

Application Technologies for Weight Reduction, Improving Crashworthiness, and Shortening of the Development Period for Automobiles[†]

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Abstract:

This paper presents representative examples of recent research and development in connection with forming and joining technologies for automotive steel products at JFE Steel. To contribute to diversification of automobile manufacturing and shortening of the development period by automakers and create a joint development system for automotive parts, JFE Steel has developed forming, crashworthiness, and durability prediction technologies, centering on the finite element method (FEM), and implemented a system which enables material proposal/supply from the design stage. The accuracy of these prediction technologies supports material and part evaluation technologies and ensures the reliability of solutions.

1. Introduction

The ULSAB (Ultra Light Steel Auto Body) Project began in Apr. 1994 with the joint sponsorship of 32 steel makers in 15 countries. In order to realize weight reduction in the automobile body in white (BIW), this project investigated (1) adoption of high tensile strength materials, (2) adoption of TWB (tailored welded blanks), (3) adoption of HF (hydroformed) parts, (4) positive use of the laser welding method, and (5) elimination of reinforcements. As a result, it was suggested that weight reductions on the order of 20% are possible in the BIW, and concretely, DH (demonstration hardware) was manufactured and the results were publicized.¹⁻⁷⁾ The achievements of the project were timely in encouraging the

adoption of TWB and HF parts by domestic automakers in Japan and served to indicate directions for auto weight reduction. In the subsequent auto weight reduction project, ULSAB-AVC (Ultra Light Steel Auto Body-Advanced Vehicle Concepts Project), structural materials up to TS980 MPa grade were proposed in response to progressive adoption of high strength steel materials by the auto industry and heightened requirements for crashworthiness. On the other hand, because it is known that the formability of high strength steel sheets decreases as base material strength increases, the development of technologies for evaluating material formability and properties from the standpoint of sheet use will be important for further expansion of the applications of high tensile strength materials in the future. Against this background, this paper describes the creation of a cooperative part development system with automakers and part makers by introduction and development of a full complement of laboratory evaluation devices and powerful analytic techniques, and the establishment of a system which makes it possible to supply a wide range of problem-solving type solutions from material selection in the basic structural concept to forming technologies and part property evaluation.

2. Test and Evaluation Technologies

The trend toward high tensile strength in automotive materials is now clear. JFE Steel possesses technologies for evaluating the press-formability of high tensile strength materials and properties of formed parts which

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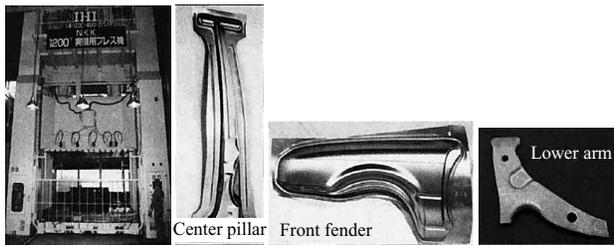


Photo 1 1 200 t single action mechanical press machine and pressed samples

make it possible to supply customers with the optimum materials for their intended applications. This chapter presents an outline of a large-scale press machine, which is capable of evaluating the press formability of high tensile strength and coated steel sheets at the actual-machine level, and a dynamic testing machine, which is capable of investigating the dynamic properties that govern crashworthiness at the test part level.

(1) 1 200 t Experimental Press Machine

This device, which was installed at JFE Steel, makes it possible to measure changes in the blank holding force, stroke, forming load, and other parameters of the forming process in the single-action mechanical press machines used in mass production by auto-makers. The press capacity of this device is 1 200 t, and the maximum blank holding force is 300 t. Using model dies for the front fender, door outer, center pillar outer, lower arm, and similar parts, it is possible to research the forming behavior of actual parts and evaluate the formability of actual parts made from newly developed materials. Because the press is equipped with an internal NC die cushion device, it is also possible to control the blank holding force during the forming process. The press machine and examples of formed parts are shown in **Photo 1**.

