

Application Technologies that Contribute to the Effective Use of High-strength Steel for Automobiles

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Abstract:

To achieve both lightweighting of automobiles and enhancement of collision safety, high-strength steel (HSS) has been applied to structural components. To overcome the issues associated with HSS, such as decline in formability, weldability and vehicle body performance due to thinning, JFE Steel has developed various application technologies and established a solution proposal system for automobile manufacturers and parts manufacturers. In this paper, press forming technologies for suppression of cracking, wrinkling and springback are first introduced. Furthermore, technologies for improving vehicle body performance and welding technologies that overcome various welding issues and enable short-pitch welding are reviewed.

1. Introduction

Needs for lightweighting of automobiles to achieve improved fuel and electricity consumption and enhanced collision performance in response to increasingly strict collision safety regulations are increasing year by year. To satisfy these requirements, application of high-strength steel (HSS) to the automotive frame is advancing. In recent years, ultra-high strength steel (UHSS) of the 1 470 MPa grade for cold forming have also been adopted in frame components around the cabin. JFE Steel is developing high-formability high-strength steel sheets that simultaneously satisfy both strength and formability requirements. However, to respond to electrification and the rapid evolution of vehicle body structures, such as integration of component parts, of recent years, there is a tendency toward

larger scale and more complex part geometries, and in cold forming of these parts, poor formability, including cracking and wrinkling, is still a longstanding problem. Moreover, in achieving high strength, an increase in added elements is unavoidable, but this also gives rise to concern about liquid metal embrittlement (LME) cracking, reduced joint strength and other problems related to resistance spot welding.

On the other hand, poor shape (springback) that occurs in cold forming and reduced vehicle body rigidity due to thinning are problems which cannot be controlled by the properties of the material itself.

Therefore, in order to achieve the use of UHSS, not only material development, but also the development of application technologies that overcome the above-mentioned problems and enable effective use are necessary and indispensable. JFE Steel is developing application technologies for cold forming, improved vehicle body performance and welding, and has also established a solution proposal system to support better vehicle manufacturing. This paper introduces some of those application technologies.

2. Cold Forming Technology

2.1 Cracking and Wrinkling Countermeasures

In cold forming of automotive components, cracking and wrinkling occur easily in parts with curved shapes. For hard-to-form parts, JFE Steel developed a pre-forming technology in which forming of the product is divided into multiple processes, and the pre-forming geometry is designed optimally to reduce

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the strain that occurs in the final forming process. This chapter introduces the pre-forming methods for two types of curved parts (side-view curved parts and top-view curved parts).

2.1.1 Shear-Inducing Pre-Forming (Wrinkling Suppression Method)

In the forming of parts with side-view curvature, the material flows in the direction perpendicular to the ridge line of bending, as illustrated in **Fig. 1 (a)**, resulting in excess or insufficient material in the top surface or flange parts, which easily causes cracking and wrinkling. Inducing in-plane shear deformation in the vertical walls is an effective technique for achieving the ideal state in which excess/insufficient material does not occur (**Fig. 1 (b)**). Therefore, a pre-forming geometry was designed, focusing on the fact that in-plane shear deformation can be applied by out-of-plane torsion¹⁾. Concretely, by causing inclination of the vertical wall of the convex curved part and flattening the concave curved part, it is possible to obtain a shape with a twisted curved surface (as shown in **Fig. 2**) in the vertical wall between the convex and concave curved parts.

Figure 3 shows prototype formed parts produced by the conventional forming method and developed method using a 1 180 MPa grade UHSS sheet with a sheet thickness of 1.4 mm. In both processes, the parts were formed by the two processes of drawing $\Rightarrow$ bending. However, in the pre-forming geometry in the conventional process, only the top surface is formed by

