JFE TECHNICAL REPORT
No. 24 (Mar. 2019)

Trend of Application Technologies for High Strength Steel Sheets for Light Weight Car Body

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Abstract:

JFE Steel has developed application technologies for high strength steel sheets to make car bodies lighter in weight and better in performances in the area of press forming, improvement in crashworthiness and body stiffness, and joining. JFE Steel has sufficient competence at present in proposing from optimal material selection to application technologies to car manufacturers. Some of the developed technologies are reviewed in this paper.

1. Introduction

From the viewpoint of environmental protection, lighter weight is demanded in car bodies in order to improve fuel consumption and reduce CO_2 emissions. On the other hand, car body weight tends to increase due to tougher collision safety regulations[1)], the increasing number of parts used in cars, etc. Efforts to reduce car body weight by expanding the application of high strength steel sheets to the car body structure are indispensable as a means of solving this problem.

For this, examples in which high strength steel sheets with tensile strength of 980 and 1 180 MPa are used in car body structure parts are increasing. However, it is known that the press formability and weldability of steel sheets decrease as tensile strength increases[2)]. Therefore, JFE Steel Corporation has developed press forming technologies, technologies for improving car body stiffness/crash performance and welding technologies that enable effective use of high strength steel sheets. JFE Steel has also constructed a system for proposing solutions based on a full range of competences from optimal material selection to application technologies for high strength steel sheets in order to further expand the application of these materials in the future.

This report introduces the above-mentioned original application technologies developed by JFE Steel.

2. High Strength Steel Sheet Forming Technologies

The main issues in press forming of high strength steel sheets are cracks and wrinkles that occur during forming and poor dimensional accuracy accompanying increased springback in higher strength materials. In addition, with higher strength steel sheets, the problems of trimmer tool damage[3)], die galling, etc. have also become apparent. JFE Steel has developed prediction technologies and countermeasure technologies for these problems utilizing both CAE (Computer Aided Engineering) and experimental approaches. The following introduces some of these efforts.

2.1 Technologies for Press Cracks

2.1.1 Crack prediction technologies

As the strength of high strength steel sheets increases, elongation and stretch flangeability tend to decrease. Evaluation by the Forming Limit Diagram (FLD) is widely used for stretch cracks and drawing cracks that occur during press forming. However, the FLD cannot be used to evaluate stretch flange fracture, which occurs from the edge of the steel sheet in hole expansion and flange-up forming, and bending fracture of the outer surface of bent parts because the mecha-

[†] Originally published in *JFE GIHO* No. 41 (Feb. 2018), p. 6−13

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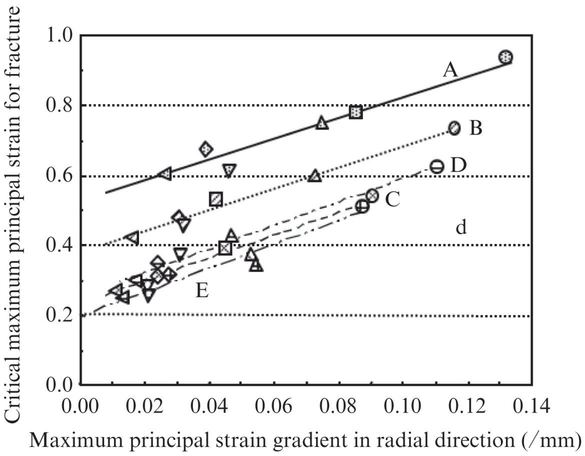


Fig. 1 Effect of maximum principal strain gradient in radial direction on critical strain for fracture

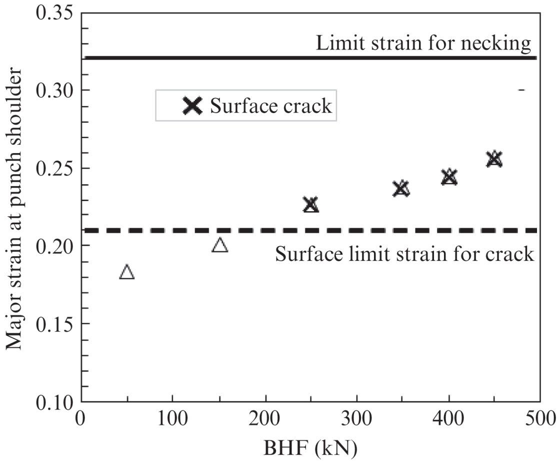


Fig. 2 Relationship between BHF and maximum major strain in punch corner position in 1 180 MPa

nism in which cracking initiates from the interior of the steel sheet and eventually results in fracture is different[4]. Therefore, as a stretch flange fracture prediction method, the critical strain for fracture in stretch forming was defined considering the hole expandability of the material, the maximum principal strain gradient at the edge of the steel sheet and the shear working conditions, making it possible to predict stretch flange fracture by a forming simulation (**Fig. 1**)[5].

