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Development of Next Generation Resistance Spot Welding Technologies Contributing to Auto Body Weight Reduction†

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Abstract:

New generation resistance spot welding technologies were developed to reduce the weight of auto body. By varying the force and welding current during welding, Intelligent Spot™ welding made it possible to perform easier three-sheet-lap-welding more frequently performed with increased application of high strength steels. Pulse Spot™ welding, which utilizes high current conduction with short periods as a post-weld heating treatment, increased the weld joint strength of high strength steels without extending welding time. The single-side spot welding which controls the electrode force and welding current during welding realized high applicability to closed-sectional structures by the stable nugget formation only with single-side electrode access.

1. Introduction

Application of various types of high performance, high tensile strength steel sheets to automobile bodies have been studied as a means of realizing auto body weight reduction and improved crashworthiness. However, in the auto body assembly process, welding technologies which enable more effective application of these steel sheets are increasingly important. Therefore, as well as supplying various types of high performance, high tensile strength steel sheets, JFE Steel is actively engaged in research and development of welding technologies for auto body assembly with the aim of applying various types of steel sheets to auto bodies. While resistance welding, arc welding, laser welding, and other welding methods are mainly used as assembly welding of auto bodies, the most widely used method is resistance spot welding. Moreover, considering its high robustness and versatility, this method will also be regarded as a key welding technology in the future.

This paper introduces three resistance spot welding technologies which were developed by JFE Steel for auto body assembly welding and are expected to contribute to expanded application of high tensile strength steel sheets in the future. These are Intelligent Spot™ Welding[1,2], Pulse Spot™ welding[3], and a single-side spot welding technology which enables efficient welding of closed sectional structures[4].

2. Intelligent Spot™ Welding Technology

High tensile strength steel sheets are frequently applied to auto body reinforcement members, and in this case, three-sheet-lap-welding of steel sheet combination comprising an outer panel (mild steel sheet), reinforcement member (high tensile strength steel sheet), and inner structure (high tensile strength steel sheet) is performed. In resistance spot welding, a nugget is formed near the center of lapped sheets which is being welded. Therefore, if the sheet thickness ratio in a thin sheet-thick sheet-thick sheet joint is large, it becomes difficult to form a nugget between the thin sheet and the adjoining thick sheet ((Sheet thickness ratio) = (Total sheet thickness of joint) / (Thickness of the thin sheet, which is positioned on the outer side of the set of sheets)). For

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this reason, the upper limit of the weldable sheet thickness ratio is generally considered to be 4–5. This limitation on the sheet thickness ratio is a key issue for welding technology. As a resistance spot welding technology that makes it possible to mitigate this sheet thickness ratio limitation, JFE Steel developed Intelligent Spot™ Welding technology[1,2], which is a “2-step force, 2-step current” process that enables formation of nuggets both between the thin sheet and thick sheet and between the two thick sheets in 3-sheet-lap welding.

One distinctive feature of Intelligent Spot™ Welding technology is the fact that the electrode force and welding current are varied during welding. That is, at the first stage of this welding process, heat is generated reliably between the thin sheet and the thick sheet by applying low electrode force, short welding time and high current conditions, and at the second stage, a nugget is formed mainly between the two thick sheets using high electrode force and long welding time conditions. This welding technology has already been applied to the auto body assembly lines of automobile manufacturers. In addition to expanding the upper limit of the sheet thickness ratio, effective results in achieving low expulsion in assembly welding of high sheet thickness ratio joints have been obtained.

3. Pulse Spot™ Welding Technology

3.1 Issues in Welding of High Tensile Strength Steel Sheets

The strength of resistance spot welded joints is important for improving auto body rigidity. However, increasing the strength of steel sheets results in hardening of welds. Therefore, as shown in **Fig. 1**, while the tension shear strength (JIS Z 3136 (JIS: Japanese Industrial Standard)) of joints increases, cross tension strength (JIS Z 3137) remains constant, independent of the strength of the sheet, and rather tends to decrease in cases where interface failure occurs in the nugget.

In-process tempering treatment has long been studied as a spot welding technology for improving joint strength[5–8]. However, because in-process tempering treatment is a process in which tempering is performed after once cooling the nugget and heat affected zone, extended periods of cooling time and temper treatment time are necessary, which greatly increases manufacturing time. Therefore, JFE Steel developed the Pulse Spot™ welding method to minimize the increase in manufacturing time, which makes it possible to realize high joint strength with a short manufacturing time.

