

Arc Welding Technology for Automotive Steel Sheets

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Abstract

Recent research progresses of arc welding techniques are described, focusing on the automotive chassis members or body members. As for welded joint performance, static strength and fatigue strength are improved with increasing of steel strength less than 780 MPa tensile strength. Additionally, galvanized steel sheets contribute to corrosion resistance of weld parts. Developed welding materials have made it possible to improve welding activities such as reducing spatters, gap allowance or weldability of galvanized steel sheets. In contrast, components of the steel sheet also effects on welding phenomenon, a flat bead geometry is obtained by increasing Si content of steel sheets. Low heat input welding such as CMT (Cold metal transfer) welding has begun to use for body welding and cross tension strength of advanced high tensile strength steel are improved by CMT applied arc spot welding.

1. Introduction

In order to reduce CO₂ emission, decreasing body weight is an urgent requirement in the automotive industry, and in this context, the need for application of thinner steel sheets of higher strength is increasing. While high-strength steel sheets of 440 and 590-MPa classes have been used mainly for chassis parts, use of 780-MPa class steel is looked for in response to the need for light car weight. On the other hand, for body parts, the use of steel sheets of yet higher strength, of a 1,470-MPa class, has already begun.

Arc welding is widely used for chassis parts because of advantages such as the ease of continuous joining to secure high strength and rigidity of joints and wide freedom of joint shape to allow easy joining to pipes, brackets, or other accessories.¹⁾ Since chassis parts are composed of many components welded together, it is essential that weld joints are highly resistant to fatigue and corrosion. In addition, besides reducing spatter, welding methods and consumables must be able to deal with gaps often seen with press-formed sheets.

In view of strengthening of chassis, specimens of arc-welded joints of steel sheets of tensile strengths up to 780 MPa were prepared, and their static strength, fatigue strength, and corrosion resistance were examined. In addition, new welding consumables aiming at suppressing spattering and improving gap weldability were developed. This paper reports the results of these studies and development activities. Besides these, because arc weldability changes depending on the chemical components of steel, this paper also describes the effects of steel chemistry over the forming mechanism of weld beads.

On the other hand, with respect to body parts, although arc welding is not widely applied, it is sometimes employed in place of resistance spot welding. Closed-section structure is advantageous for increasing the strength and reducing the weight of car bodies, but in this structure, resistance spot welding that needs access both from outside and inside is not applicable. When resistance spot welding must be applied to closed-section parts, working holes are required, which, in a great number, spoil the structural rigidity of the work.

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As a solution, arc welding is sometimes opted for because of the workability from one side only.²⁾ Ultra-high-strength steel sheets of tensile strength exceeding 980 MPa have been used for body parts, but there have been reports to the effect that spot-welded joints of such sheets exhibit low cross-tension strength. In consideration of this, the authors focused on arc spot welding, which has an advantage of low heat input and is applicable to thin steel sheets with a thickness of approximately 1 mm, typical of car body materials, and they examined the strength of their joints. The result is also presented herein.

2. Arc Welding for Chassis Parts

2.1 Weld joint properties

2.1.1 Static strength of weld joints

Weld joints are designed, generally, so as to overmatch the base metal, that is, to have strength higher than that of the base metal, and for this reason, high-strength welding wires are often used for welding high-strength steel sheets. However, in the manufacture of auto parts, welding wires of a 490-MPa class for general applications are often used regardless of the strength of the base metal because using different welding wires for different parts is costly, and besides this, in welding of thin sheets, weld metal tends to harden because of dilution with the base metal. In consideration of this, steel sheets of different strengths were welded by changing the strength of the wires, and evaluated the mechanical properties of the joints.

Fig. 1 shows the static tensile shear strength of fillet lap joints of hot-rolled (HR) steel sheets with a thickness of 2.3-3.2 mm and tensile strength of 440, 590, and 780 MPa; here, the strength is expressed in terms of stress, which is obtained by dividing fracture load by the sectional area of the base metal. The joints were welded by pulsed metal active gas (MAG) arc welding using wires with a diameter of 1.2 mm and tensile strengths of 490-780 MPa at currents of 250-320 A and a welding speed of 100 cm/min. All the joints failed at the base metal or the weld toe, and the strength did not vary depending on the grade of welding wire.