On the other hand, bending fracture of the outer surface of bent parts occurs from the outer surface, which is subjected to tensile bending, and is not accompanied by necking. As a bending fracture prediction method, the surface limit strain for fracture obtained by a V-bending test was defined as the critical strain for fracture at the outer surface subjected to tensile bending, enabling prediction of bending fracture with high accuracy. **Figure 2** shows an example of the results of a bending fracture prediction of the punch corner position in hat forming. The surface strain at the punch corner position increases with increasing blank holder force (BHF). Cracking occurred at the surface when the maximum major strain at the punch shoulder exceeded the surface limit strain obtained in the V-bending test, showing that it is possible to predict bending fracture, which cannot be judged by the conventional FLD[6].

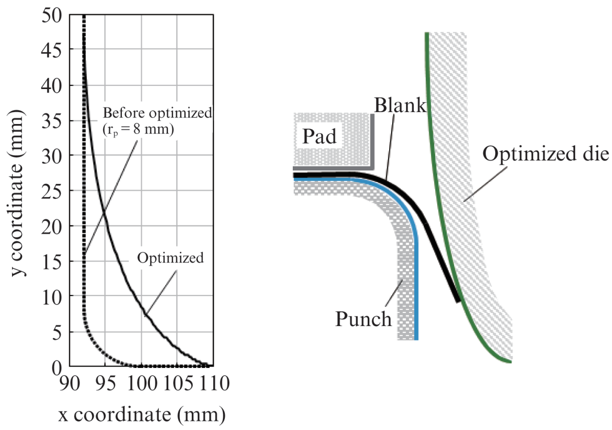
2.1.2 Crack countermeasure technologies

The general practice for preventing fracture is adoption of a more moderate part shape. However, technologies have also been developed to enable forming without changing the part shape. These include a stretch preforming technology[7], in which forming is divided into two processes, the shape in the first process is the optimum shape calculated theoretically and the actual part shape is obtained in the second process, and a technology (JIM-Form^{TM}) in which the motion of the servo press is controlled so as to minimize the stress generated at a portion with a risk of fracture[8].

2.2 Prediction and countermeasure technologies for press wrinkle

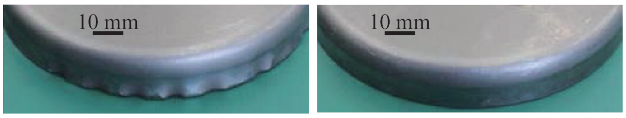
Press wrinkle occurs more easily as the sheet thickness becomes thinner and the strength of the steel sheet increases. Although sensory evaluation is the main wrinkle evaluation method in both forming simulations and actual panels, efforts have also been made to evaluate wrinkle quantitatively[4].

The main wrinkle prevention methods are use of a pad for punch bottom wrinkles and control of BHF for die face wrinkles. Although there was no effective technology for preventing edge wrinkles, a technology for preventing edge wrinkles by reducing the distance from the contact point between the forming die and blank to the blank edge was developed (**Fig. 3**)[9]. As



(a) Optimized die shape (b) Cross section of optimized die

Fig. 3 Optimized die shape



(a) Before optimization (b) Optimized

Fig. 4 Samples formed (a) with die before optimization, and (b) with optimized die

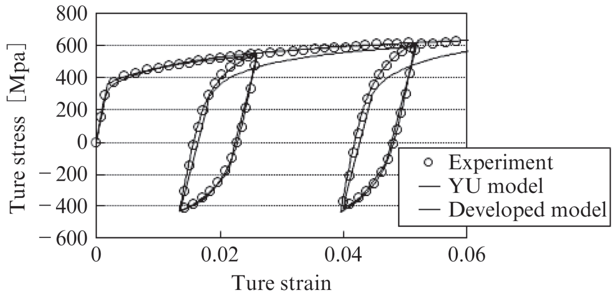


Fig. 5 Comparison of stress-strain curves between experimental result and calculated results of YU model and developed model

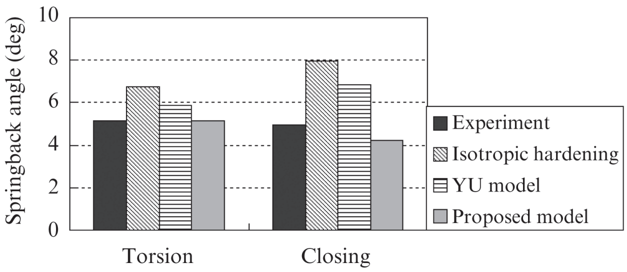


Fig. 6 Comparison of springback angle between experimental and calculation results

shown in **Fig. 4**, edge wrinkles were successfully prevented by adopting a forming die shape that enables forming while maintaining constant contact between the blank edge and the forming die.