3.2 Weld Heat Generation Mode by Pulse Current Conduction

The temperature distribution when welding 1 180 MPa grade high tensile strength steel sheets with a sheet thickness of 1.6 mm was analyzed using a finite element analysis software for resistance spot welding, “SORPAS” (SWANTEC Software and Engineering Applications ApS). **Figure 2** shows the temperature distribution in the cross section of the joint when a nugget was formed by conducting a current under a constant electrode force, cooled for a set time, and applied to a high current for a short time (hereafter pulse current). Figure 2(b) shows the temperature distribution after the pulse current. The temperature is higher in the periphery of the nugget within the heat affected zone than in its center. In conventional resistance spot welding, the highest temperature occurs at the center of the nugget due to the balance of heat generation in the weld and heat removal by the water-cooled electrodes. However, in short time and high current pulse current conduction, the area of high current density at the periphery of the nugget, which is shown in Fig. 2(c), becomes a high temperature area as-heated by the welding current. This phenomenon is considered to occur because the Joule heat generation rate by current conduction exceeds the heat removal rate by thermal conduction under short time and high current conditions.

Next, in order to verify the numerical simulation results described above, the edges of steel sheets were

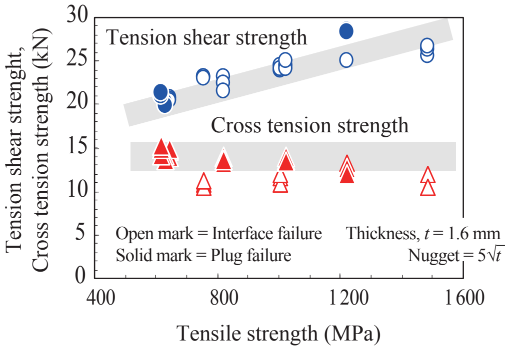


Fig. 1 Comparison of tension shear strength and cross tension strength of the weld joints with respect to steel grade

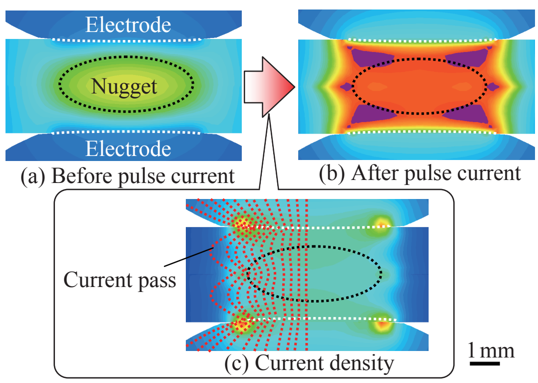


Fig. 2 Effect of pulse current on temperature distribution and current density distribution

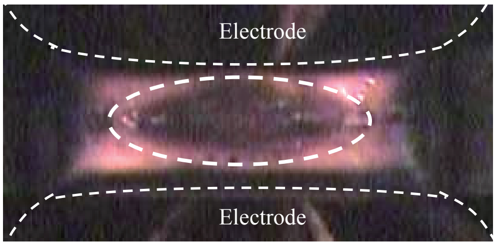


Fig. 3 Heat distribution after pulse current

actually welded using the same current pattern as in Fig. 2, and the heat generation mode of the cross section of the joint was observed using a high speed video camera. The material was a 1 180 MPa grade high tensile strength steel sheet with a sheet thickness of 1.6 mm. **Figure 3** shows the obtained results. As in the results of the numerical simulation, a phenomenon of selective heating at the periphery of the nugget was observed.

The results described here showed that it is possible to reheat the periphery of the nugget in a short time by pulse current after the main current.

3.3 Weld Properties in Pulse Spot™ Welding

Figure 4 shows the current pattern in Pulse Spot™ welding, in which a process of cooling and pulse current is performed repeatedly, as developed based on the above results. **Photo 1** shows a comparison of the cross-sectional macrostructures of a joint welded using only the main current (hereinafter, conventional welding) and a Pulse Spot™ welding joint. Although the nugget diameter is the same in both joints, a large difference can be observed in the inner microstructure of the nuggets. This is attributed to the effect of reheating by the pulse current.