(2) Dynamic Impact Deformation Testing Machine

JFE Steel has also installed an impact deformation testing machine with a 50 t dynamic load, which makes it possible to study the absorbed energy and deformation behavior of auto parts in collisions. It is possible to investigate the crushing properties of parts up to 500 mm $h \times$ 300 mm $w \times$ 300 mm h and the impact bending properties of parts up to 1 200 mm $l \times$ 200 mm w at varying speeds from 0.1 m/s to 14 m/s. As features of the device, because the speed can be held constant during the test process, systematic investigation of the effects of material strength and thickness on the impact properties of materials with strain rate dependency is possible. The testing machine is equipped with a high-speed video camera, enabling detailed study of the relationship between load-displacement behavior and the deformation behavior of parts, and a device which enables study of deformation characteristics under low tem-

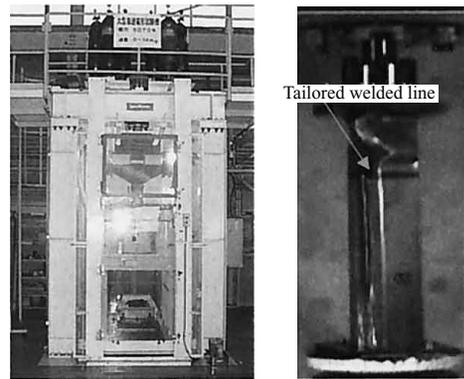


Photo 2 Dynamic testing machine and crashed specimen

perature environments, making it possible to propose proper high tensile strength materials considering low temperature environments. The testing machine and a crushed specimen are shown in **Photo 2**.

3. Tailored Welded Blank (TWB) Technology^{8,9)}

Tailored Welded Blank (TWB) refers to blank materials which are jointed by laser, mashseam, plasma arc, or other welding methods prior to press forming. When initially developed, TWB was also employed to improve material yield. However, because this technology makes it possible to manufacture parts with the optimum arrangement of materials using a small number of dies, TWB is now becoming an indispensable mass production technology for achieving high performance and weight reduction in automobiles. **Figure 1** shows an example of the material arrangement in a tailored welded blank. From the viewpoints of TWB formability and external appearance, laser welding is the optimum welding method. To obtain sound welds, the accuracy of alignment of the blanks of welding materials and the laser welding position must be controlled with an accuracy of 0.1 mm. **Figure 2** shows the results of an investigation of the effect of the weld configuration on the tensile strength and fracture characteristics of TWB welds in terms of the width of the welded section, W . T_{av} is the

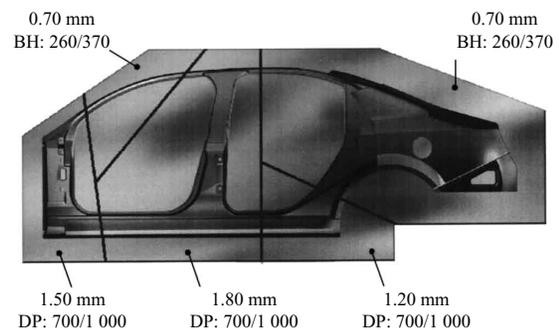


Fig. 1 Application of tailored welded blanks to automotive body (ULSAB-AVC project (ultra light steel auto body-advanced vehicle concepts project))