2.3 Technology for Dimensional Accuracy Defects

2.3.1 Springback prediction technologies

The accuracy of springback prediction depends on whether the material model can reproduce material properties such as the Bauschinger effect and average Young's modulus after plastic deformation. Therefore, the unloading and reloading characteristics of high strength steel sheets under uniaxial and biaxial stress conditions were investigated, and a model that reproduces the nonlinear stress-strain relationship during stress reversal was created. **Figures 5** and **6** show the results of verification of the prediction accuracy of a springback analysis by the proposed model[10]. It can be understood that the prediction accuracy of the proposed model improved in comparison with the isotropic hardening model and the Y-U model.

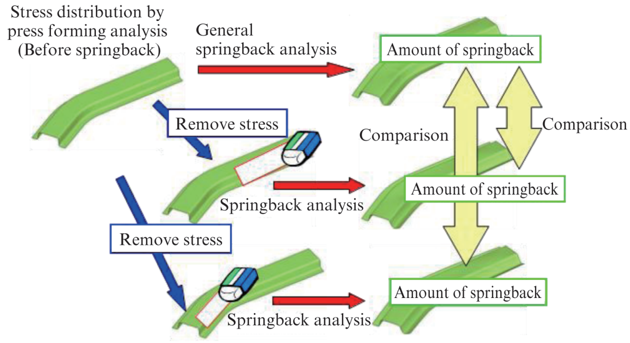


Fig. 7 Schematic diagram of springback cause analysis

2.3.2 Springback countermeasure technologies

Springback is a type of deformation which is caused by the release of the stress that exists in a product at the bottom dead point (bottom dead point stress) accompanying removal from the die, and the amount of springback increases with material strength. Therefore, it is important to develop a springback prevention technology and a technology for improvement of prediction accuracy for springback, which is a cause of dimensional accuracy defects. A springback-root-cause analysis method (**Fig. 7**)[11,12] was developed for this purpose. In this method, the root cause of springback is clarified by establishing the relationship between springback and the bottom dead point stress at the bottom dead point in press forming. Use of this method makes it possible to develop countermeasures for springback reduction that do not depend on the experience and intuition of skilled engineers.

3. Crash Analysis Technology and Evaluation Technologies

Application of high strength steel sheets to car bodies has an important meaning not only for body weight reduction, but also for improvement of the vehicle crashworthiness. Because evaluation of the crash behavior of the vehicle body and parts is important for this, a technology for predicting the load-deformation (force-stroke) curve in collisions with high accuracy by FEM analysis was developed.

In FEM crash analysis, a material model that considers the strain rate dependency of the material is necessary. Therefore, the strain rate dependency of high strength steel sheets was modeled[13] as shown in **Fig. 8** by using an original high speed tensile test method developed by JFE Steel. In this high speed tensile test method, high accuracy is realized in the material model

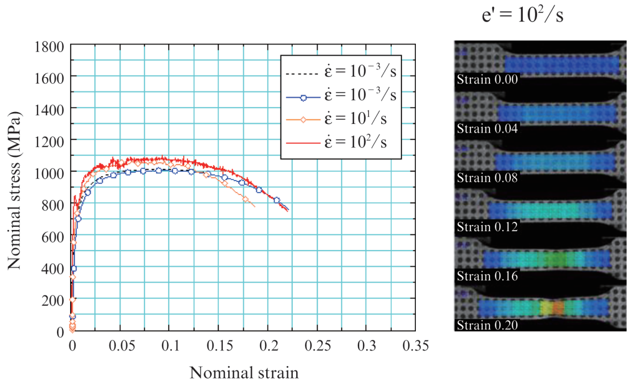


Fig. 8 Comparison of stress-strain curves and strain distribution

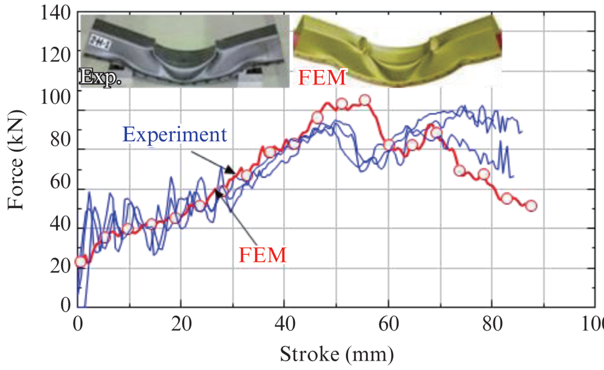


Fig. 9 Comparison of force stroke curves between experimental and FEM analysis data

