in high sheet thickness ratio joints, resulting in problems of generated expulsion adhering to the auto body and the increased man-hours necessary to remove it.

Applying Intelligent Spot™ welding makes it possible to weld even joints with high sheet thickness ratios, which are not used at present, and to relax sheet thickness ratio limits. Thus, a reduction of man-hours for zigzag processing and an increased degree of freedom can be expected. It is also possible to reduce expulsion in case of welding joints within the range of the sheet thickness ratio limit because it is no longer necessary to set an excessive current in order to secure the nugget diameter between the thin sheet and thick sheet. From this viewpoint, high expectations are placed on Intelligent Spot™ welding as a low expulsion welding technology.

The Intelligent Spot™ welding technology can also be used in combination with Pulse Spot™ welding, as there are no restrictions on the welding conditions after the second step current, which forms a nugget of the necessary diameter. Combined use of Intelligent Spot™ welding and Pulse Spot™ welding secures the necessary nugget diameter between all steel sheets in welding of three sheet lap joints with high thickness ratio, including high strength steel sheets in structural members such as the center pillar, etc., and also makes it possible to secure increased weld joint strength in welds of high strength steel sheets.

3.4 Example of Application of Intelligent Spot^{TM} Welding

This technology has also been studied in joint research and development with auto makers, considering the effects of various disturbances when applied to auto body assembly lines, and practical application has already begun. As one example, it has been applied to the center pillar part, which has a high sheet thickness ratio, and its effect in reducing expulsion has been confirmed.

4. Conclusion

Both high performance in terms of steel sheet material quality and the development of manufacturing processes such as press technologies and welding technologies are crucial for application of high-functionality, high-strength steel sheets to auto bodies. These reports introduced examples of the development of two new spot welding technologies that realize improved joint strength and weldability. Authors would like to promote practical application of these welding technologies, and contribute to improved environmental performance by auto body weight reduction, as well as improved crashworthiness, by expanding the applications of high strength steel sheets.

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