Fig. 2 shows the hardness of the weld metals. From the graph shown in this figure, it can be seen that the hardness of the weld metals of the same base metal changes depending on the grade of welding wire, and the hardness of weld metals of the same welding wire increases with the strength of the base metal. Since welding of thin sheets is mostly done in a single pass, base metal accounts for a high proportion of the composition of weld metal; under usual weld-

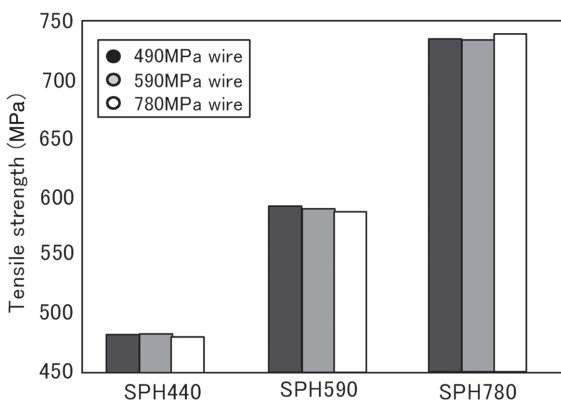


Fig. 1 Static strength of arc welded joints

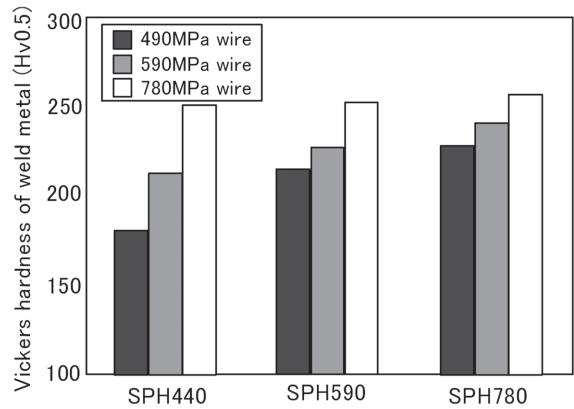


Fig. 2 Vickers hardness of arc welded joints

ing conditions, 30 to 40% of weld metal comes from the base metal, and for this reason, the hardness of weld metal is strongly influenced by the base metal chemistry. In addition, because the heat input for welding thin sheets is comparatively low, the cooling rate is high, and weld metal tends to be hardened. This is the reason why high strength is secured with weld joints of high-strength steel sheets even when welding wire of lower grades is used. It has to be noted in this relation that, as will be mentioned in the following section, in the alloy design of many welding wires for automotive steel sheets, emphasis is placed on workability, and as a consequence, with different base metals, the hardness of weld metal is not always the same even when welding wire of a 490-MPa class is used.

2.1.2 Fatigue strength of weld joints

As the use of high-strength steel sheets increased, better fatigue strength of weld joints proportionate to the strength of base metal were required. However, it has been considered that, there are residual tensile stress and high stress concentrations in a weld joint; therefore, higher strength of base metal does not necessarily lead to better fatigue strength of weld joints.³⁾ Various techniques have been developed to improve the fatigue strength; for example, ultrasonic impact treatment⁴⁾ and welding consumables of low transformation temperature⁵⁾ have been practically applied in the fields of bridges, shipbuilding, and other heavy steel structures.

However, the knowledge of the fatigue strength of weld joints has been accumulated mainly regarding heavy steel plates, and there have been only a limited number of reports on weld joints of thin sheets. Given this situation, to clarify the relationship between the strength of thin-sheet base metal and fatigue strength of weld joints, the following tests were conducted: HR steel sheets with a thickness of 2.3 mm in and of 440-, 590-, and 780-MPa classes were welded into fillet lap joints under the same conditions as in the previous subsection using a 490-MPa class welding wire with a diameter of 1.2 mm for general application. Fatigue strength was evaluated through alternating bending fatigue test at a stress ratio R of -1. To prevent fatigue cracks from the root, welding was applied also to the reverse side of the joint.

Fig. 3 shows the results of the fatigue test. Conventional knowledge was that the fatigue strength of weld joints would be unaffected by the strength of the base metal, but the graph shows that the fatigue strength of weld joints of base metals of the 590- and 780-MPa classes is higher than that of the 440-MPa class. This is presumably because, in the case of thin sheets, the stress concentration at weld toes is small, and residual stress is also small because out-

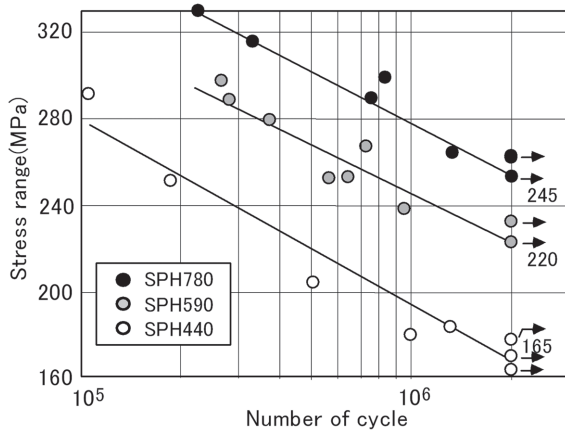


Fig. 3 Fatigue strength of arc welded joints

of-plane deformation of test pieces occurs easily. Therefore, it is expected that, when the shape of the beads is uniform and stress concentration is more or less even, the fatigue strength of weld joints increases with the strength of base metal. The present study assumed that cracks would develop from weld toes, but it is more realistic to suppose that cracks develop from various places around a weld bead, and for this reason, fatigue strength evaluation on real parts is indispensable.

