# Technical Review

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# Progress and Perspective of Welding and Joining Technology for Thin Steel Sheets for Automobiles

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# Abstract

The demand for collision safety and fuel economy of automobiles is increasing more than ever before. To cope with this movement, the application of advanced high strength steel (AHSS) sheets to automobiles is rapidly expanding. Therefore, research works for resistance spot welding (RSW), laser welding and adhesive technology to AHSS are summarized. The peel strength of spot welded joints of AHSS is considered to be predominated by weld toughness. To improve the peel strength, suppressing the solidification segregation of weld nugget and facilitating the tempering martensite in weld are important. Strength characteristics of dissimilar strength steel joints, spot welded tailored blanks and single sided spot welding are also discussed. As for laser welding, the characteristics of tensile shear strength and L-shaped joint tensile strength for various types of steel are discussed and the dependence of solidification crackability on chemical composition is summarized. The strength characteristics of adhesive joints are also discussed. Static strength depends on the yield load of steel and fatigue strength is constant regardless of steel strength.

### 1. Introduction

Higher levels of collision safety and fuel economy are demanded for automobiles. Europe's particularly strict fuel economy regulations require that the reference value of  $CO_2$  emissions from passenger cars in 2021 be 95 g/km,<sup>1)</sup> although it is currently 130 g/km (weighted average car weight: 1372 kg). When these values are converted into fuel economy,<sup>2)</sup> they are equivalent to 24.4 and 17.9 km/L, respectively. Japan's target value by FY2020 is 19 km/L (JC08 mode, car weight: 1311 to 1420 kg).

To satisfy such requirements —high levels of safety and fuel economy— the application of advanced high strength steel sheets to automobiles is rapidly expanding. The usage of ultra high strength steel sheets with the tensile strength (TS) exceeding 780 MPa was approximately 1% in 2004 and it has increased to approximately 11% in 2015. According to one survey<sup>3</sup> the usage will continue increasing in the future and the rate will exceed 30% around 2025.

Automobiles are manufactured using various welding and joining technologies. The main technologies are resistance spot welding (RSW), arc welding, laser welding, and adhesive technologies (typically, weld-bonding). Joints made by such technologies behave variously as steel sheets become stronger. Arc welding is separately discussed in detail in other reports.<sup>4–6)</sup> This paper reports the mechanical characteristics of joints made by other welding technologies when steel sheets become stronger.

#### 2. Progress of Welding and Joining Technologies

#### 2.1 Resistance spot welding

- 2.1.1 Strength of joints of advanced high strength steel sheets by spot welding
- (1) Controlling factors of peel strength of joints

The cooling speed of spot-welded sections is high<sup>7</sup> and the cooling time from 800°C to 500°C is approximately 0.5 s. Therefore, the welds of advanced high strength steel sheets become martensite structure by quenching.<sup>8</sup> When such a joint is examined in a cross tension test (JIS Z 3137) (peeling test), it breaks easily at the weld nugget at the interface between the overlapped steel sheets as shown

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in **Fig. 1**. A cleavage fracture is seen in such break<sup>9)</sup> and the plastic strain at the broken section is small. Such brittle fracture needs to be handled from the fracture mechanics aspect. That is to say, the fracture of joints in a cross tension test is considered as a problem with the progress of cracks starting from around the nuggets.

Nippon Steel & Sumitomo Metal Corporation has reported such handling in the past.<sup>10</sup> It was considered that lowering the crack propagation driving force at the edge of a weld nugget or increasing the fracture toughness value (J) would be effective for enhancing the cross tension strength (CTS). Nippon Steel & Sumitomo Metal has also reported that providing a certain period of cooling time after nugget formation and applying current for a short period of time for post-heating as shown in Fig. 2 resulted in a satisfactory result. Possible reasons why the CTS was increased by the post-heat current (hereinafter, post-heating) were lowered force for developing the crack due to an expanded softened zone in the heat affected zone (HAZ) and increased toughness of the nugget due to the reduction of solidification segregation.<sup>10)</sup> Such reduction of solidification segregation due to post-heating and improvement in the CTS as a result of such reduction can occur on materials other than ultra high strength steel sheets.<sup>11)</sup> In addition, Sadasue, et al. also studied handling of cross tension tests from the fracture mechanics aspect.<sup>12)</sup> Taniguchi et al. also pointed out that post-heating for a short period of time increases CTS.13)

#### (2) Influence of softening of HAZs on CTS

Dual phase (DP) steel is high strength steel in which two structures—soft ferrite and hard martensite—have been dispersed. Martensite formed by rapid cooling is tempered and softened when reheated. Softening occurs in HAZ even by spot welding or laser welding involving rapid heating and rapid cooling.