by utilizing a strain distribution analysis technology by digital image processing. An FEM analysis technology[15] that enables highly accurate prediction of the force-stroke curve[14] when a hat-shaped member of 980 MPa material undergoes bending crushing, is shown in **Fig. 9**.

Moreover, accompanying increased material strength, cases in which the material fractures in a collision and fails to demonstrate its designed crash performance have occurred. Therefore, researchers have attempted to determine the fracture criteria depending on stress triaxiality and predict fracture of the base material on this basis. **Figure 10** shows an example in which the structure of the upper part of the center pillar was studied by an FEM analysis that considered fracture during a collision. The accuracy of predictions of crash performance is improved by consideration of fracture.

Development of technologies for evaluation of the crash performance of actual parts is also progressing. Because crash safety regulations are becoming stricter by the year, tests at an impact speed of 90 km/h are also being studied. For this, JFE Steel introduced an automotive crash simulator which makes it possible to conduct crash performance experiments by impacting a

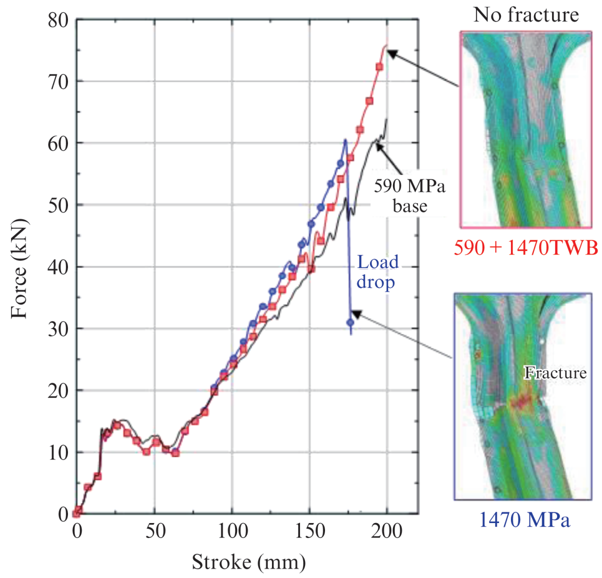


Fig. 10 Comparison of force stroke curves between proposed structure without fracture and conventional structure with fracture

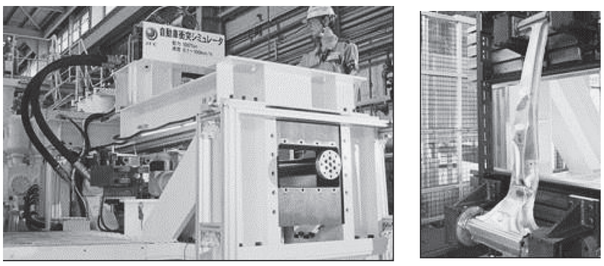
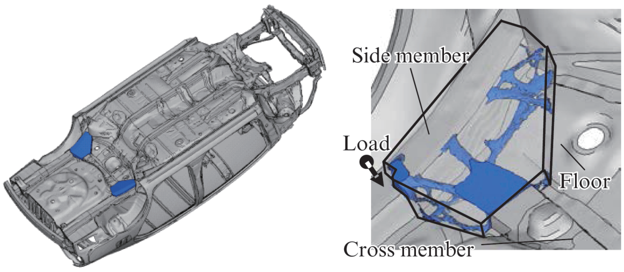


Photo 1 Dynamic testing machine and crashed parts

moving object with a maximum weight of 700 kg into members with heights up to 2 000 mm and widths up to 1 500 mm at an arbitrary speed from 0.1 to 100 km/h (**Photo 1**). 3D deformation analysis is possible by using multiple high speed cameras. FEM analysis technologies and crash evaluation technologies that anticipate future crashworthiness regulations have made it possible to propose lightweight, high performance car body structures and the optimum materials for those structures.

