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# Finite Element Simulation of Resistance Spot Welding Process for Automotive Steel

Hideki UEDA\* Manabu F Hiroki FUJIMOTO Kazuo OK Shota KIKUCHI Eisuke NA Tohru OKADA Masanori

Manabu FUKUMOTO Kazuo OKAMURA Eisuke NAKAYAMA Masanori YASUYAMA

# Abstract

This work aims to develop the FEM analysis system for evaluating the overall phenomena during resistance spot welding. The framework of this system is the finite element calculation based on the incrementally coupled electrical- thermal-mechanical simulation procedure. Using this analysis system, the weldability lobes of mild steel and high strength steel are predicted, which shows the validity and capability of this model. In addition, this analysis system is applied to three-dimensional model simulation door opening, and influences of the shunt, member rigidity and plate gap on welding are examined. Moreover, it is applied to the estimation of the mixing ratio of molten metal, and then the flow curves and fracture limit in the weld metal are calculated. Predicted fracture modes and joint strengths show good agreement with the experimental results.

#### 1. Introduction

Resistance spot welding (hereinafter referred to as "spot welding") is widely used as a joining method in the assembling process of automotive bodies and parts. Spot welding has been used for more than 100 years. Due to the high productivity and low cost, spot welding is still a major joining method in the field of automotive body manufacturing. At the same time, the need to meet the requirements regarding a reduction in weight and crash safety of automobiles is increasing the production rate of high tensile strength steel plates/sheets used for automobile members. The use of hot-stamped steel plates/sheets of which tensile strength after quenching reaches 1470 MPa has also expanded.

Against this backdrop, the number of locations where steel plates are joined into assemblies by spot welding has increased per vehicle body structure, complicating the determination of appropriate welding conditions for all joining locations. Given the situation, we have developed a spot welding analysis system based on an incrementally coupled analysis method between the electric, temperature, and stress fields using the finite element method analysis (hereinafter referred to as the "FEM analysis"), as part of our continued initiatives to establish basic technology for accurately forecasting a nugget growth under arbitrary sheet joining/welding conditions.<sup>1, 2)</sup> Furthermore, based on the initiatives, we have developed a coated steel plate analysis model taking into account the melting and evaporation of the coating, and also a spattering prediction model inside of which molten metal starts to be spattered. This has enabled weldability lobe prediction for actual steel sheet assemblies including coated steel sheets.<sup>3)</sup>

In the past, studies were conducted assuming the most fundamental welding conditions, i.e., cases in which strip specimens (test coupons) were single-spot welded in a laboratory (stationary welding machine). In addition, analyses using axially symmetric models with the upper or lower electrode center axis used as the symmetrical axis have been prevalent. This means that studies have been limited to cases in which the influence of the electrode axis misalignment or steel sheet deformation on the weldability is considered to be small. However, when welding for assembling an actual automotive body is assumed, various factors may affect welding conditions; such factors include current shunting caused by contact with an adjacent already-welded point or another member, presence of sheet gaps caused by less accurate component forming, and the rigidity in the vicinity of a welding area determined by the shape of the com-

Senior Researcher, Materials Reliability Research Lab., Steel Research Laboratories 1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891



8 : Microstructure-dependent material properties, transformation expansion, and transformation plasticity

Fig. 1 Schematic illustration of the incrementally coupled electrical-thermal-mechanical analysis procedure

ponent. Given this, the spot welding simulation technology was applied to a 3D model that simulated a door opening as a part of an actual automotive structure to examine the influence of current shunting, member rigidity, and sheet gaps on the weldability in comparison with the single-spot welding of strip specimens.<sup>4)</sup>

4, 7 : Latent heat

In addition, the application of the spot welding simulation technology for the weld area strength evaluation was examined. If the spot welding nugget diameter or weld pitch of an automobile member is different from the value as instructed in the drawing, the weld area may fracture due to collision deformation. For this reason, the development of fracture prediction technology is required when designing a member. The joint strength and form of a fracture of a spot welding joint are significant depending on the load mode on the weld area. Considering this, a fracturing criterion was created for a spot weld area using the fracturing strain that took into account the influence of stress triaxiality (hereinafter referred to as the "fracturing limit value"). By applying the fracturing limit value to the FEM analysis, a fracturing prediction FEM analysis approach capable of accurately reproducing the strength and fracture form of a spotwelded joint was developed.<sup>5)</sup> Structural members of automobiles use many sheet assemblies with different materials and thicknesses (hereinafter referred to as the "dissimilar material/thickness sheet assembly"). In order to improve the fracturing prediction accuracy for dissimilar material/thickness sheet assemblies, an analysis model was built using the deformation resistance and fracturing limit value that were calculated based on the mixing ratio in the nugget molten area volume (hereinafter referred to as the "molten area mixing ratio") calculated in a spot welding simulation.<sup>6)</sup> This article describes the details of these initiatives.