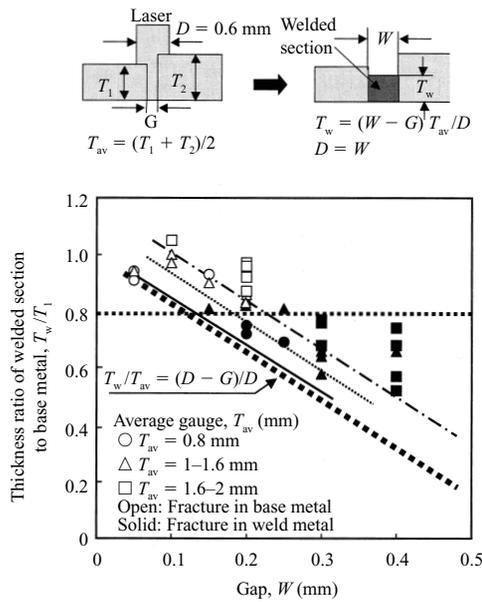


Fig. 2 Relationship between configuration and quality of laser welds

average value of the sheet thickness at joints between materials of differing thicknesses. From the figure, it can be understood that the thickness ratio of the welded section to the base metal decreases as the gap increases, and welds possess satisfactory quality when this thickness ratio is approximately 0.8 or higher, independent of T_{av} and mechanical properties⁹⁾. The figure also shows that it is important to strictly control the gap, G between the TWB materials to within 0.1 mm at this time. In the press-forming stage, the forming behavior of TWB materials can basically be classified into cases where large strain is generated in the direction of the weld line and cases where large strain is generated perpendicular to the weld line. When large strain is generated in the direction of the weld line, the ductility of the weld and ductility of the base material (strain dispersion capacity: n -value) control formability. Therefore, as shown in **Fig. 3**, the limit strain is arranged using the sum of the hardness of the welded section and the hardness of the base material as a parameter.⁸⁾ Furthermore, the ductility of the welded section can be arranged in terms of the base metal composition (carbon equivalent: C_{eq}). When large strain is generated perpendicular to the weld line, the balance of base metal strength and thickness determines formability.⁹⁾ The joining position is optimized based on this thinking, using a simulation of the forming of actual parts of TWB materials by the finite element method (FEM).

Based on the knowledge of TWB materials described above, JFE Steel plans to introduce TWB equipment from the German company ThyssenKrupp AG, with which it has a technical tie-up, in Aug. 2004 and begin research and development in connection with high value-added TWB production.

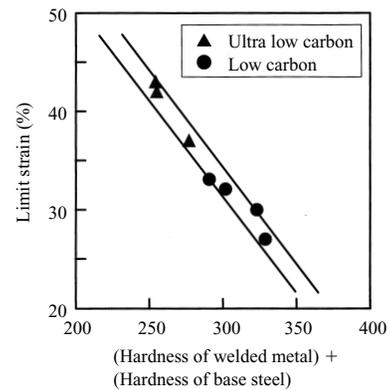


Fig. 3 Relationship between limit strain and hardness of weld metal and base metal

CAD-CAE systems, which are discussed in the following, are necessary and indispensable as advance prediction techniques for the stiffness, high strain rate strength, and other characteristics of parts manufactured with TWB. In verifying the accuracy of analytical results, JFE Steel makes full use of the test and evaluation devices described above. Using this system, JFE Steel has established a technology for optimizing the material arrangement in TWB, and has also constructed the material databases necessary for forming simulations, such as forming limit diagrams (FLD) of welds in TWB manufactured by the company.

4. Hydroforming Technology^{10,11)}

Hydroforming (HF) is a forming technology in which a steel tube is set in a die and formed to fit a specified shape by applying hydraulic pressure from inside the tube while also applying force in the tube axial direction (axial feed). Parts manufactured by HF have numerous advantages in comparison with sheet metal/welding method parts. For example, because HF parts are manufactured in one piece, they have high strength and stiffness, weight reduction is possible by rational cross section design and elimination of welded flanges, and costs can be reduced by reducing part integration/die costs and welding labor.