2.1.3 Corrosion resistance of weld joints

Use of thinner steel sheets of higher strength decreases the margin for corrosion. Corrosion is considered to progress faster in weld joints, and improvement of the corrosion resistance of weld joints is important. Since automotive parts are used after chemical conversion treatment and electrodeposition coating, good adhesion of chemicals and paint is important. There have been studies reporting that, because slag sticking to the surface deteriorates the coating adhesion of weld joints, for improving it, it is effective to control the shielding gas so that the contents of CO₂ and O₂, which serve as the oxygen sources for slag forming, are less than or equal to 5% and 3%, respectively.^{6,7)}

On the other hand, as seen in Fig. 4, the use of galvanized (GA) sheets is also effective at improving the corrosion resistance of weld joints. Whereas there are paint blisters in wide areas along the heat-affected zones of the HR sheets without zinc coating, the areas of paint blisters are smaller in the case of GA sheets.

To study the condition in more detail, the maximum corrosion depth was measured. GA steel sheets having a coating weight of 45 g/m² per side were welded to form fillet lap joints under the same conditions as those in the previous subsection, and then, subjected to cyclic corrosion test. Fig. 5 shows the maximum corrosion depth in the portions along the heat affected zone. The graph clearly shows the superior corrosion resistance of GA sheets. Before the test, it was thought that there would be no difference between HR and GA sheets regarding the formation of welding slag, which serves as the starting point of red rust, but the zinc near the weld bead of GA sheets presumably provided galvanic protection, and suppressed the expansion of rust. As explained in the following section, the welding wire for GA sheets with low contents of Si and Mn proved effective at decreasing slag formation at weld toes and improve corrosion resistance.

2.2 Arc welding wire for automotive steel sheets

Solid wires suitable for robot welding that generate compara-

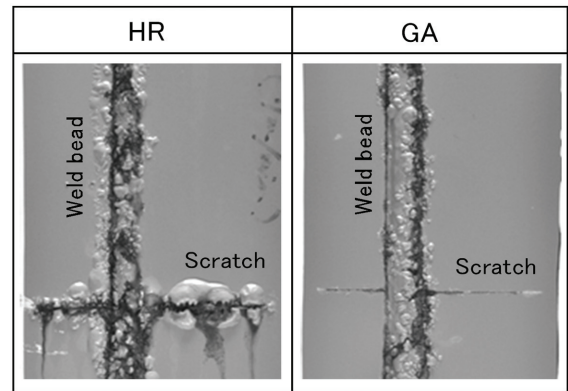


Fig. 4 Appearance of welds after corrosion test

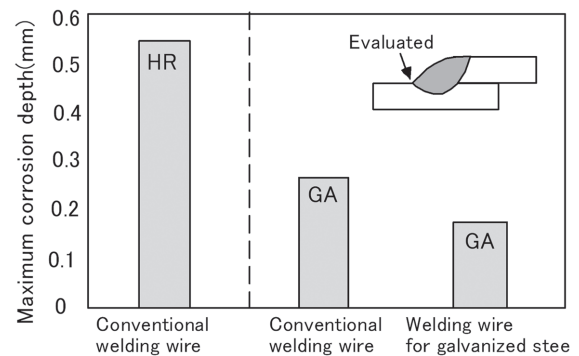


Fig. 5 Improvement of corrosion resistance of weld, by applying GA steel sheet

tively small amounts of slag and fume are chosen for welding of automotive parts. In the development of welding wires for automotive steel sheets, emphasis is usually given to welding workability rather than joint properties because welding wire of a 490-MPa class can form sufficiently strong joints for general applications. Since large-quantity production is essential for automotive parts, low spattering and flexibility about sheet gap are required for welding wires, in addition to high welding speed. Minimizing blowholes that constitute a problem in welding GA sheets is also an important requirement. These welding workability aspects are influenced by complicated welding phenomena such as arc discharge and transfer of droplets of molten metal. The Nippon Steel Corporation Group has developed a variety of welding consumables for different applications on the basis of deep understanding of these aspects of the welding process.

2.2.1 Suppression of spatter

Automotive parts are mostly welded from a low to middle current range, i.e., 150-250 A. Pulsed MAG arc welding is often employed because droplet transfer is unstable and spattering is inevitable by common DC MAG arc welding. However, use of a power supply unit specially designed for pulsed MAG arc welding is not sufficient for reducing spattering, and it is necessary to select both a suitable welding wire and adequate pulse welding conditions.