# 2. Establishment of the Spot Welding Analysis System 2.1 Overview of the system

**Figure 1** shows a schematic view of the basic concept of the incrementally coupled electrical-thermal-mechanical analysis method used in this study.<sup>1)</sup> The basic flow involves alternately repeating a coupled electrical-thermal analysis and a coupled thermal-mechanical analysis at appropriate small intervals (e.g., 1/2 cycle). This approach is characterized by the consideration of the phase change and



Fig. 2 History of nugget growth (exp. and CAE) and resistance between electrodes (CAE). 590 MPa steel, thickness =1.2 mm, electrode force=3.92 kN, current=7.1 kA

phase transformation in each coupled analysis. The main purpose for using the coupled analysis method that considers the three fields is to include the ever-changing influence of the contact pressure and the diameter of the section where the electric currents flow in the estimation of the contact resistance value to specify the resistance heat at the interface. As represented by curve (a) in **Fig. 2**, the generation and growth of a nugget could be accurately predicted using this method. The contact resistance, considered not to remain for long once the current has been applied, is likely to be viewed as unimportant; however, in fact, it is very important. As indicated by curve (b) in Fig. 2, an analysis that disregards the interface resistance heating, the resistance value does not increase sufficiently to cause ample heat generation especially at the start of current application, hindering precise prediction of nugget generation.

The analysis model has an axisymmetric structure with a pair of electrodes and two to four steel sheets. The sheet thickness and gap

between sheets can be arbitrarily set. Regarding material property data necessary for the analysis, data owned by Nippon Steel & Sumitomo Metal Corporation products was available including that of mild steel sheets and 1 180 MPa-class high tensile strength steel sheets. The consideration of surface coating is also enabled by the model newly developed through this study. Modelling of the coated steel sheet is described in the next section. This analysis system is composed of many user subroutines and our own peripheral programs based on Abaqus, a suite of general-purpose FEM analysis codes.

#### 2.2 Coated steel sheet analysis model

#### 2.2.1 Basic concept of the coated steel sheet model

When a coated steel sheet is spot-welded, the nugget formation is generally slower than that on uncoated steel sheets. The reason for this is that the coating metal on the steel sheet surface melts due to the temperature increased by the applied currents, and then is pushed out of the contact area, increasing the diameter of the section where the currents flow. Furthermore, when the steel sheet temperature increase progresses to reach the boiling point of the coating metal, the pushed molten coating metal evaporates. This is likely to be the mechanism for the disappearance of the phenomenon of diameter increase of the current flowing section. Considering the above, the analysis model of the coated steel sheet was created.

**Figure 3** shows schematic views that illustrate the basic concept of the model from the aspect of the interface between sheets. First, a region where the temperature is above the coating metal melting



Fig. 3 Modeling of coated sheet (a) Calculation of volume of melted metal, (b) Enlarging current path, and (c) Restoring current path

point is determined from the temperature distribution obtained as an analysis result; the volume of the molten coating metal is calculated from the film thickness and density of the coating metal, as shown in Fig. 3(a). While assuming that the sheet separation area is filled with the molten metal in the calculated volume, the continuity condition is applied considering the range in which the molten coating metal is present as the diameter of the current flowing section, as shown in Fig. 3(b). When the temperature further rises, and in the moment that the temperature in the vicinity of the sheet separation area reaches the boiling point of the coating metal, the molten coating metal pushed to the seat separation area is considered to evaporate. This causes the virtually enlarged diameter of the region where currents are flowing to be reduced to the actual contact region diameter, as shown in Fig. 3(c). Coating metal characteristics necessary for this model are the melting point, boiling point, and film thickness (or the coated amount and density).

For the interface between an electrode and sheet, although not shown in the figure, a completely identical model can be applied. For the coating layer and the virtual continuity region, no FEM mesh is defined; the entire coated steel sheet model is analytically processed.