**Figure 3**<sup>14)</sup> shows the relationship between the heating temperature and hardness when TS780 MPa grade DP steel sheets were







Fig. 2 Spot welding schedule with post-heat by direct current power supply

heated and cooled. Electric resistance direct heating type rapid heating and cooling equipment was used to reproduce the temperature history during laser welding. The graph shows that the sheets softened when the heating temperatures were 823 to 973 K. Figure 4<sup>14</sup>) shows bright field images of the samples (a) and (b) in Fig. 3 with a transmission electron microscope (TEM) along with the area fractions of the martensite ( $A_M$ ). The images show that more cementite was precipitated compared to the base metals and that as the tempering proceeded, the cementite became spherical and the  $A_M$  decreased.

At a spot-welded section, the area around the weld nugget has softened. Therefore, the stress applied to the joint is expected to disperse by the plastic strain at the softened portion, which reduces stress concentration at the edge of the nugget, which enhances the CTS. A cross tension test was carried out for the joints of hot stamped steel sheets with and without the softened portion. The joint with a softened portion was only welded and the joint without the softened portion was water hardened after the welding. The CTS of the joint that was only welded was slightly lower.<sup>15)</sup> In addition, it was considered that the influence of the expansion of the softened zone due to post-heating on the crack propagation driving force was limited.<sup>16)</sup> Therefore, differences in CTS may not be caused by stress conditions, but cracks probably grow easily on nuggets that



Fig. 3 Relationship between hardness and maximum temperature at heat treatment  $^{\rm 14)}$ 



Fig. 4 TEM bright images of base metal and heat treated steel and martensite area fraction  $(A_{yy})^{14}$ 

were only welded.

On the other hand, when softening occurs on a portion near the nugget edge, the CTS increases. The CTS of a joint that had been welded by short weld time to form a softened portion near the nugget edge increased by nearly 40% compared to a joint that had been welded in a standard weld time.<sup>17)</sup> These results show that the existence or nonexistence of a softened section does not affect the CTS, but its location is important.

#### (3) Influence of solidification segregation on peel strength

Identification of the initiation point of a crack in a peeling test of joints was attempted.<sup>18)</sup> Two types of 1.6-mm thick 0.21C-2.0Mn steel sheets for which the quantity of P was different were made by experimentally casting and rolling: 20C steel and 20CP steel. The TS was set to 1.5 GPa through hot stamping (HS). The quantity of P was less than 0.002 mass% for the 20C steel and 0.031 mass% for the 20CP steel. L-shaped joints for which the nugget diameters were the same were made with these sheets and they were pulled in the direction of the arrow in **Fig.** 5<sup>18)</sup> in a peeling test. The maximum loads (LTS) were 3 kN for the 20C steel joint and 1.5 kN for the 20CP steel joint in this test. The LTS of the joint of the 20CP steel with a large quantity of P was lower.

The loads were removed during pulling and the cross sections of the welds were examined. The corona bond area on the 20C steel started peeling when the travel distance of crosshead was 5 mm. The crack grew in the thickness direction along the bond (fusion boundary) when the load exceeded the maximum load, resulting in breakage. On the other hand, on the 20CP steel, when the travel distance was 5 mm, a crack grew in the nugget along the interface between the steel sheets and then turned into the thickness direction, resulting in breakage. The cross sections of welds of the 20CP steel for which the loads were removed when the travel distance was 1 mm and 5 mm were examined.

**Figure 6**<sup>18)</sup> shows photographs of the cross sections of joints of the 20CP steel. The reflection electron images show that the joint started breaking partially when the travel distance (displacement) was 1 mm. The distribution of P measured with an electron probe microanalyzer (EPMA) shows that the P concentrated on the line along the heat flow direction when the nugget solidified. This is because the P segregates at spaces between dendritic trees that grew along the heat flow. The observation shows that the breakage occurred along the dendrite. When the travel distance was 5 mm, the breakage occurred along the dendrite as is the case with the 1 mm. Therefore, solidification segregation of P possibly makes nuggets brittle, which may reduce the strength of the joints.

Post-heating reduces solidification segregation. An analytical solution of the heat conduction equation was used to consider how to determine optimum post-heating conditions.<sup>19)</sup> To reduce solidification segregation, a nugget is to be once solidified and then the segregated element is to be diffused. To this end, the time required to almost complete solidification needs to be adopted as the cool time in Fig. 2. According to the heat conduction analysis, the temperature of a weld decreases exponentially as the time passes after the current



Fig. 5 Schematic diagram of spot welded L-shaped joint<sup>18)</sup>

has stopped as shown in the formulas below.