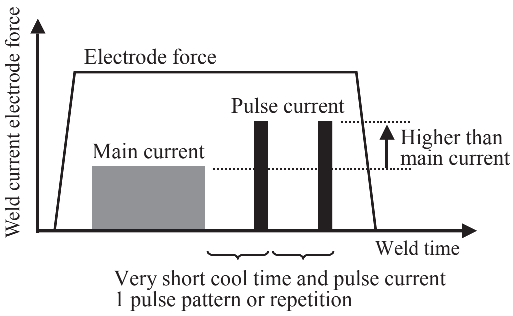


Fig. 4 Current and Electrode force pattern of Pulse Spot™ welding

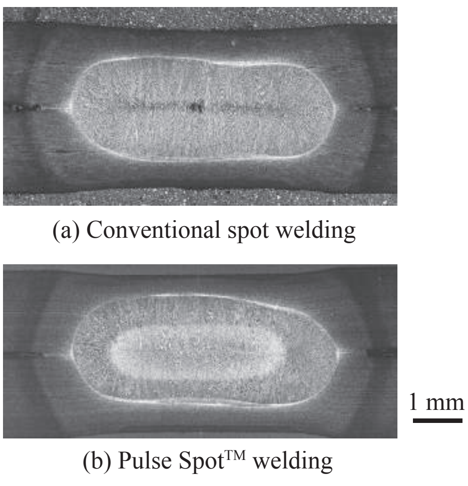


Photo 1 Cross sectional macrostructure

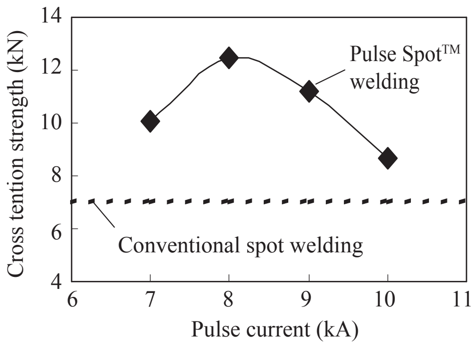


Fig. 5 Comparison of cross tention strength at nugget diameter of $4\sqrt{t}$ with respective pulsed current pattern

Next, the joint strength in Pulse Spot™ welding were evaluated. **Figure 5** shows the relationship between the current value of the pulse current at a nugget diameter of $4\sqrt{t}$ (t: sheet thickness) and cross tension strength. With conventional welding, the cross tension strength was 7.0 kN, as shown by the dotted line. In contrast to this, with Pulse Spot™ welding, joint strength was greatly increased to 1.3–1.7 times than that in conventional welding. Furthermore, higher joint strength was also achieved with a wide range of pulse currents. Thus, it can be said that this welding process is robust against external disturbance factors during welding.

Figure 6 shows the change in cross tension strength when the nugget diameter was varied in the range of $3\sqrt{t}$ to $5\sqrt{t}$. With all nugget diameters, the cross tension strength obtained by Spot Pulse™ welding increased in comparison with conventional welding. In particular, with nugget diameters of 6 mm ($\fallingdotseq 4.5\sqrt{t}$) or less, the increase was 3 kN or more. From this, it can be concluded that the effect of the pulse current is extremely large. The cross sections of the fractured joint after the cross tension strength test in Fig. 6 are shown in **Photo 2**. In Pulse Spot™ welding with nugget diameters of $3\sqrt{t}$ and $4\sqrt{t}$, in which large increases in joint strength were observed, the fracture mode with conventional welding was interface failure or partial plug failure. However, this clearly changed to plug failure with Pulse Spot™ welding.

Based on the results described above, it is clear that the large improvements in cross tension strength and the failure mode can be achieved by Pulse Spot™ welding using short time cooling and short time and high welding current, and it is also possible to realize increased

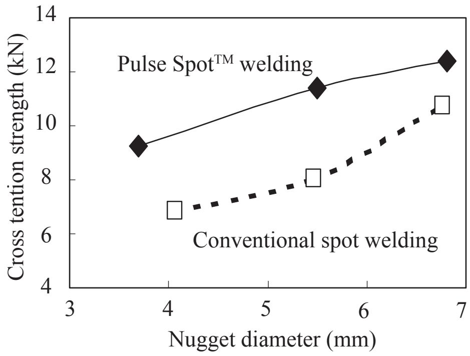


Fig. 6 Comparison of cross tention strength between of conven-tional spot welding and of Pulse Spot™ welding at each diameter