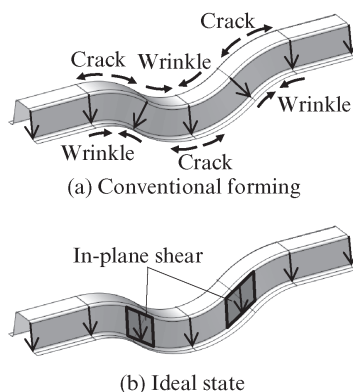


Fig. 1 Material flow in side-view curved part during forming

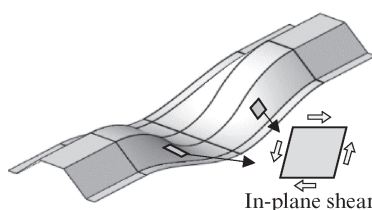


Fig. 2 Pre-form shape that induces in-plane shear deformation

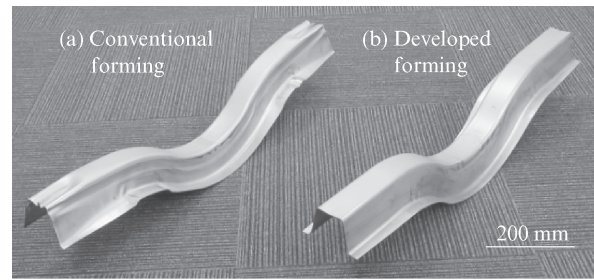


Fig. 3 Prototype formed part (1 180 MPa grade UHSS)

drawing, while in the developed method, the pre-form shape is as shown in **Fig. 2**. With the conventional method, wrinkling occurred in the flange of the convex curved section, but with the developed method, a wrinkling suppression effect was verified.

2.1.2 Large R Form (Stretch-Flanging Cracking Suppression Method)

In forming of top-view curved parts, cracking occurs at the flange edge due to stretch-flanging deformation, in which the material is elongated (stretched) in the circumferential direction in the convex curved part (**Fig. 4**). As methods for suppressing stretch-flanging deformation, a method of dispersing the deformation (strain) in the circumferential direction and a method of promoting material flow from the surrounding area to the convex curved part are effective. Therefore, JFE Steel developed a press forming technology that simultaneously achieves both of these methods by dividing the forming of the convex curved part into two processes²⁾.

In dispersing circumferential strain, the section line length is shortened by pre-forming to increase the die shoulder radius of the convex curved part (**Fig. 5 (a)**). This reduces the excess material inflow of the convex curved part by shortening the section line length, and at the same time, allows easy stretch-flanging deformation of the long and short side materials due to the effect of the enlargement of the shoulder radius. As a result, it becomes possible to disperse the strain over a wide range of the convex curved part. Furthermore, since the material flow also increases, the punch shoulder radii of the long and short sides are increased by

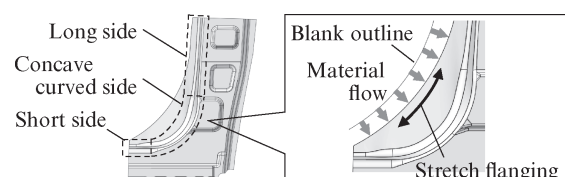


Fig. 4 Material flow in top-view curved part during forming

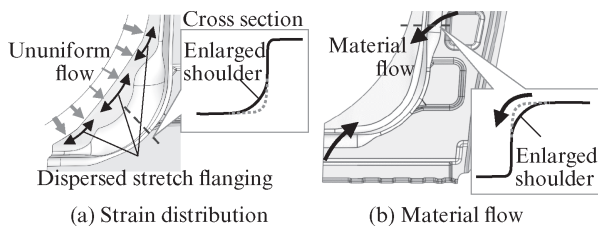


Fig. 5 Pre-form shape that promotes strain distribution and material flow

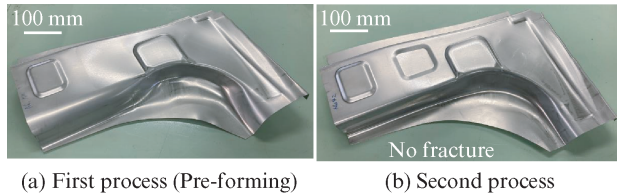


Fig. 6 Prototype formed part (1 470 MPa grade UHSS)

pre-forming, material outflow from the top to the convex curve part occurs easily due to the decrease in bending and unbending resistance (Fig. 5 (b)). The die and punch shoulders that were enlarged by pre-forming are then reformed to the correct dimensions in the second process.

Figure 6 shows prototype parts produced in the first and second processes using 1 470 MPa grade UHSS material. In both processes, forming is possible without stretch-flanging cracking, confirming the effectiveness of the developed method.