Fig. 6 shows the droplet transfer in pulsed MAG arc welding.⁸⁾ An ideal condition for transferring a droplet per pulse stably is that a droplet forms at the wire tip during a peak current time and moves to the molten pool during the subsequent base current time. For this to take place, it is important for welding wire to be such that a neck-

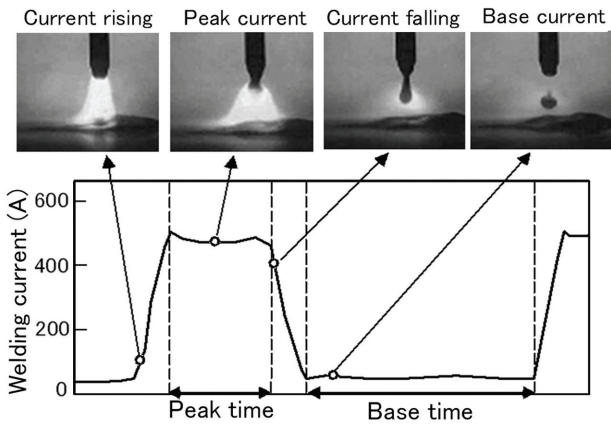


Fig. 6 Droplet transfer phenomenon in pulsed MAG arc welding

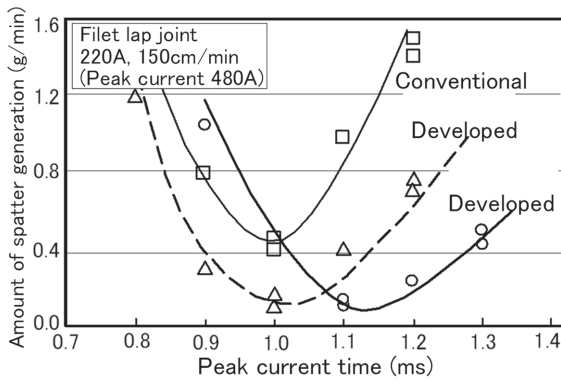


Fig. 7 Amount of spatter generation for various welding wires

ing forms near the tip during a short peak time, and a small droplet moves to the molten pool during the base time.

Fig. 7 shows the relationship between the peak current time and the amount of spatter when a conventional welding wire and those newly developed to reduce spatter were used.⁸⁾ It is clear from the graph in this figure that the amount of spatter is significantly reduced by adequate alloy design of welding wire. On the other hand, as the graph shows, the amount of spatter of all the tested welding wires changed in parabolas with respect to peak current time, the minimum being different with different wires. This is probably because, when peak time is short, the size of a droplet is too small, and when it is long, excessive melting occurs, causing two or more droplets to form. Therefore, to minimize the spatter amount, it is necessary to control pulse conditions adequately in consideration of the characteristics of the welding wire.

2.2.2 Improvement of gap weldability

Higher welding current is necessary for high-speed welding, but since the impact pressure of the arc also increases with current, gap weldability or the bridging effect of welding becomes poor at high currents. Increasing the surface tension and the viscosity of the molten pool is considered effective at improving gap weldability; Si and S are known to affect these property items. In consideration of this, increasing the surface tension and the viscosity of molten steel by increasing Si and decreasing S was envisaged.⁹⁾ Fig. 8 shows the relationship between the Si content of welding wire and the gap width

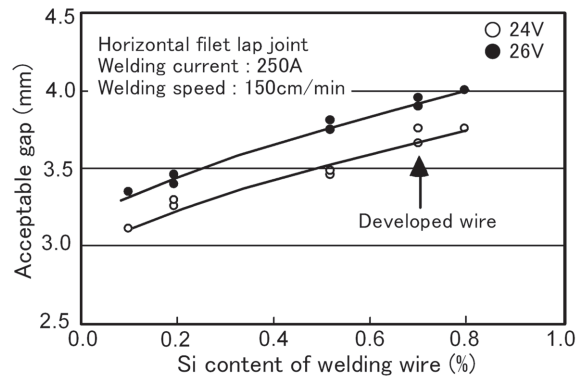


Fig. 8 Improvement of gap weldability by increasing of Si content in welding consumable

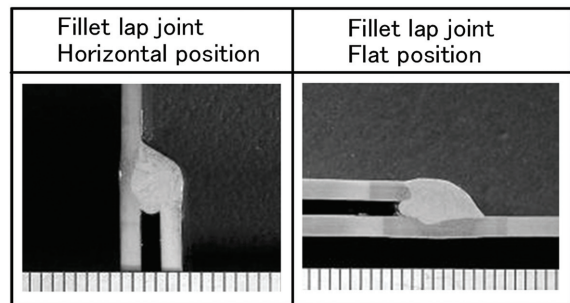


Fig. 9 Examples of cross-section of weld with sheets gap

that the weld metal can bridge; these results were obtained by horizontal-position fillet welding using test pieces having gradually increasing gaps. It is clear from the graph that gap weldability improves as the Si content increases even at a high welding speed of 150 cm/min. Examples of gap welding with the developed wire are given in Fig. 9.⁸⁾ Good fillet weld joints were obtained across gaps in either horizontal or flat position.