In recent years, as shown in **Fig. 4**, it has become the general practice in application of HF to perform various types of pre-forming in the step prior to pipe-expansion by hydraulic pressure. These pre-forming processes include bending the tube to a shape approximating the final product configuration, press crushing, and diameter reduction. Thus, in addition to technology for pipe expansion by hydroforming, the design of the pre-forming process is also important. Study items include (1) optimization of the overall pre-forming-HF process and establishment of a system for evaluating forming difficulty, (2) optimization of the loading path and establishment of the related control technology, (3) estab-

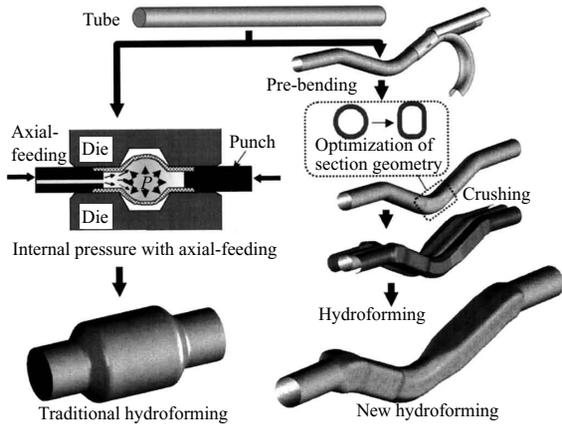


Fig. 4 Manufacturing process of hydroforming tubes

lishment of evaluation methods for HF formability and development of steel tubes with excellent formability, and (4) lubrication and others.

Elucidation and development of steel tube properties suitable for HF are also progressing steadily. In Europe and the United States, active adoption of HF utilizing laser welded tubes manufactured by winding the strip material has begun, while in Japan, use of electric resistance welded (ERW) steel tubes is the mainstream. Materials with large elongation relative to the necessary strength are desired. Specifically, high n -values are desired for alleviating localized deformation in the transverse cross section, high r -values are desired under strong axial thrust conditions, and high n -values and r -values are also desired for reducing circumferential thickness deviations in pre-forming bend sections. From this viewpoint, the CBR, which is a low-strain pipemaking process developed by JFE Steel, and HISTORY processes are also suitable for HF applications. In particular, because HISTORY tube products are manufactured by warm-reduction of ERW tubes, in addition to material properties which include high n -values and high r -values, they are also free of seam hardening and have been found to possess excellent HF and bending properties.

The most important tasks for popularizing HF technology in Japan at the same level as in Europe and the U.S. are reduction of equipment costs and substantial shortening of the HF cycle time. Recently, steady progress can be seen in a variety of newly developed HF machines, and cycle times of less than 20 s have been realized. Thus, its future growth is expected.

5. Application Technologies for High Strength Steel Sheets in Press Forming¹²⁻¹⁵⁾

The main defects which occur in press forming are rupture, wrinkles, and surface deflection. As counter-

measures from the material side, JFE Steel is continuing to develop steel sheets with high-performance mechanical properties and high lubricants which compensate for reduced formability. At the same time, from the forming technology side, the company is developing new forming technologies such as hydraulic counter pressure forming and tension control forming, as well as numerical simulation technologies for advance prediction of forming defects. **Figure 5** shows the high pressure liquid lubrication (HPLL) forming method proposed by JFE Steel as a new forming method. In this method, forming is performed while supplying a liquid at high pressure from the die to the space between the die and the material. **Figure 6** is an example of the effect of HPLL forming, and shows that the improvement in the limit drawing ratio (LDR) by HPLL is equivalent to an increase of 0.4 in the r -value of the material, even when this method

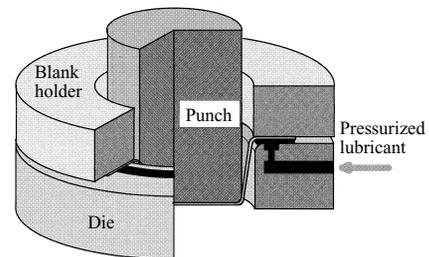


Fig. 5 High pressure liquid lubrication method

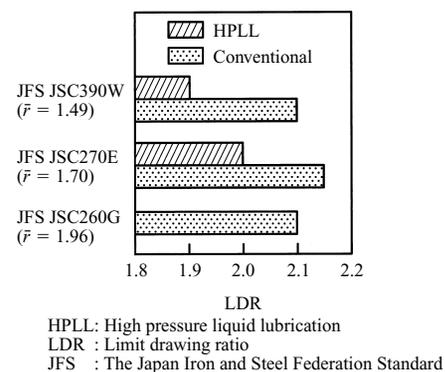


Fig. 6 Effect of high pressure liquid lubrication method on limit drawing ratio in cylindrical deep drawing