2.2 Springback Countermeasures

Springback is a type of deformation that occurs upon elastic recovery of the stress that exists in a blank part at the bottom dead center (BDC: lowest point of die), and increases with the strength of high-strength materials. This section introduces two press forming methods which control the stress that causes springback.

2.2.1 Flange Position Control (Twist Suppression Method)

In forming long, curved parts with a hat-shaped cross section, in-plane stress (tension or compression) occurs in the flange at the BDC, and this stress causes twist springback when released at the time of die release. Since reversing the stress by slightly restoring strain is considered effective for reducing flange strain that causes springback, JFE Steel developed a press forming method that achieves stress reversal³⁾ (Fig. 7). In this method, before forming (left in Fig. 7), the mechanism which applies upward pressure with a cushion to the punch used to form the top surface and ver-

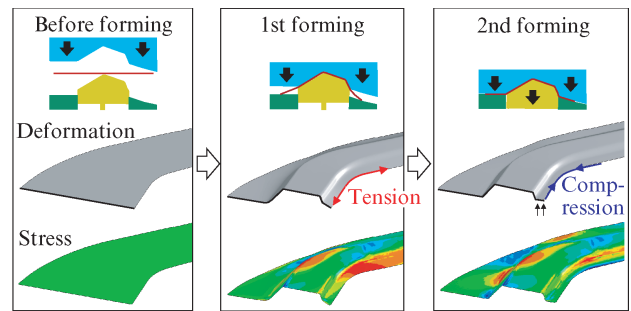


Fig. 7 Press forming method for twist springback

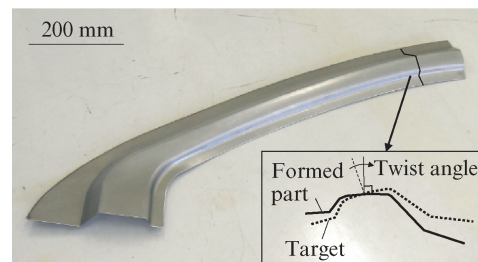


Fig. 8 Prototype formed part (1 180 MPa grade UHSS)

tical walls is held in standby at a position higher than the normal position. Then, in 1st forming (center of Fig. 7), the top surface and vertical walls are formed by the die and punch, after which the flange is formed by lowering the die and punch while pressing the top surface and walls in 2nd forming (right in Fig. 7). This process results in deformation in which the flange is first stretched and then compressed. This induces stress reversal in the flange, and as a result, the tensile stress in the longitudinal direction can be reduced. When a prototype formed part (Fig. 8) was produced by the conventional method using 1 180 MPa grade UHSS with a thickness of 1.4 mm, a twist of 2.9° occurred in the part end. However, when the developed method was used, the twist angle could be reduced to 0.3° by optimizing the standby position of the punch.

In addition to this method, JFE Steel has also developed a method⁴⁾ that reduces springback in the camber direction. This method, which also utilizes stress reversal, is explained in detail in the next report.

2.2.2 Wall-Bend and Restrike Method (Sidewall Curl Suppression Method)

Although many press formed parts have a top surface and vertical walls, sidewall curl caused by springback after forming is a problem. The main factor in this problem is the residual stress on the front and back sides of the steel sheet caused by moment causing at the BDC of press forming (Fig. 9). Sidewall curl can be suppressed effectively by canceling out this residual

stress by inducing a moment with an opposite component (inverse moment) in the preceding process. As a technique for inducing an inverse moment, JFE Steel developed the “Wall-bend and restrike method”⁵⁾, in which a wall-bend shape like that shown in **Fig. 10** is formed in the preceding process, and restrike forming is performed in the succeeding process. This method makes it possible to induce an inverse moment in the sidewalls after restriking in the succeeding process. In the wall-bend and restrike method, the magnitude of the inverse moment can be adjusted by the height, bending angle and bend radius of the wall-bend part. Since the moment causing springback increases with the strength of the sheet, including both the curl moment and the inverse moment, it is possible to respond to variations in material strength by taking countermeasures that cancel out both of these moments, as in the developed method. The developed method is applicable to a wide range of automotive parts where sidewall curl is an issue. As an example, **Fig. 11** shows a cross-section of the results of application to parts with a cross-sectional hat shape when using 1 180 MPa grade steel sheets with a thickness of 1.0 mm. The results demonstrated that wall opening could be suppressed and flange parts with the standard