Temperature of a weld 
$$\propto \exp(-t/\tau)$$
 (1)

$$\tau = \frac{4L^2}{k_{Fe}\pi^2} \text{ with } L^* = L + l\sqrt{k_{Fe}/k_{Cu}}$$
(2)

L: Thickness,

- *l*: Distance from the end of the electrode to the water cooling end,  $k_{r_e}$ : Thermal diffusivity of iron,
- $k_{C_{\mu}}$ : Thermal diffusivity of the electrode copper alloy,
- *t*: Time elapsed after the welding current stopped,
- $\pi$ : Circle ratio

Where,  $\tau$  is the time constant of the exponential function and  $L^*$  is the equivalent conversion thickness including the distance to the cooling end. As a result of the consideration, the cool time of approximately 0.25  $\tau$  is appropriate.  $\tau$  includes the thickness and the formula (2) shows that the cool time required to solidify a nugget is proportional to the square of the thickness.

Through post-heating by post-heat current, the nugget edge is kept as hot as possible within the range at which the nugget does not melt again, and the time during which the segregated element will diffuse is secured. The rise of temperature by post-heat current depends on the temperature when the cooling is stopped and the current value as shown in **Fig. 7**.<sup>19</sup> When the post-heating current value is too high, the temperature rapidly increases. When it is too low, the temperature lowers. The appropriate current value is possibly approximately 90% of the welding current.

In addition, the degree of the temperature rise due to post-heat current is given by the following formula to the time elapsed after post-heat current was started.

Degree of the temperature rise due to post-heat current  

$$\propto 1 - \exp(-t/\tau)$$
 (3)

Post-heat current conditions were considered based on these factors. The post-heat time  $(t_{post})$  to the thickness (L (mm)) can be calculated with the following formula.

$$t_{post} = 0.2L - 0.2(s) \tag{4}$$

**Table 1**<sup>19)</sup> summarizes the consideration results. The diffusion distance required to reduce solidification segregation can be obtained under these conditions.



(a) At displacement of 1mm (b) At displacement of 5mm

Fig. 6 Relationship between portion of fracture occurrence and solidification segregation in nugget of unloaded specimens at halfway of tensile test<sup>18</sup>)

			1 1	1			
Sheet thickness	Analytically recommended conditions				Experimental appropriate conditions		
(mm)	$\tau(s)$	$t_{cool}(s) \simeq 0.25 \times \tau$	$t_{post}\left(s\right)$	$I_{post}/I_{weld}$	$t_{cool}(s)$	$t_{post}\left(s\right)$	$I_{post}/I_{weld}$
2.0	0.42	0.12	0.20	Around 0.9	0.12	0.20	0.9
1.6	0.30	0.08	0.12	Around 0.9	0.08	0.12	0.9
1.4	0.24	0.06	0.08	Around 0.9	0.04	0.08	0.9

Table 1 Example of post-heat current for post heat<sup>19)</sup>



Fig. 7 Temperature change at nugget edge due to post heating<sup>19)</sup>

(4) Influence of tempering on CTS

The toughness of low-alloy steel martensite that was only quenched is low but it is increased by tempering. The weld nugget structure of a 0.2C cold rolled (CR) steel sheet welded with the hold time of the electrode of 5 cyc (50 Hz) was examined and it was martensite structure containing many carbides. These carbides were possibly formed by automatic tempering.<sup>8)</sup> Therefore, the relationship between the CTS and the hold time that significantly affects the cooling speed after welding was investigated. The quantity of C in CR steel sheets (test specimen) was 0.2 mass% and the thickness was 1.4 mm. When joints were made, the electrode force was 440 kgf (4.3 kN) and the weld time was 11 cyc (50 Hz). The diameter of a nugget is usually expressed as how many times of the square root of the thickness (t (mm)) it is. The welding current was 7.1 kA that could form a nugget of  $5\sqrt{t}$  (5.9 mm). As the hold time was shorter, more carbides precipitated at the nugget edges and the CTS was higher as shown in Fig. 8.20)

Paint baking (heat treatment) also changes the strength of joints. TS780 MPa grade CR steel sheets with a thickness of 1.6 mm were used to study how heat treatment of  $170^{\circ}$ C × 20 min would affect the LTS. As shown in **Fig. 9**,<sup>21)</sup> it was confirmed that the LTS became higher at the small nugget joints that broke in the nugget along the interface of sheets. The hardness of the nugget slightly decreased due to the heat treatment, so the toughness of the nugget probably increased by the tempering.