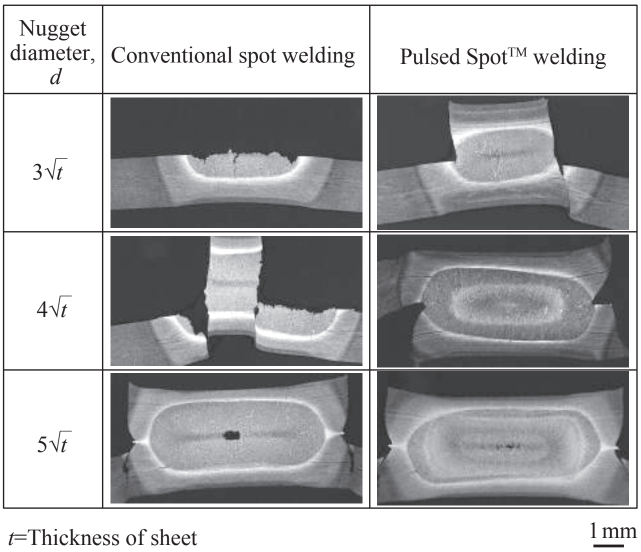


Photo 2 Comparison of fracture pattern between conventional spot welding and Pulse Spot™ welding

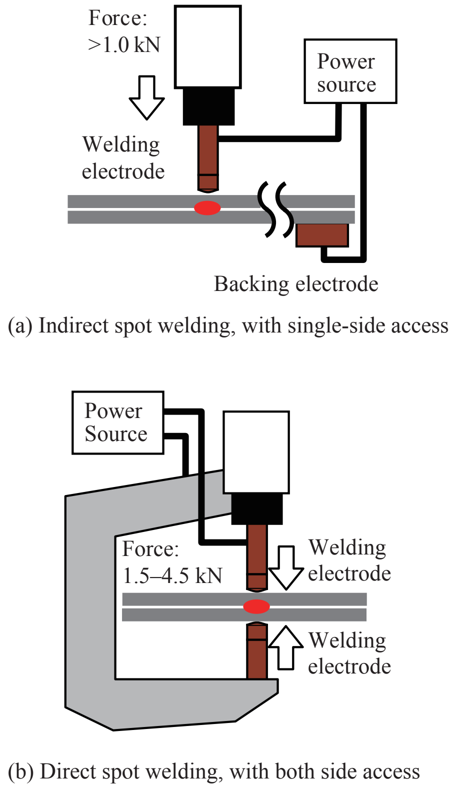


Fig. 7 Schematic diagrams of resistance welding processes

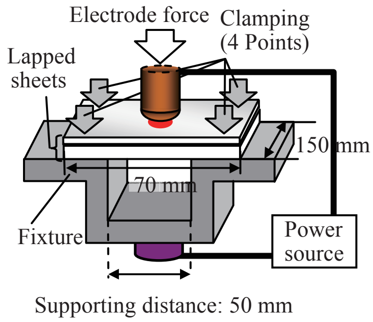


Fig. 8 Experimental setup of single-side spot welding

welded joint strength when using 1 180 MPa grade steel sheets. Moreover, although a cooling and welding time over 1 s is necessary for a cooling time and weld time after nugget formation in conventional in-process tempering treatment, when a pulse current is used, it is possible to reduce this to 0.5 s or less. As a result, Pulse Spot™ welding is also effective for minimizing increases in weld time during welding processes.

4. Single-Side Spot Welding Technology

4.1 Effect of Welding Conditions on Single-Side Spot Weldability

The indirect single-side spot welding process (**Fig. 7**(a))[9,10] is a welding method that enables welding from one side. However, in this welding process, the electrode force is lower and the conduction path between the electrodes is longer compared with normal resistance spot welding (Fig. 7(b)) in which electrode access from both sides is possible. For this reason, it is considered that shunting, in which the current conducts through locations other than the welding spot, occurs easily in single-side spot welding.

Using the experimental setup shown in **Fig. 8**, indirect single-side spot welding was performed on lapped sheets comprising a 270 MPa grade cold-rolled steel sheet with a thickness of 0.7 mm as the top sheet and a 980 MPa grade cold-rolled steel sheet with a thickness of 1.6 mm as the bottom sheet. In the case where shunting was to be increased, tight contact between the sheets was applied by 4-point clamping. Welding was performed with a constant welding current and electrode force pattern, as shown in **Fig. 9**, using a single radius shaped electrode with a tip curvature radius of 40 mm.