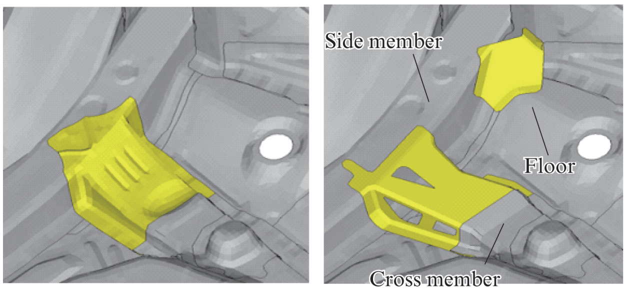
4. Car Body Stiffness Improvement Technology

Although application of high strength steel sheets to car bodies to reduce body weight is progressing, the stiffness of parts decreases due to the thinner material thickness, and the stiffness of the car body as a whole also decreases. However, adding parts to improve stiffness has the undesirable effect of increasing weight, which reduces the effect of applying high strength steel sheets. Topology optimization is known as a technology for improving stiffness with the minimum weight increase. In topology optimization the elements neces-



(a) Optimizing object (b) Residual area

Fig. 11 Residual areas of connecting area in the full vehicle model

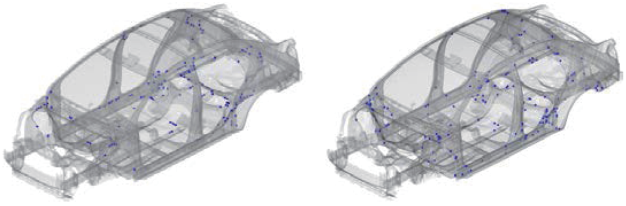


(a) Original shape (b) Optimized shape

Fig. 12 Optimized shape of connecting area in the full vehicle model

sary to meet performance requirements are retained from a given design space. This technology has a long history of use in creation of the shapes of engine blocks and other castings. Until now, it had been difficult to apply topology optimization to car bodies, which consist of thin sheet materials, but the development of an application technology using solid elements has made it possible to create part shapes that realize light weight and also greatly improve stiffness. The analytical process of topology optimization was applied to optimization of the spot welding points, enabling efficient improvement of car body stiffness. As shown in **Figs. 11** and **12**, a full vehicle model[16] of the body-in-white which is publicly available from the National Crash Analysis Center (NCAC) was used in optimization of the part shape of the connecting area of the rear side member and rear cross member in order to improve torsional body stiffness[17]. It was possible to improve stiffness by 4.3% in comparison with the original part shape by using the part shape prepared based on the residual areas of topology optimization.

Figure 13 shows the results of a study of a high efficiency arrangement of welding points for improvement of torsional body stiffness when spot welding points were added to those comprising the original body-in-white[18]. In the conventional method, spot welding points were added near those where high strain



(a) Conventional method (b) Topology method

Fig. 13 Added spot welding points by conventional method and topology method

occurred when the body was subjected to torsional deformation. In comparison with that approach, results showing extremely good efficiency, namely, a stiffness improvement rate of approximately 2.5 times, were obtained by the topology optimization method by adding 200 welding points.

JFE Steel is also developing technologies for evaluating car body stiffness and has demonstrated a high stiffness car body obtained by topology optimization through a stiffness evaluation of the body-in-white.

As described above, improvement of car body stiffness can be realized with good efficiency by using the topology optimization method. Since the objects of topology optimization are not limited to static stiffness, but also extend to vibration characteristics and collision characteristics, it is thought that this technology will accelerate the application of high strength steel sheets to car bodies.

5. Welding Technologies for High Strength Steel Sheets

Applications of various types of materials, including steels, to the car body and chassis are being studied, and the multi-materials structure, integrating steel materials, nonferrous metal materials, synthetic resin materials and others, has attracted attention in recent years from the viewpoint of weight reduction. However, because steel materials are more economical than other materials and are also superior in terms of workability, many have expressed the desire to continue the orientation toward structures consisting mainly of steel materials. In response to those requests, JFE Steel has developed a wide variety of high strength steel sheets and high performance steel sheets. Although designs using these steel sheets also consider weldability, it is important to develop the optimum welding technologies for high strength steel sheets in order to contribute to body weight reduction and high strength by making the most fully possible use of the advantages of steel sheets.

This chapter presents an overview of the trends in the development of various types of welding technologies for the car body and chassis in JFE Steel.