If automatic tempering can be actively promoted in the welding process, the CTS of joints can be higher. This issue is discussed in detail in another report.  $^{22}$ 

(5) Fracture toughness values of weld nuggets

Fracture toughness values of nuggets were actually measured.<sup>23)</sup> TS1470 MPa grade aluminum coated HS steel was used as a test specimen. Steel sheets with 2.0 mm thickness were used to form spot welds for which the diameters of the nuggets were  $5\sqrt{t}$  (7.1 mm). As welding conditions, single impulse with post-heating by



 $t_{cool}$ : Cool time,  $t_{post}$ : Post-heat time,  $I_{post}$ : Post-heat current,  $I_{weld}$ : Welding current

Fig. 9 Effect of paint baking cycles on LTS<sup>21)</sup> N.F.: Nugget fracture, B.F.: Base metal fracture, I.F.: Interfacial fracture

which it was confirmed that the CTS would increase were used. There is a fracture toughness test method that uses compact tension (CT) test specimens defined in the ASTM standards. Relatively small test specimens can be used in this method. Small CT test specimens for which a pre-crack tip was provided at each nugget edge were cut out from the welds to carry out a fracture toughness test. Figure 10<sup>23)</sup> shows the appearance of the test specimen and fracture toughness values  $(J_{a})$  calculated from the maximum loads. The figure also shows a nugget on 0.13C TS980 steel formed by single impulse spot welding for comparison. The values are 32.4 kN/m for the TS980 steel nugget, 16.8 kN/m for the HS steel nugget by the single impulse welding, and 22.5 kN/m for the nugget formed by the post-heating. In addition, it has been confirmed that when partial plug failure occurs, the CTS increases due to post-heating and more dimples are created on the fracture.<sup>9)</sup> In other words, it has been confirmed that post-heating undoubtedly increases the toughness of weld nuggets.

When a steel sheet is thick and the diameter of a nugget is large, partial plug failure occurs at a spot-welded joint in a peeling test as shown in Fig. 1. In this case, the crack changes direction from the interface direction of the steel sheets to the sheet thickness direction. This phenomenon probably is caused by changes in the crack propagation driving force and differences in the fracture toughness on the path along which the crack propagates. Therefore, anisotropy of fracture toughness in a weld nugget was studied.<sup>24)</sup> CT test specimens were cut out from a nugget on a 4-mm thick TS1470 MPa grade HS steel sheet. The nugget was formed by current to a single sheet. Pre-cracks were made by electrical discharge machining using a wire with the diameter of 50  $\mu$ m. **Figure 11**<sup>24</sup> shows the locations (A to E) from which the test specimens were cut out as the positions of the pre-crack tips and the directions in which the cracks propagate. **Figure 12**<sup>24</sup> shows the measured fracture toughness values.

Although the  $J_c$  at A at the edge of the weld nugget was slightly higher than that measured by Watanabe, et al.,<sup>23)</sup> anisotropy was



Fig. 10 Appearance of CT test specimen and fracture toughness of nuggets<sup>23)</sup>



Fig. 11 Pre-crack tip position and direction of CT test specimens<sup>24)</sup>



Fig. 12 Fracture toughness at several points in nugget<sup>24)</sup>

confirmed in the nugget. That is to say, the  $J_c$  at the nugget edge is lower in the interface direction than that in the thickness direction. In addition, the inner fracture toughness value in the thickness direction is lower than that in the interface direction. These values possibly correspond to the directions in which the cracks propagated in the partial plug failure. Usually, dendrite grows in the thickness direction at the nugget center during solidification. Segregation with many impurity elements occurs between the primary arms of such dendrite. On the other hand, solidification segregation at the final solidification position is not that strong, so the toughness is possibly lower in the thickness direction than that in the interface direction at the center of the weld nugget.

2.1.2 Influence of softening of HAZs on the performance of members

HAZ softening does not affect the tensile shear strength (TSS) and CTS of spot welded joints much.<sup>15)</sup> However, when steel sheets including spot weld are pulled like a B-pillar flange in a side collision, it is assumed that strain concentrates on the softened portion, which causes breakage even at a small displacement.

Test specimens for a tensile test were made from a TS1470 MPa grade HS steel sheet (thickness: 1.6 mm). A 440 MPa grade steel sheet was positioned and spot welded at the center of the reduced section. **Figure 13**<sup>25)</sup> is a schematic diagram of the test specimen. The electrode force was 3.43 kN, the weld time was 18 cyc (60 Hz), and the hold time was 10 cyc. The current was changed to form weld nuggets with various diameters. **Figure 14**<sup>25)</sup> shows the hardness distribution of a weld for which the nugget diameter is  $4\sqrt{t}$ . **Figure 15**<sup>25)</sup> shows the maximum stress and total elongation when the test specimen was stretched. The maximum stress did not decrease much, but it shows that the HAZ softened portion broke when there was a weld and the total elongation became extremely small. The same tests were carried out for various types of high strength steel sheets to study the relationship between the degree of softening and the total elongation. **Figure 16**<sup>26)</sup> shows the relation-



Fig. 13 Schematic diagram of tensile test specimen for investigating effect of HAZ softening<sup>25)</sup>







Fig. 16 Effect of hardness ratio of softened HAZ to base metal on fracture elongation in tensile test<sup>26)</sup>

ship between the hardness ratio and elongation ratio of the softened HAZ portions to the base metals. It shows that when the hardness ratio falls below 80%, the elongation ratio rapidly decreases. When a steel sheet which causes strong softening in HAZ is used, consideration is required such that strain does not overly concentrate on the softened portion.