Figure 10 shows the influence on nugget formation when the shunting condition was varied with clamping (larger shunting) or without clamping (minimum shunting). Figure 10(a) shows the relationship between weld-

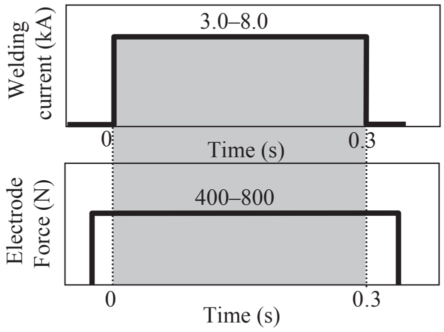
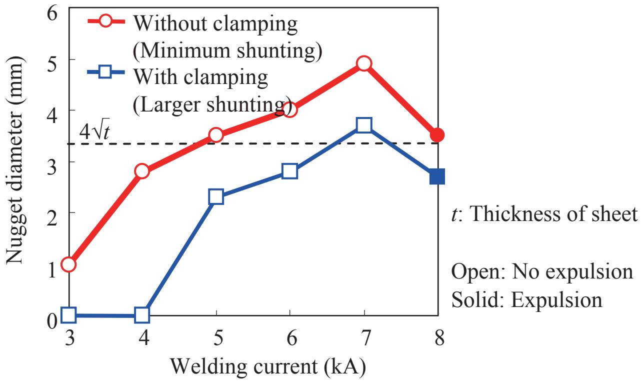
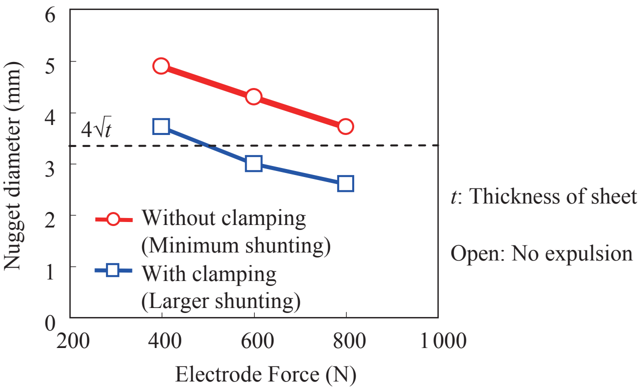


Fig. 9 Welding conditions of constant welding current and electrode force process



(a) As a function of welding current at 400 N of electrode force



(b) As a function of electrode force at 7.0 kA of welding current

Fig. 10 Influence of shunting on nugget formation with constant welding current and electrode force

ing current and nugget diameter with a constant electrode force (current dependency of nugget diameter), and Fig. 10(b) shows the relationship between electrode force and nugget diameter with a constant current (force dependency of nugget diameter). The nugget diameter shows a tendency to increase as the current increases or the electrode force decreases. However, in both of these relationships, the nugget diameter decreases remarkably when clamping is applied. This shows that increased shunting has a considerable effect on nugget formation.

4.2 Welding Process Utilizing Electrode Current and Force Control

Welding was performed with multi-step control of the welding current and electrode force, as shown in **Fig. 11**. The combination of steel sheets and equipment setup was the same as in section 4.1, and welding was performed using an a single radius shaped electrode with a tip curvature radius of 40 mm under the condition with clamping. For the current values I_A and I_B in the 1st Stage, the relationship $I_A < I_B < 8$ kA was adopted, and for the electrode force F_A and F_B, the relationship was 400 N $< F_A < F_B$.