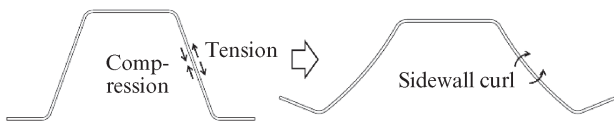


Fig. 9 Sidewall curl of the part with top and wall

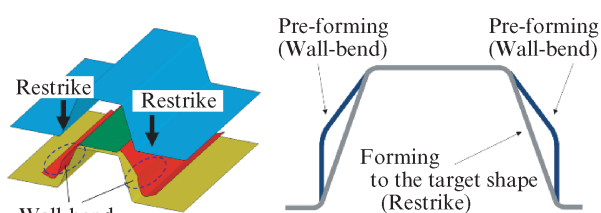


Fig. 10 Press forming method for sidewall curl springback

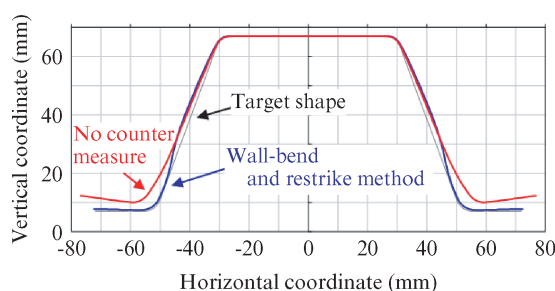


Fig. 11 Effect of “Wall-bend and restrike method”

dimensions could be produced by applying this technology.

3. Vehicle Body Performance Improvement Technologies

Even though lightweighting that satisfies collision safety performance requirements can be achieved by material thinning if UHSS is used, reduced rigidity due to thinning is sometimes a problem. Utilizing rigidity evaluation technologies, JFE Steel is also engaged in the development of vehicle structures by structural optimization from the viewpoint of rigidity.

3.1 Vehicle Rigidity Evaluation Technologies

JFE Steel independently evaluates the torsional rigidity of vehicle frames by the method shown in **Fig. 12**. The body-in-white (BIW) is placed on the test bed, the designated positions at the front and back ends are fixed, and the positions of the front right and left shock towers are input in the direction of torsion by an actuator. The angle of torsion (twist angle) θ is then calculated by measuring the displacement of the bottom surface of the side sills in the vehicle height direction at this time at several locations in the vehicle length direction in order to obtain data related to torsional rigidity ($\text{kN}\cdot\text{m}/\theta$). Together with accumulating these data, these tests are also performed to verify high-rigidity vehicle bodies and components obtained by structural optimization, as described in following section.

3.2 Structural Optimization Technologies

As noted above, the rigidity of automotive parts decreases as a result of thinning of the steel sheet thickness, and the rigidity of the vehicle as a whole is also reduced. If parts are added to increase rigidity, the weight of the vehicle will increase, reducing the effect

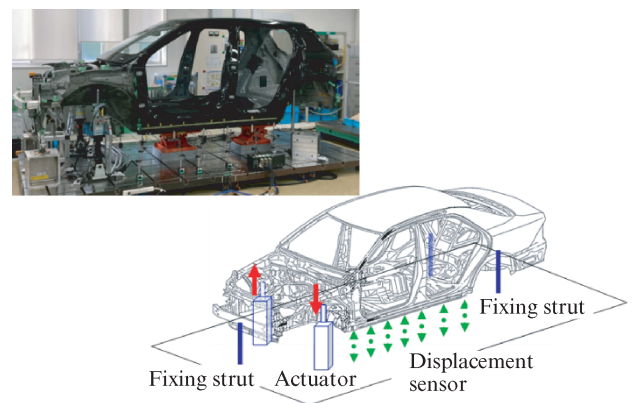


Fig. 12 Evaluation method of torsional rigidity for body-in-white

of applying UHSS. This section introduces technologies for improving rigidity while minimizing this weight increase.