#### 2.1.3 Spot-welded tailored blanks

For frame members such as B pillar, steel sheets are usually overlapped for reinforcement at sections requiring strength. When HS steel sheets are used, steel sheets formed by hot stamping are overlapped by spot welding as shown in **Fig. 17** (a).<sup>27)</sup> Members can be manufactured in different procedures by stamping at high temperature. That is to say, as shown in Fig. 17(b), steel sheets are overlapped in advance at a section to be reinforced and they are then spot welded. After that, they are hot stamped as one piece to manufacture a member.

The welds on such spot-welded tailored blanks (TBs) are cooled and then re-heated to approximately 900°C for quenching. Therefore, solidification segregation in the weld nuggets is reduced as is the case with spot welding under the conditions with post heating. As a result, the TSS does not change much, but the CTS significantly increases as shown in **Fig. 18**.<sup>27)</sup>

Uncoated HS steel sheets are shot blasted to remove scales







Fig. 18 Comparison of spot welded joint CTS between conventional process and tailored blank process<sup>27)</sup>



Fig. 19 Fatigue strength of spot welded joint in spot welding tailored blank<sup>28)</sup>

formed during the heating. The shot blasting increases the fatigue strength of joints. **Figure 19**<sup>28)</sup> shows tensile-tensile fatigue strength at a load ratio (R) of 0.1. The fatigue strength of the spot welded joints of HS steel sheets is the same as that of the spot welded joints of the TS590 MPa grade and TS980 MPa grade high strength steel sheets. However, the fatigue strength of the spot welded joint of the TB sheet was high, approximately 1.4 times that of the fatigue limit.

In a tensile fatigue test of a spot welded joint, a fatigue crack usually initiates just outside the corona bond on the contact surface of the sheets. Meanwhile, shot blasting causes compressive residual stress on the surface of the steel sheets, but it does not affect the sheet surfaces at the interface. Still, the shot blasting improved the fatigue strength of the spot welded joint of the TB sheet. This is because when the joint is pulled, the deformation changes due to the residual stress by shot blasting: As a result, the stress at the portion at which a fatigue crack initiates possibly lowers, which may increase the joint's fatigue strength.

2.1.4 Strength of joints of steel sheets with different thickness and strength

When HS steel sheets and other high strength steel sheets are actually used, it is rare that the other side steel sheet is the same type of steel sheet. The thickness and strength of the other steel sheet are often different. The strength of such joints was studied. In this study, TS1470 MPa grade HS steel sheet with a thickness of 1.2 mm was used to study how differences in the thickness or strength would affect the joint strength.<sup>29)</sup>

The thickness of the steel sheet on one side was fixed at 1.2 mm and that of the sheet on the other side varied from 1.2 mm to 2.3 mm. An L-shaped joint strength was measured. A DR type electrode tip of 6 mm in face diameter was used for welding. The air electrode force was 3.43 kN. The weld time was set to 16 to 22 cyc (60 Hz) according to the thickness. The current value was adjusted to form  $4\sqrt{t}$  and  $5\sqrt{t}$  weld nuggets. The hold time was 10 cyc. The width of the L-shaped joints was 30 mm, the flange height was 20 mm, and the welding point was at 10 mm.

As shown in **Fig. 20**<sup>29</sup>, as the other sheet becomes thicker, the LTS increases regardless of the diameters of the nuggets. A tensile shear test was carried out using the same sheet pairs. Interfacial failure occurred on the  $4\sqrt{t}$  and the TSS was not affected by the thickness of the other side steel sheets. For the  $5\sqrt{t}$ , although interfacial failure occurred, the TSS slowly increased as the thickness of the other side steel sheet increased.

To study the influence of the other side steel sheet strength on LTS, the thickness of steel sheets was fixed at 1.2 mm and the other side steel strength was changed from 270 MPa to 980 MPa.<sup>30)</sup> The weld time was fixed at 16 cyc (60 Hz). The current was adjusted such that the diameters of nuggets became  $5\sqrt{t}$ . Other test conditions are the same as those of the above-mentioned test.

**Figure 21**<sup>30)</sup> shows LTS. The LTS values are close to those of joints made by two same type steel sheets. Failure occurred only on the lower strength steel sheets. Meanwhile, the CTS showed a peculiar behavior as shown in **Fig. 22**.<sup>30)</sup> The main failure mode is partial plug on the HS steel sheets. When the counterpart sheets were high



Fig. 20 Effect of thickness difference on LTS<sup>29)</sup>

strength steel sheets, the CTS was much lower than that of joints of the same type of steel grades. On the other hand, the TSS values were almost the same as those of joints of the same type steel sheets and they became higher as the counterpart steel sheets became stronger.