2.2.3 Welding wire for galvanized steel sheets

Application of GA steel sheets to chassis parts is expanding for better corrosion resistance. In the welding of GA sheets, however, the formation of weld beads is sometimes disturbed by the evaporation of zinc because of welding heat. With fillet lap joints, particularly when the two sheets contact each other without a gap, blowholes and pits are likely to generate in the weld metal. When the strength of the base metal is low, the weld metal overmatches and blowholes would not cause problems, unless there are too many of them, but when the base metal strength is high, the overmatching margin of the weld metal is small, and the decrease in the joint strength due to blowholes becomes significant. For this reason, more attention must be paid to blowholes in the welding of high-strength GA sheets.

To minimize the generation of blowholes, it is essential to prevent zinc vapor from mixing in the weld pool and quickly removing it from the pool; to this end, various mechanisms and measures have been proposed.^{10, 11)} Of such measures, a welding wire⁸⁾ that aims at lowering the viscosity of molten metal by reducing the contents of Si and Mn is presented below. Fig. 10 shows how zinc vapor is discharged from a weld pool as observed through a high-speed camera.

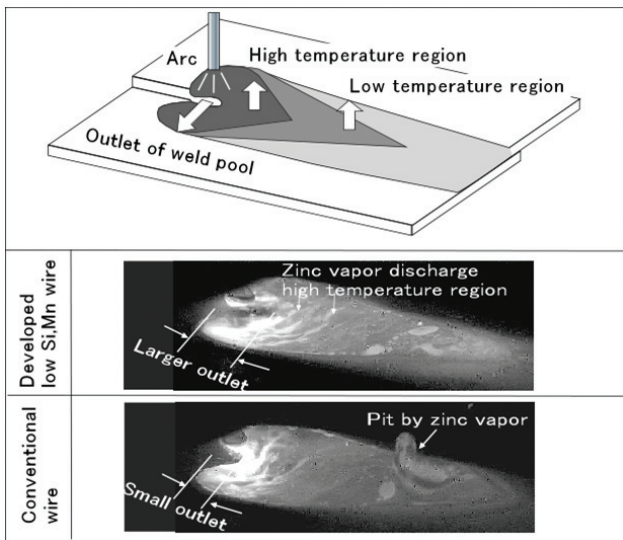


Fig. 10 Difference in zinc vapor discharge from molten pool with different welding wires

Zinc vapor blows out from the overlap of two sheets, and discharges through the opening of the overlap just below the arc, the pool portion of relatively high temperature behind the arc, and another of relatively low temperature before solidification. With a wire having low contents of Si and Mn, the opening in weld pool is large, and zinc vapor is easily discharged without mixing in the pool. Even when it is entrapped in the pool, it is easily discharged from the pool portion of comparatively high temperature, and consequently, the density of blowholes is low.

With a conventional wire, in contrast, the opening of the weld pool below the arc is smaller, and more amount of zinc vapor is presumed to get into the pool. There were also cases where zinc vapor escaped from a solidifying portion of the pool, leaving pits of escape holes. The decrease of blowholes is presumably because the viscosity of the molten steel decreases and the weld pool is blown backwards more easily by the blowing pressure of the arc, and in addition, the bubbles of zinc vapor go up to the surface against less resistance.

Fig. 11 shows the generation of pits and blowholes with a low-Si/Mn wire developed for welding of GA sheets. As the angle of downward welding increases, the weld pool flows more in the direction of the arc, and the generation of pits and blowholes tends to increase. With the developed wire, in contrast, few pits were found even in downward welding as far as the downward angle was less than 30°, and the number of blowholes halved.⁸⁾ Note that an alloy element that increases the solubility of nitrogen¹²⁾ was added to the developed wire as a countermeasure against poor shielding due to zinc evaporation. In addition, the strength of the developed wire was increased for application to high-strength GA sheets.

2.3 Forming mechanism of weld beads

As the use of steel sheets of higher strength and thinner gauges expanded, it became increasingly desirable to form weld toes as smooth as possible to improve the fatigue strength of weld joints. Since high-strength steel sheets contain large amounts of alloy elements, steel chemistry is an important factor for obtaining good bead shape.

Fig. 12 compares the effects of the Si content in base metal and

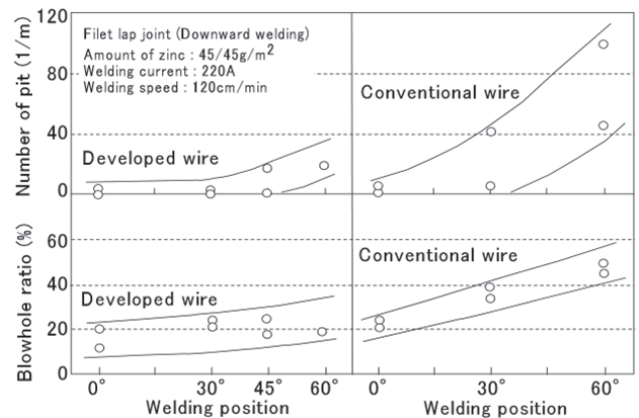


Fig. 11 Effects of decreasing blowholes and pits in weld beads by developed wire for welding GA sheets