Figure 12 shows the change in the nugget diameter when the current in the 2nd Stage was varied using the current and force pattern shown in Fig. 11. The appropriate welding current range for a nugget diameter of $4\sqrt{t}$ or larger and no occurrence of explusion was 1 kA or less in the case of the constant current and force pattern shown in Fig. 10(a) with clamping. However, the appropriate welding current range was expanded in the case of the variable current and force pattern in Fig. 12. Furthermore, the appropriate welding current range in case of current I_A and electrode force F_A in the 1st Stage was 1.6 kA, but this was greatly improved to 2.6 kA in the case of current I_B and electrode force F_B. **Photo 3**

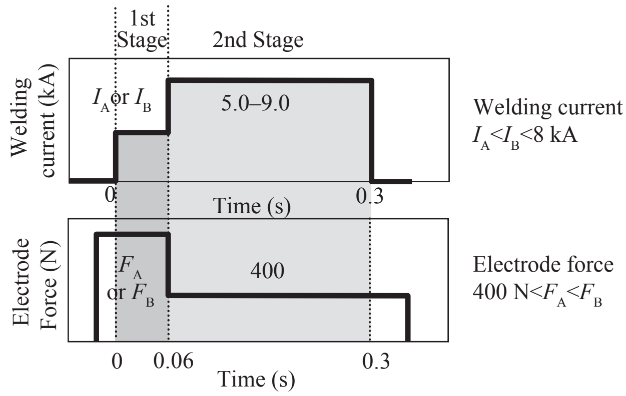


Fig. 11 Welding conditions of variable current and force control

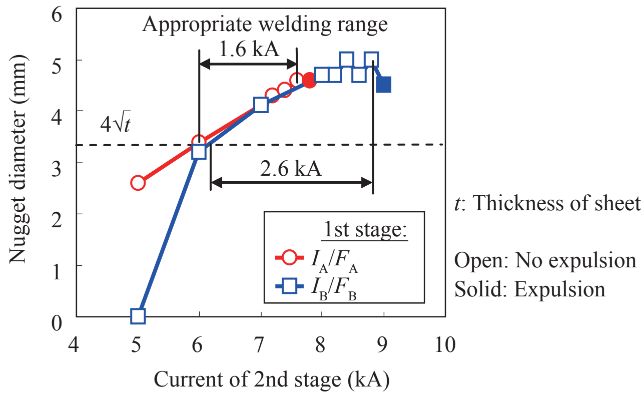
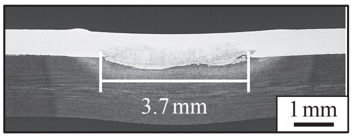
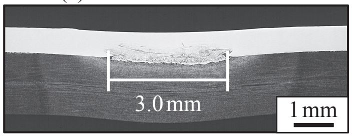


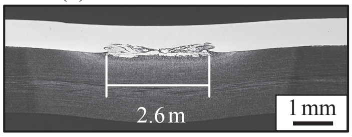
Fig. 12 Welding current range test results (with clamping)



(a) Electrode force: 400N

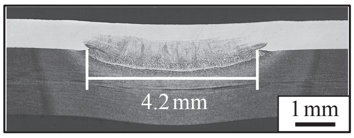


(b) Electrode force: 600N

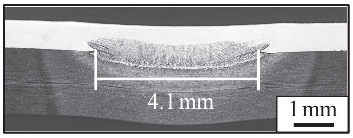


(c) Electrode force: 800N

Photo 3 Cross-sectional macrostructures of the welds with constant current and force (at 7.0 kA, with clamping)



(a) Electrode force at 1st stage: 600 N



(b) Electrode force at 1st stage: 800 N

Photo 4 Cross-sectional macrostructures of the welds with variable current and force control (at 7.0 kA, with clamping)

shows the cross-sectional macrostructure of the weld in case the welding current was 7.0 kA with the constant current and force pattern shown in Fig. 10; **Photo 4** shows the cross-sectional macrostructure of the weld with the same current of 7.0 kA when using the variable current and force control pattern shown in Fig. 12. In comparison with the constant current and force pattern, the nugget diameter increased with the variable current and force control pattern.

4.3 Analysis of Welding Process by Numerical Simulation

In order to study the effect of multi-step control of the welding current and electrode force on nugget formation, welding phenomena were analyzed by a two dimensional axisymmetric model (thermo-elastic-plastic finite element method) using a dedicated finite element analysis program for spot welding, "Quick Spot" (Research Center for Computational Mechanics, Inc.). This analysis considered the temperature dependency of the physical properties of the steel sheets and the electrode (thermal conductivity, specific heat, electrical conductivity, Young's modulus, yield stress, and coefficient of linear expansion).