2.1.5 Multipoint single-side spot welding

When hollow-body parts such as high strength steel pipes and hydroformed pipes are used, they need to be welded to panels. In such a case, it is desirable to carry out spot welding from one side as shown in **Fig. 23**.<sup>31)</sup> In this single-side spot welding, it is impossible to put steel sheets between electrodes to concentrate current between them. In addition, when there is an existing welding point, shunt current proceeds to it, which makes welding more difficult. The equivalent circuit shown in **Fig. 24** will be discussed. The welding is carried out by the current control mode and the electrical potential of the electrode in contact with the steel sheet is fixed. When *V* is



Backing electrode

Fig. 23 Single-side spot welding for closed cross section member<sup>31)</sup>



Fig. 24 Evaluation of effective current by equivalent circuit

the voltage between the electrodes, the ratio of the effective current flowing at the welding point  $(i_w)$  to the total current (I) is equal to the ratio of the heat generation by the effective current to the total heat generation. This is calculated with the following formula.

$$\frac{\dot{l}_w}{I} = \frac{V\dot{l}_w}{VI} = \frac{r_s}{r_w + r_s} \tag{5}$$

Where,  $r_w$  is electrical resistance of the current circuit passing the welding point and  $r_s$  is the resistance of the shunt circuit. Figure 24 also shows the dependence of the  $i_w/I$  to  $r_s/r_w$ . The welding is strongly influenced unless the resistance of the shunt circuit is very high.

We studied how the distance to an existing welding point would affect welding in the layout shown in **Fig. 25**.<sup>31)</sup> A mild steel sheet with a thickness of 2 mm was used as a test specimen. An R type electrode tip with a radius of curvature of 40 mm was used. An electrode tip sinks during welding due to electrode force. The R type does not change the contact status between the electrode tip and steel sheet rapidly thanks to its shape.<sup>32)</sup>

**Figure 26**<sup>31)</sup> shows the dependence of the diameters of weld nuggets on the distance between welding points (*D*). This figure shows the nugget diameters by single-side spot welding and usual direct spot welding. As the *D* becomes longer, the nugget diameters are nearing 4.5 mm in either welding method. The diameter of 4.5 mm is that of nuggets obtained by single-point welding. Meanwhile, when the *D* falls below 40 mm, the nugget diameters by single-side welding become rapidly smaller. At 30 mm or shorter, no nuggets could be formed.

Figure 27<sup>31)</sup> is photographs of cross sections of welds comparing the effect of electrode placement and the influence of existing weld point. In the direct spot welding, even if there was a shunt current, the interface between the steel sheets started melting. On the other hand, melting in the single-side welding started from the steel sheet on the electrode side. When an existing welding point was near, the steel sheet on the opposite side could not be melted by the end of the welding. In single-side welding, the steel sheet on the electrode side does not come into contact with the opposite side steel sheet sufficiently even when weld force is applied by an electrode. Therefore, in the early stage of weld time, the electrical resistance  $(r_{\rm w})$  of the circuit that forms a nugget between the steel sheets is high. Therefore, it is thought that the  $r_s/r_w$  becomes extremely small and the quantity of Joule heat is not sufficient to form a nugget. When single-side spot welding is applied, the length of the current circuit effective for forming a nugget and shunt circuit, and changes in electrical resistance due to changes in the contact status and due to temperature rise need to be thoroughly considered.





Fig. 26 Dependence of nugget diameter on distance to already welded point  $^{\rm 31)}$ 



Fig. 27 Nugget formation difference between welding method and already welded point<sup>31</sup>)

#### 2.2 Laser welding

2.2.1 Strength of joints

Laser welding is sometimes used to reduce the weight of automobile bodies and enhance the rigidity. We have reported the strength of laser welded lap joints in the past.<sup>33)</sup> However, the strength of steel sheets to be welded has improved compared to that time. Therefore, recent study results of the strength of laser welded lap joints will be discussed mainly regarding high strength steel sheets.

(1) Tensile-shear strength of lap joints (TSS)

**Figure 28**<sup>34)</sup> shows the TSS of laser welded lap joints of 1.2-mm thick steel sheets with a TS of 270 MPa to 1470 MPa. The width of test specimens and overlapped length were 30 mm. The full width

of the test specimens was welded at the center of the overlapped section. The weld width at the interface between the overlapped steel sheets is approximately 0.8 mm. The figure also shows the strength of spot welded joints with the nuggets diameters of  $5\sqrt{t}$ . For both types of joints, as the strength of the steel sheets increases, the TSS increases. In addition, for the laser welded joints, a shear fracture occurred on the weld metals at the interfaces between the overlapped steel sheets except the joint of the TS270 MPa grade steel.