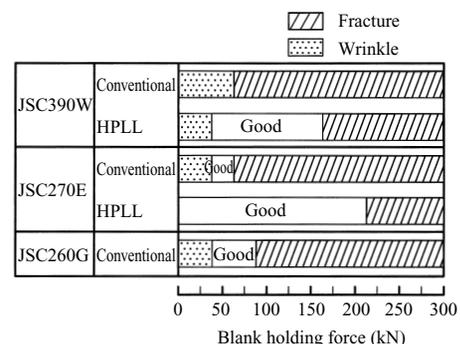


Fig. 7 Effect of high pressure liquid lubrication method on formable range in cylindrical deep drawing

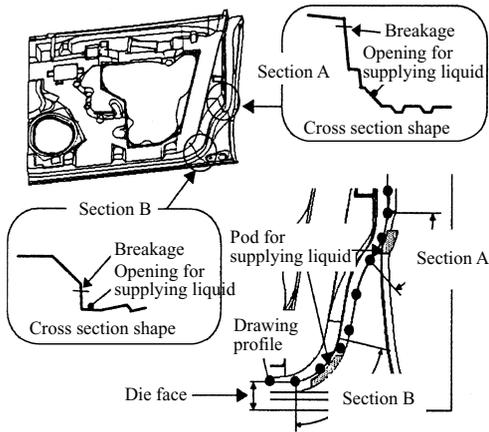


Fig. 8 Application of high pressure liquid lubricant in door inner panel

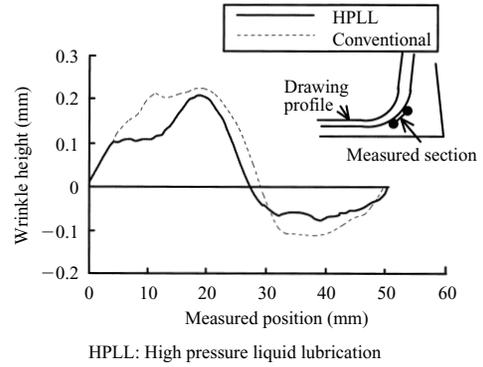


Fig. 9 Comparison of the profile of cross section at the wrinkle generated by the high pressure liquid lubricant method and the conventional process

Table 1 High pressure liquid lubrication method on the limit cushion force in the door inner press forming

(a) Section A

	Cushion force (× 10 kN)						
	50	55	60	65	70	75	80
HPLL	○	○	○	○	△	△	×
Conventional	○	×					

(b) Section B

	Cushion force (× 10 kN)						
	90	95	100	105	110	115	120
HPLL	○	○	○	○	○	△	×
Conventional	○	×					

HPLL: High pressure liquid lubrication,
○ : Good, △ : Necking, × : Fracture

is applied only on the die side. **Figure 7** shows the available forming range at a drawing ratio of 2.0. Use of the HPLL forming method remarkably expands the available forming range, and is equivalent to an increase of more than 0.4 in the *r*-value of the material. The following presents an example of a study of application to forming of the front door inner.

Figure 8 shows the tool shape and high pressure liquid lubrication supply positions. **Table 1** shows the effect of the high pressure liquid lubricant in sections A and B in the figure. Effectiveness was confirmed in both parts, even though different forming modes are used. Moreover, in section B, which is a reduced flange forming section, a flange wrinkle suppression effect was apparent, as shown in **Fig. 9**. In the forming described above, a commercially-available compact high-pressure pump (maximum hydraulic pressure: 53.9 MPa, discharge rate: 1.9 l/min) was used to supply the liquid lubricant. Forming was performed at 10 SPM (sheets per minute), which is the average mass production speed, using a mechanical press machine.