3.2.1 Multi-Material Structure Using a Small Amount of Resin

Although increasing the thickness of steel sheets is effective for improving rigidity, this results in an increase in vehicle weight. Therefore, JFE Steel developed a multi-material structure that remarkably improves rigidity and crashworthiness using resin, which is a low-density material^{6, 7)}. **Figure 13** shows the developed multi-material structure. In contrast to the conventional structure, a high-ductility, high-adhesive strength resin, coated to a thickness of 0.2 to 1 mm, is sandwiched between the outer panel of UHSS and a patch of extremely thin mild steel. The resin is then cured in the auto body baking process after painting by electrodeposition coating. **Figure 14** shows the vibration characteristics and axial collapse performance of the multi-material structure. As a result of the improvement of rigidity by increasing the total thickness of the sheet, the peak of the natural frequency of vibration evaluated by a hammering test shifted to the high frequency region, and the damping property also improved due to the decrease in the peak height. As an additional benefit, since fracture of the base metal is avoided during axial collapse, crashworthiness was improved, even with the same part weight.

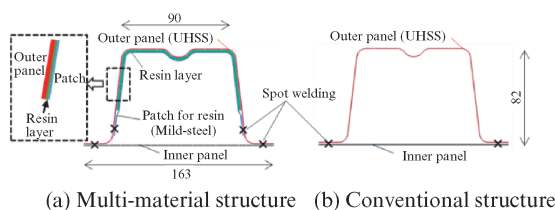


Fig. 13 Section view of multi-material structure

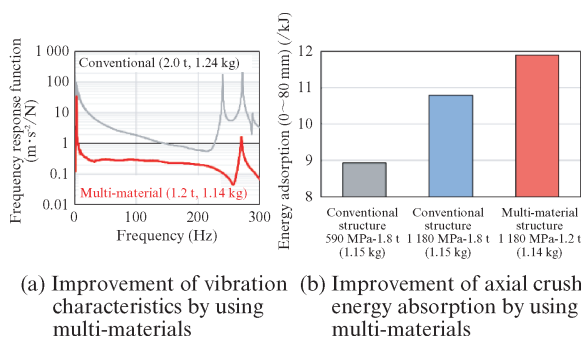


Fig. 14 Performance improvement by applying multi-material structure

3.2.2 Topology Optimization Technology

Topology optimization is a technique in which the elements necessary to satisfy property requirements are retained in a given design space. Until now, it had been considered difficult to apply topology optimization to vehicle bodies that consist of thin sheets. However, JFE Steel developed an application technology utilizing solid elements that enables the creation of part shapes that are both lightweight and have greatly improved rigidity⁸⁾. This analysis was also applied to optimization of spot welding positions, making it possible to improve vehicle body rigidity more efficiently.

Using a BIW model⁹⁾ which is publicly available from the National Crash Analysis Center (NCAC), efficient spot welding positions for improvement of vehicle torsional rigidity were derived by the topology optimization technique, and an additional 200 spot-weld points were added to the spot-weld points that originally used in the BIW, as illustrated in **Fig. 15**¹⁰⁾. The results were then compared with the conventional method, in which spot-weld points are added near spot welds where high strain occurs when torsional deformation is applied to the vehicle body. As a result, a rigidity improvement factor of approximately 2.5 was obtained, showing that extremely efficient results can be obtained with the topology optimization technique.

As described above, vehicle rigidity can be improved efficiently by using the topology optimization technique. Recently, application to battery electric vehicles (BEV) and truck cabs has also progressed^{11,12)}. Moreover, the performance when the topology optimization technique is applied is not limited to static rigidity. Expansion of this technique to vibration characteristics and crashworthiness can also be seen, suggesting that application to vehicle bodies in which high-strength steel sheets are used will also be promoted in the future.

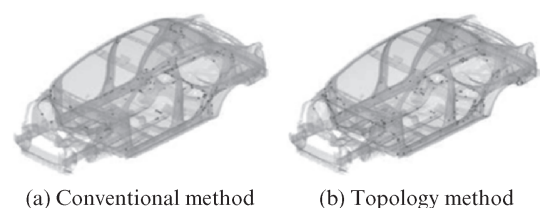


Fig. 15 Added spot-welding points by conventional method and topology method

4. Welding Technology

4.1 Technology for Suppression of Liquid Metal Embrittlement and Improvement of Joint Strength (J-NEKST Spot™ Welding Technology)

With advances in the use of high-strength materials in vehicle structures, application of hot-dip Zn-coated UHSS exceeding the 980 MPa grade to corrosion-resistant parts is also progressing. In resistance spot welding of UHSS that includes Zn-coated steel sheets, liquid metal embrittlement (LME) cracking may occur in the heat affected zone (HAZ) due to disturbances in the welding process, such as electrode inclination (excessive electrode tilt angle) relative to the steel sheet during welding¹³⁾. Furthermore, with regard to joint strength, since an embrittled microstructure can easily occur in welds of steel sheets with a high carbon equivalent, reduction of cross tension strength (CTS) caused by brittle fracture is a concern.