Regarding laser welded joints for which rather narrow weld beads are formed on high strength thick steel sheets, rotational deformation around the welds during pulling is small and shear fracture occurs at the weld beads at the interfaces between the overlapped steel sheets. The TSS of such joints is well expressed by the product of the bead width at the interface between the overlapped steel sheets and the hardness of the weld metal as shown in **Fig. 29**.<sup>35)</sup> Although the figure shows the results up to 780 MPa grade steel sheets, this analysis can be applied to 1470 MPa grade HS steel sheets shown in Fig. 28 as well.

The TSS differs depending on the relationship between the welding direction and loading direction even for the same beads. As shown in **Fig. 30**,<sup>35</sup> the TSS is higher when weld beads are formed in parallel to the loading direction. It is a case when 20-mm long beads are formed on 30-mm wide test specimens.

(2) Tensile strength of L-shaped joints (LTS)

The same type of steel sheets and welding conditions as those shown in Fig. 28 were used to form L-shaped lap joints to study LTS. **Figure 31**<sup>34</sup> shows the dependence of LTS on the strength of



Fig. 28 Dependence of TSS of laser welded lap joint on base metal tensile strength  $^{\rm 34)}$ 



Fig. 29 Regression analysis of TSS by product of width and hardness of weld bead<sup>35)</sup>

steel sheets. As is the case with the CTS by spot welding, the LTS of the laser welded lap joints becomes maximum when the strength of the steel sheets is approximately 590 MPa. When the strength exceeds this level, as the strength of the steel sheets increases, the LTS lowers.

However, as shown in **Fig. 32**,<sup>34)</sup> welding near the bend R part can increase the LTS. This is possibly because as the distance from the tension axis to the weld toe becomes shorter, the stress working



Fig. 30 Dependence of TSS of laser welded lap joint on welding direction<sup>35)</sup>



Fig. 31 Dependence of LTS of laser welded lap joint on base metal tensile strength  $^{\rm 34)}$ 



on the weld at the interface of the steel sheets decreases, even pulling with the same load.

In addition, as shown in **Fig. 33**,<sup>35</sup>) the dependence of the LTS on the weld line direction is more obvious compared to TSS. For L-shaped joints, welding in the stress direction causes breakage starting from the weld egde, so the LTS becomes significantly lower. 2.2.2 Laser weldability of zinc coated steel sheets

Laser welding used to assemble car bodies is lap welding. Laser welding of alloyed hot dip galvanized (GA) steel sheets that were overlapped without gap generate a large quantity of spatter, so the weld bead is not satisfactory as shown in the left side of **Fig. 34**.<sup>36</sup> This is because zinc vapor generated at the contact surface of the steel sheets carries molten steel.

However, hot stamped GA steel sheets do not release much spatter. As shown on the right side of Fig. 34, as the heating time in hot stamping is longer, weld defects decrease. This is probably because Zn is solid dissolved in the base metal and thereby the boiling point of Zn increases. In addition, overlap fillet welding by arc reduces pores.<sup>37</sup>

# 2.2.3 Solidification cracking

Laser welding at the edge of a steel sheet may cause solidification cracking. **Figure 35**<sup>38)</sup> shows the dependence of solidification crackability on the quantity of C. The distance from the edge when no solidification cracking occurs is used as an index. As the index values are larger, solidification cracking occurs more easily. When



Fig. 33 Dependence of LTS on welding direction<sup>35)</sup>



Fig. 34 Change of laser lap weldability due to HS treatment<sup>36)</sup>

the quantity of C is 0.08 mass%, cracking occurs most easily. When the quantity of C exceeds this level, the crackability slightly decreases to the level of 0.3 mass%. Possible causes of such differences are differences in the width of the solid-liquid coexistence temperature range and in the microstructure at solidification. That is to say, the solid-liquid coexistence range of steel with C of 0.08 mass% or more is wider than that of 0.02C steel, which makes it easier to cause solidification cracking. On the other hand, as shown in Fig. 36, $^{38)}$  the solidification microstructure of the steel with C of 0.08 mass% or less is cellular dendrite where not many projections and depressions are seen at the interface between the solid and liquid phases. Meanwhile, on the steel containing C of 0.1 mass% or more, the microstructure is columnar dendrite where secondary arms have grown. This probably increased projections and depressions at the interface, which increased resistance to solidification cracking even when the solid-liquid coexistence temperature range was wide.