The greatest challenge in forming when using high tensile strength materials in automobile structural parts

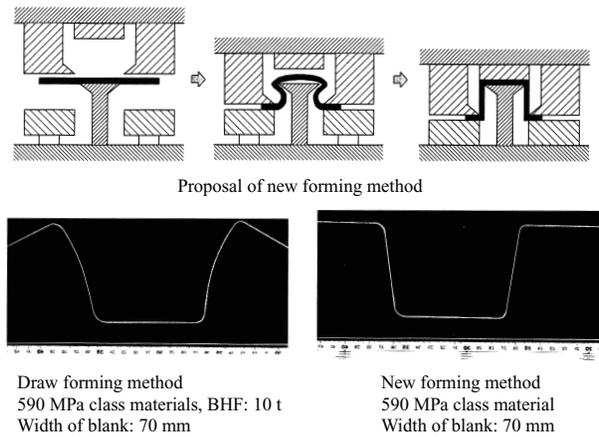


Fig. 10 Proposal of new forming method for improving shape fixability

is the dimensional accuracy of the formed parts. To meet this challenge, JFE Steel is studying countermeasures from the forming technology side, such as reducing springback and wall warping by employing tension control forming or changing the forming mode from drawing to bending, and methods of optimizing the tool shape using numerical simulation. **Figure 10** shows an example of a tension control forming technology in which the cross-sectional configuration of the tool was optimized (proposed in 1997). With simple shapes, it has been found that dimensional accuracy equal to that with mild steel can be obtained even with TS980 MPa material. At present, this method is being expanded to parts with complex shapes.

6. Application Technologies for CAD-CAE Systems

Computer simulation technologies have progressed dramatically in recent years as a result of advanced FEM and improved computer performance, and are now increasingly applied to analysis of press forming and other problems which had been considered difficult in the past. Automakers now frequently use computer simulations as a tool for studying part performance and press

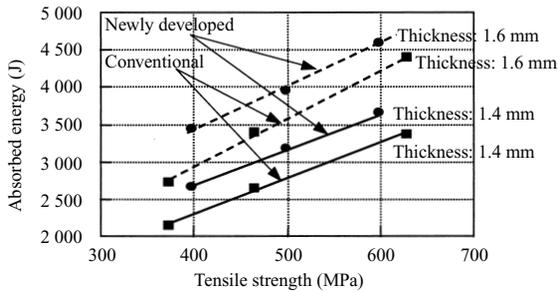


Fig. 11 Improving crashworthiness of hat square column by using new developed material

formability in the automobile body development process. Likewise, JFE Steel improved its CAD data processing, FEM calculation, and pre- and post-processing capabilities in order to strengthen its system of cooperation with automakers from the initial stage of auto body development, and created an environment where it is possible to use joint databases with automakers. This is contributing to shortening the lead time in auto body development and expanding the applications of high strength steels. Prediction of cracking and wrinkles in press forming is now basically possible using FEM. At the same time, improved accuracy, including material composition equations, has been achieved with spring-back.

Where crashworthiness is concerned, the creation of a database for stress-strain curves at high strain rates has made high accuracy calculations possible, and it is also possible to analyze collision behavior considering stress changes due to deformation during forming and painting/baking after forming. **Figure 11** shows an example of a crashworthiness analysis which considers deformation during forming¹⁶⁾. The objects are a conventional sheet and a newly developed sheet which displays greatly improved strength when paint baking is performed after forming.

JFE Steel is also studying the problem of slight irregularities (surface deflection) on panel surfaces, analysis of galling accompanying stress in the sheet thickness direction, and other problems.