Since LME cracking between two sheets occurs at the time of electrode release¹⁴⁾, a technology for suppressing LME cracking by extending the hold time from the end of energizing until electrode release has been proposed¹⁵⁾, and to improve CTS, a pulsed current technology using a post-heating current (post-current) for tempering of the HAZ and relaxation of P segregation in the nugget was also proposed^{16–18)}. However, with the conventional technology, it was difficult to simultaneously achieve both suppression of LME cracking and improvement of CTS when welding combinations of UHSS materials that include Zn-coated steel sheets.

Figure 16 shows the concept of the J-NEKST Spot™ welding method^{19–21)} developed as a technology that solves the above-mentioned problem. Since this

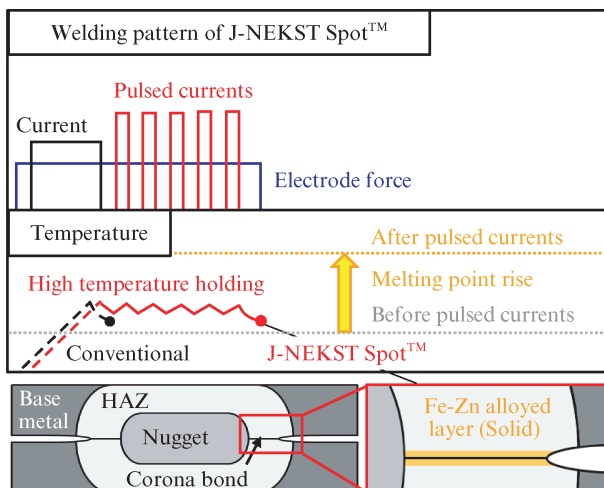


Fig. 16 Concept of J-NEKST Spot™

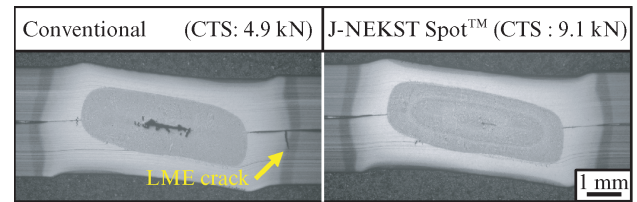


Fig. 17 Results of LME sensitivity and joint strength

technology features repeated application of a high-current and short-time pulsed current, it not only improves joint strength, but also incorporates the completely new technical concept of promoting Fe-Zn alloying by long-time holding in the high-temperature of the corona bond area, where LME cracking initiates. This process suppresses LME cracking by forming a high-melting point Zn alloy layer from the Zn coating and solidification of that layer as a solid phase.

Figure 17 shows the results of verification of the effects of LME cracking suppression (LME sensitivity) and joint strength improvement. As the test material, a high-alloy 980 MPa grade galvanized steel sheet (thickness: 1.6 mm), which had extremely poor joint strength, was intentionally prepared for verification of the effects of the developed method, and the evaluation of LME cracking was carried out under an extreme disturbance condition (electrode tilt angle: 7°) to intentionally induce LME cracking. Although LME cracking occurred between the sheets in welding with the normal single current welding pattern, LME cracking was suppressed by J-NEKST Spot welding. In the evaluation of joint strength (CTS), CTS showed a remarkable increase with J-NEKST Spot welding in comparison with the single current welding pattern. As described above, the J-NEKST Spot welding technology simultaneously achieved both suppression of LME cracking and improvement of CTS when welding a combination of UHSS sheets that included Zn-coated steel sheets.