2.2.4 Tailored blank of HS steel sheets

When a steel sheet is subject to tailored blank (TB) and then hot stamped, the mechanical characteristics of the TB weld cannot be considered similarly to those of a conventional TB weld. **Figure 37**<sup>34</sup> shows the distribution of hardness at the weld before and after hot stamping on a steel sheet that becomes TS1470 MPa grade after



Fig. 35 Dependence of solidification crackability at laser welding of sheet edge on carbon content<sup>38)</sup>



Fig. 36 Dependence of solidification cracked surface on carbon contents<sup>38)</sup>



Fig. 37 Hardness distribution of laser weld before and after hot stamping<sup>34)</sup>

quenching. After laser welding, the weld metal is harder than the base metal. Usually, TBs, which weld beads, are cold pressed. Meanwhile, considering that TBs are subject to hot stamping, the strength of the base metal will be equivalent to that of the weld metal after austenite transformation. Therefore, if the thickness of the weld bead has been reduced due to a gap between the butted sheets compared to the base metal, strain will concentrate on the weld bead in hot stamping and the weld bead may break. In addition, the strength of the weld metal and base metal is not different on a hot stamped member as shown in Fig. 37 and the hardness at the weld is distributed uniformly. Therefore, when the thickness of a weld bead has been reduced, more strain will concentrate on the weld bead at the time of load input to a member, which may affect the mechanical characteristics adversely. To avoid this, for hot stamping of tailored blanks, the strength of the counterpart to be subject to tailored blank, the thickness, and the location of the weld line need to be thoroughly considered assuming the weld bead for which the thickness has been most reduced and on which strain may concentrate. 2.3 Adhesion

More structural adhesives may be used in the future to improve the rigidity and NVH (noise, vibration, and harshness) characteristics of auto bodies. A study was then conducted to investigate the static strength and the fatigue strength of adhesive joints, with various degrees of strength and thickness of steel sheets.<sup>39)</sup> 2.3.1 Static strength of adhesive joints

CR and GA steel sheets with TS270 to 980 MPa were employed in this study. The thickness was 0.7 mm to 1.8 mm. The thickness is less than 1 mm only for 270 MPa grade steel sheets. Two types of impact resistant adhesives (one component heat curing type epoxy adhesives) A and B were used. Adhesive B was developed for GA steel sheets, in particular. As a result of a tensile test of the adhesives themselves, the tensile strength of adhesive A was approximately 32 MPa and that of adhesive B was approximately 26 MPa. The breaking elongation of A was larger than that of B. The width of adhesive joints was 25 mm, the bonding width (overlapping width) was 12.5 mm, and the thickness of the adhesion layers was 0.2 mm.

**Figure 38**<sup>39)</sup> shows the TSS of the adhesive joints and **Fig. 39**<sup>39)</sup> is a photograph showing the appearance of the adhesion layers after breaking. The TSS increases as the yield load ( $\sigma_y \times t \times w$ ) of the steel sheets increases. When the yield load is high, the TSS remains almost the same, where  $\sigma_y$  is the yield strength of the steel sheet, t is the thickness, and w is the width of the test specimen. The TSS of the joints with adhesive A is higher than that of adhesive B. In addition, no significant differences were seen between the TSS of the



Fig. 38 Dependence of adhesive joint TSS on yield load of steel sheet<sup>39)</sup>



Fig. 39 Appearance of adhesive joint after tensile test<sup>39)</sup>

CR steel sheet joints and that of the GA steel sheet joints. The joint of the 270 MPa grade CR steel sheets broke in adhesion fracture mode, indicating that fracture occurred between the adhesive and substrate. Regarding the high strength steel sheets, cohesive failure occurred in the adhesive material itself. GA steel sheet joints break easily because of delamination of the coating layer from the base steel. **Figure 40**<sup>39)</sup> shows the ratio of delamination of the coating layer on GA steel sheet joints. This ratio of adhesive A is higher than that of B. In addition, the delamination ratio tends to be higher on steel sheets with lower yield strength, in particular. A steel sheet joint with lower yield strength largely rotates at the bonded section, which applies peel stress to the adhesion layer. This peel stress pos-



Fig. 40 Coating failure ratio in tensile test with various joints<sup>39)</sup>



Fig. 41 Fatigue strength of adhesive joints<sup>39)</sup>

sibly caused adhesion fracture and delamination of the coating layer. 2.3.2 Fatigue strength of adhesive joints

Figure 41<sup>39</sup> shows the fatigue strength at  $10^6$  cycles in a fatigue test of joints. The shape of the test specimen used in the fatigue test was the same as that used in the static tensile test. The loads were sine wave tensile-tensile load with the stress ratio (R) of 0.1. The fatigue strength at  $10^6$  cycles was not influenced by the strength of the steel sheets and presence or absence of coating and it remained almost constant. In a fatigue test of CR steel sheet joints, they broke in adhesion fracture mode regardless of the strength of the steel sheets. Regarding the GA steel sheet joints, cohesive failure occurred in the adhesives regardless of the strength of the steel sheets.

#### 3. Conclusion

Steel sheets for automobiles are demanded to be stronger and have more formability. Nippon Steel & Sumitomo Metal considers that it is necessary to provide such advanced high strength steel sheets along with technologies for using such steel sheets efficiently. We summarized the recent research results on the mechanical characteristics exhibited by welded and bonded joints of high strength steel sheets and the approaches by which excellent mechanical characteristics can be obtained. We hope our studies will be of help in the use of advanced high strength steel sheets.

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