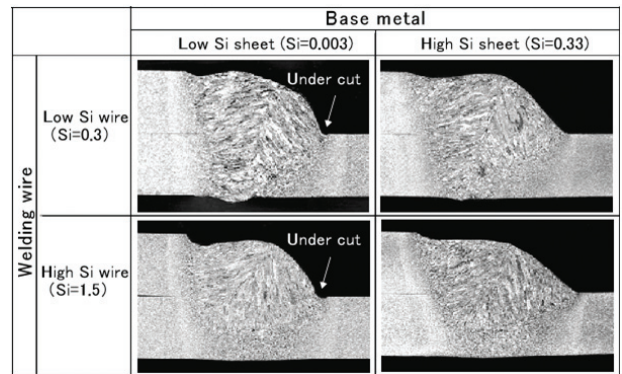


Fig. 12 Effect of Si content of steel sheet on weld bead shape

those of the Si content in welding wire over the bead shape.¹³⁾ Fillet lap joints of 3.2-mm thick sheets were formed by pulsed MAG arc welding at a speed of as high as 100 cm/min. The photographs show that, whereas the bead became convex shape when the Si content of the base metal was 0.003%, it was flat and smooth when the Si content was increased to 0.33%;¹⁴⁾ this result was the same regardless of the Si content of the wire. There was a slight undercut at the weld toe of the low-Si specimen, but in contrast, the weld toe of the high-Si specimen was smooth, which is considered good for decreasing stress concentration and improving the fatigue strength of the joint. It was found, in addition, that, with low-Si base metal, undercut tended to be more conspicuous at higher welding speeds; therefore, Si addition to base metal was considered advantageous for the fatigue strength of weld joints.

The test results that the shape of weld beads depended more on the chemistry of the base metal than on that of welding wire seemed to point to the possibility of uneven distribution of Si concentration in weld metal. To make this clear, Si concentration at sections of weld beads was measured to see how the materials of the base metal and welding wire were mixed with each other.¹³⁾ Fig. 13 shows the distribution of Si concentration at weld bead sections; the Si concentrations at weld toes and roots are also given. When low-Si base metals are welded using a high-Si wire, Si concentration becomes low near weld toes on the lower and upper sheets. Besides, it is higher near the root than at the center of the weld metal. When

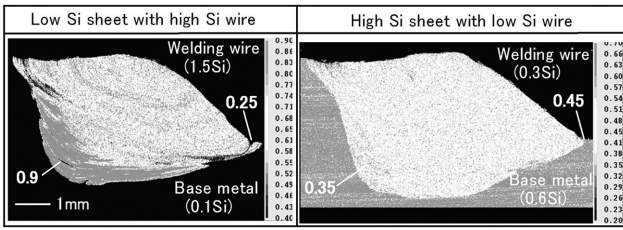


Fig. 13 Concentration distribution of Si in weld metals

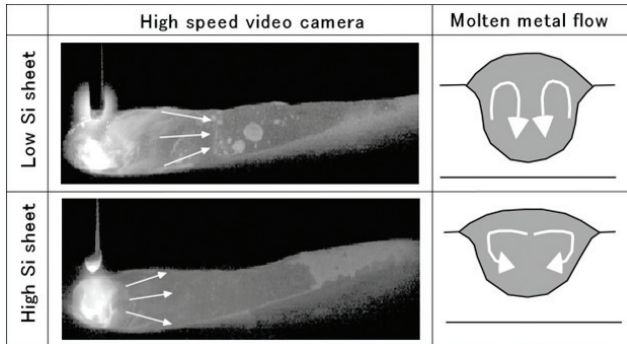


Fig. 14 Difference in molten pool flow due to difference in Si content of base metal

high-Si base metals are welded using a low-Si wire, on the other hand, although distinct comparison is difficult because of smaller difference in the Si content between the two, Si concentration is clearly lower at the root. These observations made it clear that the base metal chemistry showed more dominantly at the toes and the wire chemistry at the roots.

The effects of the Si content of base metal over the flow of the weld pool were examined in more detail through observation using a high-speed camera. Fig. 14 shows the difference in the surface flow of the weld pools in the cases of different Si contents of base metals. The observation confirmed that whereas the flow of the weld pool of the low-Si base metal tended to converge on a point behind the arc, the same of the high-Si base metal tended to spread in the width direction. The Marangoni convection is considered to play a significant role in the surface flow of the pool. There have been reports to the effect that, under surface tension measurement of molten steel in an argon atmosphere containing a small amount of oxygen by the electromagnetic levitation method,¹⁵⁾ the surface tension of low-Si molten steel exhibits temperature dependence, and it increases with temperature, and the surface tension of high-Si molten steel is higher than that of low-Si molten steel, but it exhibits little temperature dependence. This seems to indicate that, with low-Si base metal, an inward Marangoni convection occurs from near weld toes, where the surface tension is low, toward the center of the pool, where it is high.