5.1 Trends in Development of Welding Technologies for Car Body

The welding and joining techniques used in the production of car bodies include resistance spot welding, laser welding, gas shielded arc welding, adhesive bonding, mechanical joining and others. Among these, resistance spot welding and laser welding will be taken up here as main technology, and friction stir welding (FSW), which is considered an expected technology for the future, will also be introduced in the following.

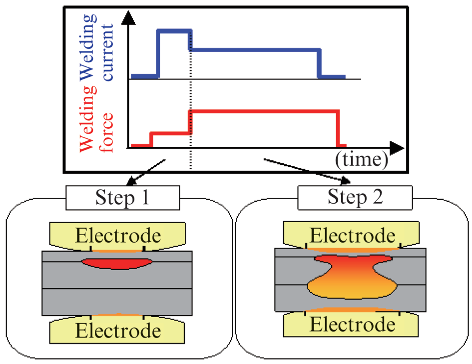


Fig. 14 Welding current and electrode pattern of Intelligent Spot™ Welding

5.1.1 Resistance spot welding technologies

Among the above-mentioned welding methods, resistance spot welding is the most frequently used welding method in car body assembly processes. One vehicle contains 3 000 to 6 000 welding points. Resistance spot welding is a method that utilizes the Joule heat (resistance heat) generated by conducting a large electric current through the welding area. It is particularly effective in mass production because low cost, high efficiency production is possible in comparison with the other welding technologies owing to its extremely short welding time. Moreover, great progress has been achieved in resistance spot welding systems in recent years by integrating articulated welding robots and welding controllers (current waveform control). So-called integrated systems have been designed, in which not only robot operation but also control of the electrode force, welding current and other welding conditions are performed in an integrated manner from the robot control panel, making it possible to set the welding current and electrode force freely[19,20]. For example, this technology has been applied with good results to optimization of the electrode tip trajectory when moving from one welding point to the position of another welding point (improvement of production efficiency) and optimization of the electrode force at individual welding points with different combinations of steel sheets and member conditions (improvement of welding quality). Focusing on progress in this type of welding system, and in particular, the remarkable advances in welding current and electrode force control functions, JFE Steel is actively involved in developing various welding technologies to improve weld performance.

Intelligent Spot™ Welding is a welding technology which JFE Steel developed for three-sheet lap joints with a high sheet thickness ratio, with which stable nugget formation is considered difficult[21]. Joints with a high sheet thickness ratio are increasing accompanying the expanding application of high strength steel sheets. However, with this technology, the nugget formation phenomenon is successfully controlled by a two-stage electrode force/two-stage welding current welding process, as illustrated in **Fig. 14**. In conventional welding, the nugget is formed at the midpoint between the two electrodes, which means it is difficult to form nuggets between a thin sheet and a thick sheet. However, use of a low electrode force, short weld time and high welding current in Step 1 enables preferential heat generation between the thin sheet and the thick sheet. Heat generation between the two thick sheets is then promoted in Step 2 by using a high electrode force and long weld time, enabling stable nugget formation.

Single-Side Spot™ Welding is also a welding technology that utilizes two-stage electrode force/two-stage welding current control[22]. The application of closed section structures using high strength steel sheets is considered effective for realizing higher body stiffness and requires a welding method with access from only one side. Therefore, JFE Steel developed the indirect-type one-side spot welding with a nugget formation stabilization technology by electrode force/welding current control enabling robust welding control. The two-stage electrode force/ two-stage welding current pattern is the opposite to that of Intelligent Spot™ Welding: In the Single-Side Spot™ Welding process, contact between the sheets is secured in Stage 1, which is performed under high electrode force/low welding current conditions, after which satisfactory nugget formation is achieved in Stage 2 under low electrode force/high welding current conditions.

Pulse Spot™ Welding is a spot welding technology to improve the cross tensile strength of joints by controlling the post-heating welding current pattern[23]. The carbon equivalent generally increases in higher strength steel sheets, which tends to deteriorate the strength of resistance spot welded joints[24]. For a resistance spot welding technology that solves this problem, JFE Steel developed a welding process incorporating short-time cooling and a pulse welding current repeatedly after the main welding current that forms the nugget. With this welding process, it is possible to improve nugget toughness by mitigating P segregation in the nugget and relieve stress concentration at the nugget by reducing the hardness of the HAZ, which results in great improvement of joint strength. The fact that the weld properties are controlled, without the need to control nugget formation (nugget diameter) is a distinctive feature of this technology.