4.2 Nugget Diameter Stabilization Technology in Short-Pitch Welding (J-MAC Spot™ Welding Technology)

One effective technique for enhancing the crashworthiness of vehicle bodies is increased rigidity of the component parts. To increase the rigidity of spot welds, reduction of the weld pitch (short-pitch welding) has been studied. However, in short-pitch welding, shunting to spots that have already been welded becomes remarkable, making the stable formation of nuggets extremely difficult. To address this problem, JFE Steel proposed a resistance spot-welding technology using adaptive control as a welding method that enables stable nugget formation^{22, 23)}. Resistance spot-welding uti-

lizing adaptive control is a method in which the quantity of heat is calculated by monitoring the current and interelectrode voltage during welding, and gradually changing the welding current so that the quantity of heat matches the target heat set in advance. However, since shunting to previously weld spots becomes remarkable when the weld pitch is extremely short, the full effect of the technology could not be obtained. J-MAC SpotTM welding^{24, 25)} is a technology which solves this problem and stabilizes nugget formation in short-pitch welding by performing heat control in a multi-step current pattern with optimized adaptive control zones.

Figure 18 shows the mechanism of stable nugget diameter formation in J-MAC SpotTM welding. In short-pitch welding of high-strength steel sheets by conventional one-stage adaptive control, interelectrode resistance increases compared to that in welding with no previously welded spots (i.e., no shunting), and as a result, the welding current decreases. The increase in interelectrode resistance also occurs if the current is forced to follow a shunt path where high resistance exists. Since that case is mistakenly recognized as excessive quantity of heat, the welding current decreases, and the nugget diameter is smaller than the aimed diameter²⁵⁾. In J-MAC SpotTM welding, this problem is solved by setting the target value low in the first divided adaptive control zone, and then stabilizing the current at the welding target position by expanding the diameter of current path between the sheets. This suppresses shunting in the following 2nd stage, avoiding decreases in the welding current due to mis-recognition of the quantity of heat. In other words, nuggets can be grown in a condition where shunting is reduced, thereby securing a stable nugget diameter.

5. Conclusion

This paper introduced application technologies necessary for achieving effective use of ultra-high strength steel sheets (UHSS).

At present, great changes are underway in the environment in which the automobile industry operates. In addition to the improved safety and cost reduction demanded until now, consideration of the environment, including carbon neutrality and recyclability, have become important issues that the industry must address. In addition, vehicle body structures are also diversifying in response to electrification, and the trend toward integration of component parts, represented by large-scale aluminum cast parts, is causing a sweeping transformation of the automobile design and production processes. To respond to these changes, JFE Steel constantly monitors or anticipates trends in the auto-

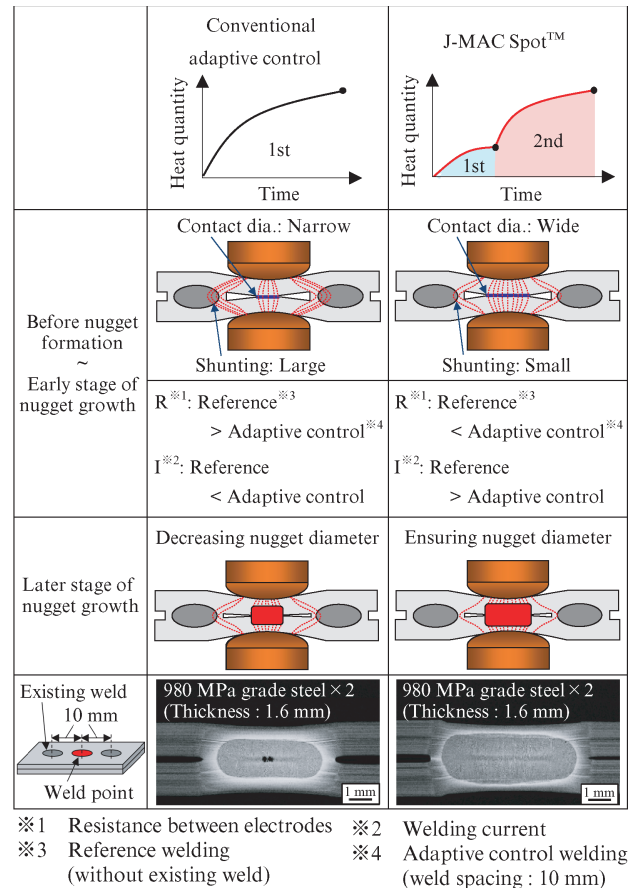


Fig. 18 Mechanism of stable nugget formation in J-MAC SpotTM welding

mobile industry, and contributes to better, more sustainable automobile manufacturing through high-strength, high-performance iron and steel materials and application technologies which meet the needs of customers.

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