With high-Si base metal, on the other hand, it is presumed that the Si content is substantially homogeneous across the weld pool, the Marangoni convection is weak as a result; therefore, outward flow becomes dominant in the pool because of the pressure from the arc. From this, it was presumed that, whereas the weld beads of low-Si base metal tend to be high along the center and undercuts are likely to form at the toes, those of high-Si base metal tend to be flat with smooth toes.

3. Arc Welding for Car Body Parts

3.1 Low heat input welding of thin steel sheets

Prevention of burn-through due to excessive heat input is important in the welding of car body parts of thin sheets. For this reason, thin welding wire with a diameter of 0.9 mm, which enables stable welding at low currents, and low-heat-input welding power sources^{16, 17)} specially designed for the application are widely used. The use of particularly cold metal transfer (CMT) power source for welding of body parts is increasing because of the ability of low-heat-input welding and significantly low spatter. As illustrated in Fig. 15, CMT power units are capable of reducing welding heat input by shortening the time of arc discharge, which is responsible for the most of welding heat input, because this power source can control the forward and backward wire feed in synchronization with the current wave form. In addition, CMT power source can decrease spatter to a very low level by lowering the welding current at the moments the wire touches the weld pool and departs from it, at which timing spattering is most likely to occur.

Fig. 16 shows examples of thin sheet welding using a conventional and a CMT power source; steel sheets with a thickness of 1 mm were gap welded using ordinary welding wire with a diameter of 1.2 mm. While the weld beads had pits and the lower sheet burnt through owing to excessive heat input by DC MAG arc welding using the conventional power source, beads of a good shape with smooth toes were obtained using the CMT power source.

3.2 Arc-spot-weld joints

Steel sheets of higher strengths are used for body parts than for chassis parts. Since higher strength means higher carbon equivalent of steel, the joint strength of spot welding, by which the weld metal is the same as the base metal, sometimes decreases because of the

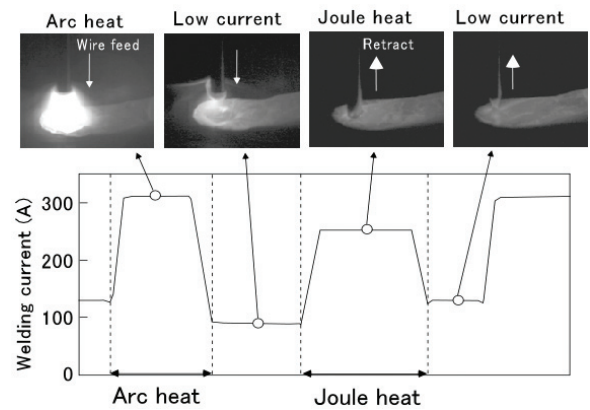


Fig. 15 Droplet transfer phenomenon in CMT welding

Power source	Weld bead appearance	Cross section
Conventional Current:80A Voltage:15.5V Velocity:50cm/min	Burn through	
CMT Current:100A Voltage:13.5V Velocity:60cm/min		

Fig. 16 Improvement of weld bead appearance by applying CMT power source

decrease in toughness. In fact, there have been papers reporting that the decrease particularly in cross tension strength (CTS) is conspicuous.

Considering the above, test in an attempt to improve CTS by applying arc spot welding were conducted,¹⁸⁾ by which it is possible to control weld metal chemistry using welding wire. Steel sheets of a 980-MPa class and with a thickness of 1.2 mm were welded using a solid wire with a diameter of 1.2 mm for 490-MPa steels at a current of 171 A and a welding time of 1.5 s. Here, to stabilize penetration, holes up to 10 mm in diameter were punched through some of the upper sheets.

Fig. 17 shows cross sections of the weld joints. When the hole diameter d of the upper sheet was greater than or equal to 6 mm, there occurred insufficient melting of the hole edge or cracking at the center of the weld metal.

Fig. 18 compares the CTS of joints welded by arc spot welding with that of the joints welded by spot welding; here, the abscissa represents the hole diameter for arc spot welding, and the nugget diameter for spot welding. By arc spot welding, CTS increased with the hole diameter, but it began to decrease when the diameter was greater than or equal to 6 mm. This was presumably because, in the diameter range, melting of the hole edge was insufficient and the

bonding area decreased. This indicates that, to obtain high CTS, the hole diameter must be within an adequate range. In contrast, CTS by spot welding was lower than that by arc spot welding. Through evaluation in terms of the diameter of the fracture surface after a tensile test, the CTS by arc spot welding proved superior compared to that by spot welding, which seems to evidence the CTS improving effects of the material quality of weld metal and the shape of weld joints.