The resistance spot welding technologies described above utilize so-called constant current control, in which the welding current is conducted at a constant value. Recently, however, continuing progress has been achieved in practical application of adaptive control welding technologies[25]. In adaptive control welding, the welding heat is calculated by monitoring the current and inter-electrode voltage during welding, and the welding current is changed continuously during welding so as to coincide with the targeted heat. Application of this technology enables uniform nugget formation at all times without changing the welding current setting, even when the pitch of the welding spots changes during production of the car body.

Although control of weld properties, as described above, is effective for securing adequate strength in spot welded joints of high strength steel sheets, it is important to stably secure a nugget diameter of the same size[26]. Anticipating the development of even higher strength steel sheets in the future, JFE Steel developed "J-MAC Spot™" welding as a spot welding technology utilizing adaptive control[27]. In conventional adaptive control spot welding, the welding heat is controlled to adjust with the change in the one welding stage, but as a distinctive feature of "J-MAC Spot™" welding, the adaptive control period is divided into multiple stages, and the welding heat is controlled to adjust changes to coincide with the targeted heat for each of these stages. The effectiveness of this technique in stabilizing the nugget diameter has been confirmed in welding of the full range of materials from mild steel to high strength steel.

5.1.2 Laser welding technologies

Although laser welding attracted attention as a next-generation welding technology earlier and is considered an effective continuous welding method for producing high rigidity members, it has failed to achieve wide use due to the high cost of the equipment and various other restrictions, such as strict assembly precision requirements for the members to be welded. Nevertheless, practical application is progressing accompanying advances in laser beam quality in recent years.

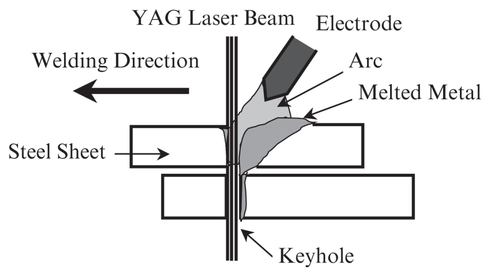


Fig. 15 Schematic illustration of Laser-Arc Hybrid Welding

Laser-Arc Hybrid Welding[28] is a welding method that combines arc welding and laser welding and makes it possible to ease the assembly precision requirements for welds by adding a filler metal. **Figure 15** shows a schematic diagram of the Laser-Arc Hybrid Welding process. By arranging an arc welding electrode to generate an arc after the laser irradiation point, it is possible to stabilize the droplet transfer in the arc plasma, even in high speed welding. Because this technique expands the critical gap tolerance between the steel sheets in two-sheet lap welding, application is expected in the future.

In contrast to this, practical application of remote laser welding, which enables higher speed welding, is already progressing[29]. As ultra-high speed welding of arbitrary geometries is possible by combining a galvanomirror that scans the laser beam and a condensing lens that enables a long focal length, this technology is considered to have a sufficient cost merit, even though expensive laser welding equipment is used. In particular, from the viewpoint that arbitrary welding geometries can be realized at low cost, application as a substitute technology for resistance spot welding, rather than improvement of rigidity by continuous welding, is under study. In the case that the arbitrary welding geometry is applied to high strength steel sheets, it is important to secure joint strength, as mentioned above in the case of resistance spot welding. Therefore, the optimum welding line geometry was clarified based on a strength evaluation by welding experiments and FEM strength analysis of the relationship between the welding line geometry and joint strength[30]. Expanded application of this technology is expected in the future.

5.1.3 Friction stir welding

Friction stir welding (FSW), as shown in **Fig. 16**[31], is a welding technology in which the materials being welded are joined by inserting a tool rotating at high speed into the materials to generate a material flow by frictional heat without fusion. Practical application of FSW to low melting point metals such as aluminum alloys, magnesium alloys, etc. as a method for obtain-

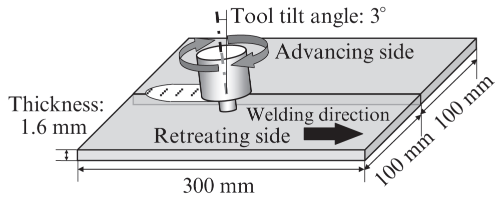


Fig. 16 Schematic illustration of Friction Stir Welding

ing low strain, high quality joints is progressing, and the same merits are also assumed in application of FSW to steel sheets. Unlike FSW of low melting point metallic materials, a welding tool with excellent high temperature strength is considered necessary when FSW is applied to steel sheets, but welding tools that can withstand welding of steel sheets have been developed in recent years. In joints produced under conditions of a tool rotation speed of 200 rpm and welding speed of 200 mm/min, joint efficiency of 96% with 780 MPa class steel sheets and 84% with 1 180 MPa class steel sheets compared to the base material has already been confirmed in tensile tests[31], and efforts to realize even high joint strength and weldability are continuing. There is considered to be a high possibility of practical application of FSW to high strength steel sheets in the future.