7. Sheet Joining Technology¹⁷⁾

High tensile strength steels are used to reduce automobile weight because a reduction in sheet thickness corresponding to the increase in strength can be expected, but because sheet thickness reduction also reduces the stiffness of parts, securing stiffness become an important problem. Continuous welding is an effective method of compensating for this type of stiffness reduction. Laser welding can be considered a representative continuous welding method and has been positively applied in recent years, particularly by European automakers. However, because it is generally necessary to

strictly control the gap between sheets to approximately 0.1 mm or less in laser welding, adoption by Japanese automakers began only recently. Problems also remain to be solved in laser welding of Zn-coated sheets. Laser lap welding is performed without any gap, so zinc vapor tends to blow off weld metal and form blowholes. To solve this problem, JFE Steel developed laser-arc hybrid welding (laser focused arc welding), as described in detail in the following sections.

7.1 Laser-Arc Hybrid Welding Method

Laser-arc hybrid welding is a combination of the YAG laser and arc welding. In comparison with conventional laser welding, hybrid welding features a large gap tolerance in lap welding, and the occurrence of blowholes in lap welding of Zn-coated sheets is slight. Therefore, strict control of the gap in lap welding is not necessary, and practical application is easy. Moreover, because the welding speed is roughly equal to that in laser welding, the high efficiency of laser welding can be utilized.

Figure 12 shows the configuration of laser-arc hybrid welding. A YAG laser is used as the laser, and the arc welding electrode is arranged behind the laser welding position, where it generates the arc. The gap between the laser welding position and the arc aiming position is controlled to 1–3 mm. A YAG laser is used because plasma does not absorb much of the laser energy, and virtually all the laser energy reaches the sheets. **Figure 13** shows the time dependence of the arc voltage between the welding wire and sheets in hybrid welding. For comparison, the voltage changes in arc welding are

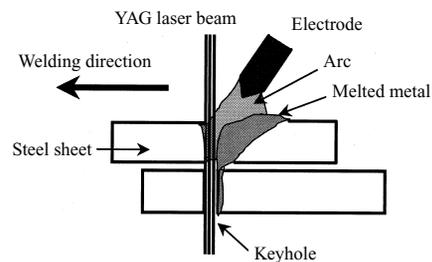


Fig. 12 Configuration of laser beam and arc electrode in laser-arc hybrid welding

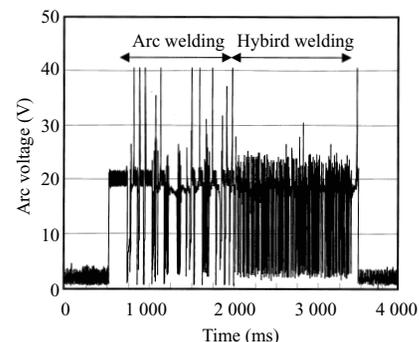
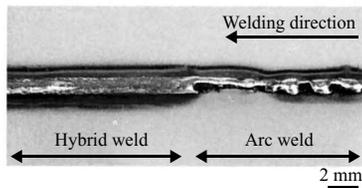


Fig. 13 Time dependence of arc voltage with and without laser radiation



Fillet joint: Upper thickness = 0.8 mm, Lower thickness = 1.2 mm
 Welding condition: Laser output = 2 kW, Arc current = 100 A, Speed = 2 m/min

Photo 3 Appearances of hybrid and arc welded bead surface

also shown. In hybrid welding, it can be understood that the voltage oscillates at high frequency in a range from 0 to approximately 20 V, and as a result, the droplet from the wire moves to short-circuit at a cycle of approximately 10 ms. Because this movement of the droplet from the wire occurs in an extremely short gap, formation of a uniform bead can be expected even at high welding speeds. **Photo 3** shows the appearance of the bead in a fillet weld with hybrid welding and arc welding. The arc welding bead is discontinuous, whereas a uniform hybrid welding bead has been formed.