4. Conclusions

The present report has outlined the problems in the arc welding of steel sheets for automotive use and the latest study results related thereto. To effectively respond to the latest need for wider use of high-strength steel sheets of thinner gauges, it is necessary to enhance the reliability of weld joints of such materials through approaches from the material technology side. Arc welding is a versatile joining method applicable to a wide variety of joint configuration such as butt, lapping, and T joints. Another advantage of the method is that dimensional errors occurring at processes of cutting, pressing, and other working can be adjusted at assembly into structures as designed. The Nippon Steel Corporation intends to continue offering measures that realize these advantages of arc welding to the fullest extent to help obtain reliable joints; therefore, intends to support the automotive and other manufacturing industries.

References

- 1) Kondo, M.: J. of Japan Welding Society (JWS). 79 (8), 42 (2010)
- 2) Kuramoto, A., Shimmei, T., Maeda, T.: Yosetsu Gijutsu (Welding Technology). 52 (2), 94 (2004)
- 3) Watanabe, O., Matsumoto, S., Nakano, Y., Saito, Y.: Quarterly J. of JWS. 13 (3), 441 (1995)
- 4) Nosé, T.: J. of JWS. 77 (3), 210 (2008)
- 5) Kasuya, T., Sasaki, K.: Quarterly J. of JWS. 27 (2), 158 (2009)
- 6) Takahashi, M., Uchihara, M., Sakota, A., Ueki, M., Niizato, F.: J. of Automotive Engineering. 28 (2), 143 (1997)
- 7) Uchihara, M., Takahashi, M., Sakota, A., Koh, T.: J. of Automotive Engineering. 28 (2), 149 (1997)
- 8) Ohmura, D.: Yosetsu Gijutsu (Welding Technology). 56 (2), 73 (2008)
- 9) Saito, M., Kimoto, I., Ohmura, D., Shibasaki, S.: Preprints of National Meeting of JWS. 83, 346-347 (2008)
- 10) Izumitani, S., Yanagi, K., Yamazaki, K., Suzuki, R., Nakamura, K., Tsuchida, Y., Uezono, T., Tashiro, S., Tanaka, M.: Preprints of National Meeting of JWS. 90, 92-93 (2012)
- 11) Nakamura, K., Tsuchida, Y., Uezono, T., Izumitani, S., Yanagi, K., Yamazaki, K., Suzuki, R., Tashiro, S., Tanaka, M.: Preprints of National Meeting of JWS. 90, 94-95 (2012)
- 12) Kimoto, I., Koyama, H., Suzuki, T., Saito, T., Matsui, H.: Preprints of National Meeting of JWS. 58, 53 (1996)
- 13) Ishida, K., Kasuya, T., Kodama, S.: Preprints of National Meeting of JWS. 88, 45-46 (2011)
- 14) Kasuya, T., Ishida, Y., Kodama, S.: Preprints of National Meeting of JWS. 86, 134-135 (2010)
- 15) Ozawa, S., Takahashi, M., Kodama, S., Ishida, Y.: CAMP-ISIJ. 24, 826 (2011)
- 16) Furukawa, K.: Keikinzoku Yosetsu (Light Metal Welding). 43 (10), 465 (2005)
- 17) Ueyama, T.: J. of JWS. 77 (2), 27 (2008)
- 18) Furusako, S., Kodama, S., Miyazaki, Y.: Preprints of National Meeting of JWS. 90, 230 (2012)

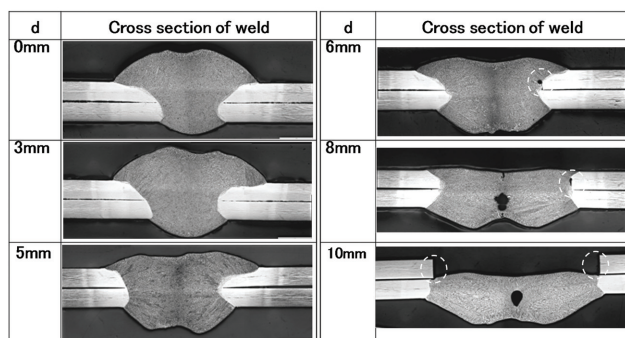


Fig. 17 Cross sections of arc spot welds

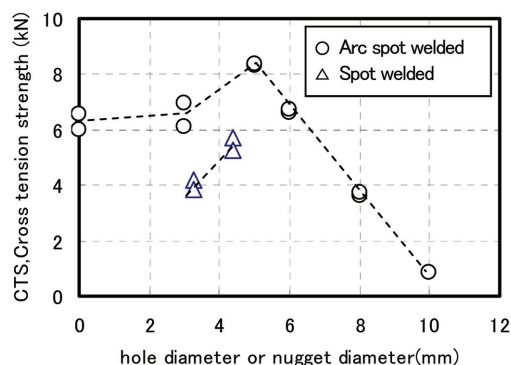


Fig. 18 Cross tensile strength of arc spot welds

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