5.2 Trends in Development of Chassis Welding Technologies

Almost all of the welding used in the manufacture of the automotive chassis is gas shielded arc welding because the objects to be welded are hot-rolled steel sheets with a thicker sheet thickness than those used in the auto body. This section introduces trends in the development of welding technologies for the automotive chassis at JFE Steel.

5.2.1 Gas shielded arc welding technologies

Gas shielded arc welding of chassis members is mainly performed on lap fillet joints. The properties demanded are related to welding workability, represented firstly with low spatter. As a low spatter CO_2 arc welding technology, JFE Steel proposed J-STAR™ welding[32], in which welding is performed with a straight polarity by using a wire containing REM (Rare Earth Metal). Since the first practical application of J-STAR™ welding was in fields such as ship construction, etc. where heavy gauge plates are used, this is considered an effective technology for application to comparatively heavy gauge members.

Fatigue strength (endurance) and corrosion resistance can also be mentioned as necessary weld properties. Particularly when there is an orientation toward

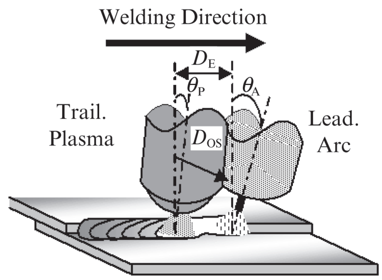


Fig.17 Schematic illustration of "Plasma-arc Hybrid™" welding

reducing material thickness by application of high strength steel sheets, securing both properties is the most critical consideration. Since the fatigue strength of joints is generally governed by stress concentration and residual stress in the weld bead toe, which becomes the origin of fatigue cracks, joint fatigue strength is not improved by increasing the strength of the steel sheets. The "Plasma-arc Hybrid™" welding method[33] was developed to solve this fatigue problem. **Figure 17** shows a schematic diagram of the "Plasma-arc Hybrid™" welding method. This is a welding method in which gas shielded arc welding is arranged in the leading position and plasma welding in the trailing position. In this welding method, an attracting force is generated in both arcs by adopting straight polarity welding in both arc welding and plasma welding, and the bead width is widened by the promoted fluidity of the molten pool, smoothening the weld bead toe part. Satisfactory fatigue strength in comparison with conventional welding methods has been obtained in a plane bending fatigue test of lap fillet welded joints of 780 MPa class hot-rolled steel with a thickness of 3.2 mm produced by "Plasma-arc Hybrid ™" welding.

As a welding technology for improving both the corrosion resistance and the fatigue strength of welds, JFE Steel proposed a low CO_2 gas shielded arc welding technology[34]. Corrosion of welds proceeds by a process in which slag adhering to the weld bead and its toe part reduces coating film adhesion, causing defects in the coating film. For this problem, improvement of the shape of the weld bead toe part and higher corrosion resistance were achieved by applying the low CO_2 gas shielded arc welding method, in which the mixing ratio of the active gas (CO_2) is reduced. Because a further decrease of fatigue strength due to reduction of sheet thickness by corrosion under the operating environment is a concern, improvement of fatigue strength by enhancing corrosion resistance is considered to be an advantage of this technology.

5.2.2 Laser–arc hybrid welding technology

In chassis members, closed section structures are used in addition to lap welded structures of flat sheets, and adoption of high strength steel sheets in closed section structures is considered effective for satisfying both weight reduction and stiffness. However, in manufacturing parts with a closed section structure from flat sheets, it is necessary to weld the seam part in a butted condition or lapped joint condition, and application is difficult with gas shielded arc welding due to the difficulty of obtaining the necessary penetration depth. Therefore, laser-arc hybrid welding, which enables full penetration welding, is considered effective. As described in section 5.1.2, this technology is a welding method that combines arc welding and laser welding. As high speed, high efficiency welding is possible and the effect of easing gap accuracy requirements is also sufficient, its suitability as a welding method for production of chassis parts with closed section structures has been confirmed[35].

6. Conclusion

As application technologies for high strength steel sheets developed by JFE Steel, press forming technologies, technologies for improving car body stiffness/crash performance and welding technologies were introduced. Because further progress in higher strength steel sheets is also expected in the future, JFE Steel will continue to promote technology development for weight reduction of the car body and chassis in addition to the application technologies for high strength steel sheets introduced in this report in the future.

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