7.2 Increase in Gap Tolerance in Lap Welding

To investigate the gap tolerance in lap joints welded by hybrid welding, sheets of varying thicknesses were lap-welded with varied gaps. **Figure 14** shows the results. For comparison purposes, the results of an investigation with laser welding are also shown. In comparison with laser welding, the gap tolerance is large in hybrid welding, and a sound welding bead is formed, even when the gap approximates the sheet thickness. The considerably larger gap tolerance in lap joints welded by hybrid welding in comparison with laser welding is explained by the fact that a filler wire is used in the hybrid method, and consequently, molten metal is supplied only to fill the gap.

7.3 Weldability of Zn-Coated Steel Sheets

Because the boiling point of Zn, approximately 900°C, is considerably lower than that of iron (approximately 1 500°C), Zn is vaporized during lap welding of

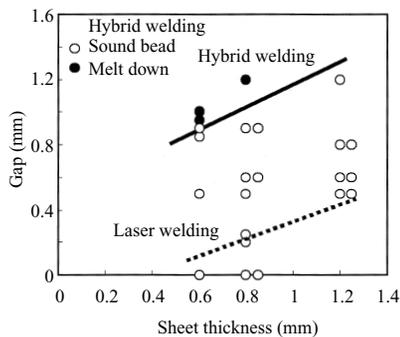


Fig. 14 Gap tolerance of lap joint in hybrid and laser welding

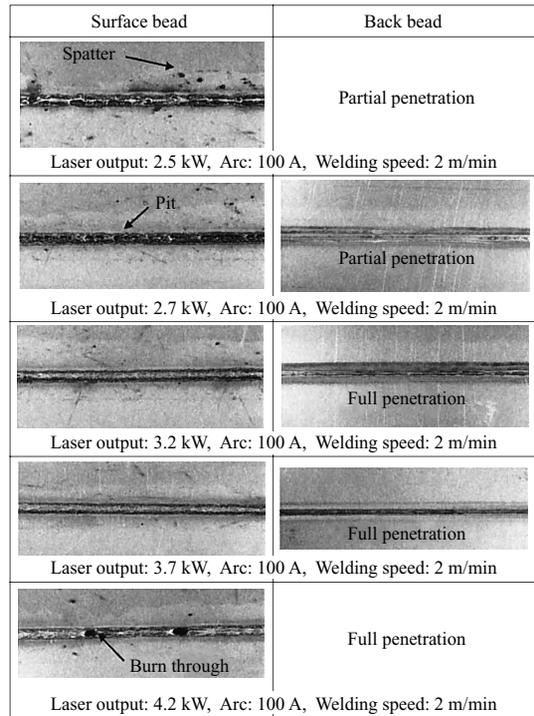


Photo 4 Appearances of lap joint of GA steel sheet welded by hybrid welding

Zn-coated sheets. This can cause various problems, in that Zn vapor may penetrate the molten metal, forming blowholes, or molten metal may be expelled, causing a hole-shaped defect. **Photo 4** shows the appearance of the surface bead and back bead in lap joints of galvanized steel sheets (GA; zinc coating weight: 45 g/m²) welded by hybrid welding. Under welding conditions where the beam does not penetrate or only partially penetrates the weld, a large number of pits and spatter occurred on the surface bead. However, pits and spatter were largely prevented by selecting welding conditions under which the beam achieved full penetration (laser output: 3.2, 3.7 kW, arc current: 100 A, welding speed: 2 m/min).

In the future, expansion of this welding method is expected to realize high stiffness in high strength parts and thereby encourage the use of high tensile strength materials in automobile structural parts.

8. Conclusion

Simultaneously with the establishment of JFE Steel, the company upgraded its evaluation equipment and predictive analysis technologies to support positive proposals in the automobile structural part design process. This paper has presented representative examples of JFE Steel's forming, application, and evaluation technologies for steel products which contribute to weight reduction, improved crashworthiness, and shortening of the development period in the automotive industry. In the future, JFE Steel intends contribute to innovative automaking by employing the technologies which it now possesses

fully and effectively and by further improving its technologies.

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