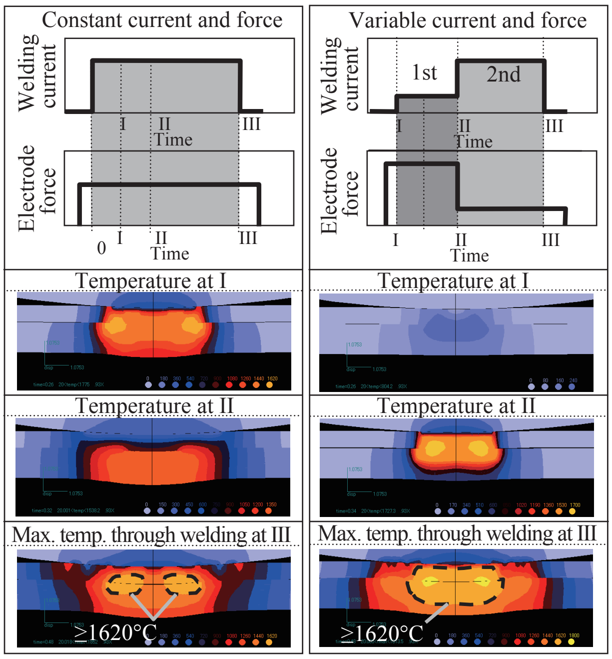


Fig. 13 Predicted temperature distribution during welding by numerical simulation

Figure 13 shows the results of the analysis of the welding process. With (a) Constant current and force pattern, heat generation between the steel sheets occurred immediately after current conduction, but thereafter, the weld temperature decreased in spite of current conduction, and virtually no temperature region which reached or exceeded the melting point was formed. On the other hand, with (b) Variable current and force pattern, the contacting diameter between the electrode and the steel sheet was assured at the 1st Stage, and at the 2nd Stage, heat generation was concentrated immediately after the start, and a high temperature region exceeding the melting point was formed, displaying a flat oval (pebble like) shape.

Based on the above, the presumed concept of the nugget formation process in the variable current and force control pattern is shown in **Fig. 14**. In the first Stage, high force and low current conditions are applied, and an area of tight contact between the upper and lower sheets is formed by preheating the sheets with an adequate electrode force. This assures a stable conduction path like in conventional resistance spot welding. Thereafter, in the second Stage, low force and high current conditions are applied, and nugget formation can be promoted by forming a concentrated heat generation area directly under the electrode by increasing the welding current, while reducing the electrode force to avoid the electrode penetration into the sheet and minimize the increase in the contact area.

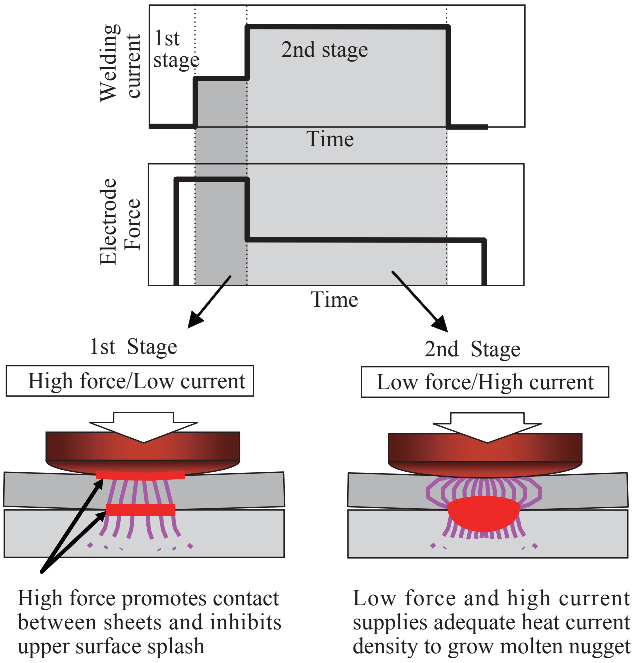


Fig. 14 Concept of nugget formation process of variable current and force control

5. Conclusion

To enable effective application of various types of high performance, high tensile strength steel sheets to automobile bodies, it is important not only to realize high performance in the material properties of the steel sheets themselves but also to develop related manufacturing technologies such as forming technologies, welding technologies, etc. Among these, this paper introduced examples of new spot welding technologies for auto body assembly developed by JFE Steel. In the future, the authors intend to promote practical applications of these technologies in order to contribute to reduction of auto body weight and improvement of crashworthiness by expanding the applications of high tensile strength steel sheets.

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