#### 2.2.2 Validity verification of the model

In order to verify the validity of this model, test pieces were prepared in a laboratory by electrogalvanizing one side of a 1.2 mmthick 590 MPa precipitation hardened steel sheet using pure zinc in the amount of 90 g/m<sup>2</sup>. Using the test pieces, the nugget formation behavior when undergoing spot welding in the following two cases was examined: One was a case in which a sheet assembly was conducted by welding two test pieces, with the coated surfaces of the test pieces overlapping each other (hereinafter referred to as "C/C"); and the other was a case of a sheet assembly with the same two test piece structure as C/C, but with the coated surfaces of the test pieces not overlapping (hereinafter referred to as "N/N"). The two assemblies were welded at an electrode force of 2.45 kN while applying electric current at 7.2 kA for 233 ms (including the up-slope control for 50 ms). The electrodes used were chromium copper electrodes of the DR type with 6R40 diameter tips.

**Figure 4** shows a graph plotting the comparison results between the nugget growing histories obtained from the experiment and cal-



Fig. 4 Comparison of nugget growth history between experiments and calculations for coated sheets

culation. The sheet assembly of N/N showed growth behavior similar to that of non-coated steel sheets. The sheet assembly of C/C showed slower nugget growth. The analysis results are in agreement with the above experimental results. **Figure 5** shows an excellentlyreproduced difference in the cross-section of each sheet assembly obtained in the middle of welding between the measurement result and calculation result. From the results described above, the validity of this coated sheet model was confirmed.

#### 2.3 Spatter prediction model

This subsection describes the development of a prediction model of spatter (so-called expulsion), which occurs from the interface between sheets. First, force balance is considered for a steel sheet that is being welded as shown in **Fig. 6**. Assuming that the force from an electrode is  $F_{E^2}$ , the force from the molten area (nugget) is  $F_{N^2}$  and the force from the steel sheet in front of the electrode is  $F_{C^2}$  the following force balance equation in the sheet thickness direction is satisfied.

$$F_N + F_C = F_F \tag{1}$$

Under an ideal condition without axis misalignment, i.e., in an analysis in which the axial symmetrical state constantly holds,  $F_E$  in Eq. (1) is equal to electrode force  $F_S$ . Given this, the following is rewritten as Eq. (1).

$$F_N + F_C = F_S \tag{2}$$

For actual welding, the balance relationship equal to Eq. (2) holds. However, axial misalignment and falling over of an electrode are unavoidable. It is reasonable to consider that force from an electrode is somewhat smaller than the force applied to the electrode (i.e., electrode force). Given this, the following is the actual force balance condition,

$$F_N^* + F_C^* = k \cdot F_S^*$$
(3)

where k is a coefficient of 1 or less, and the subscript "\*" is provided for distinction from the above ideal state in the analysis. Since the contact force between sheets should be zero when actual spatter occurs, the following formula can be used for obtaining spatter causing conditions.

$$F_C^* = 0 \tag{4}$$



Fig. 5 Cross sections of weldments after 100 ms



Fig. 6 Force balance in a welded sheet in idealized conditions

However, distinguishing the electrode force specified as welding conditions and the force from the molten area dependent on the nugget size but not affected by axial misalignment is not necessary between the analysis and actual welding. Accordingly, the following can hold.

$$F_{s} = F_{s}^{*}$$
 (5)  
 $F_{N} = F_{N}^{*}$  (6)

In conclusion, by applying Eq. (4), Eq. (5), and Eq. (6) to the difference between Eq. (2) and Eq. (3), the following formula is obtained as a relational expression that should hold in an analysis under the condition of actual spatter occurrence.

$$F_{c} = (1-k) \cdot F_{s} \tag{7}$$

In order to predict the generation of spatter by determining that Eq. (7) holds, two conditions need to be satisfied: One is that the history of  $F_c$  is obtained as the analysis result; and the other is that the value of coefficient k is already known. For the condition regarding  $F_c$ , the total of the contact pressure values at the corona bond shown in **Fig. 7** in all steps of the coupled analysis should suffice. The total can be evaluated using the following formula:

$$F_{c} = 2\pi \int_{r_{v}}^{r_{c}} r \cdot p_{c}(r) dr \tag{8}$$

where *r* is the distance from the nugget center, and  $r_N$  and  $r_C$  are the nugget radius and contact radius, respectively. Contact pressure  $p_C(r)$  can be directly obtained as the analysis result. Coefficient *k* can be determined by comparing  $F_C$  of Eq. (8) with the experimental result using some welding conditions.

Figure 8 shows the determination procedures. First, an experiment involving changing currents for a certain value of electrode force  $F_s$  is conducted to examine the time when spatter occurs in each current based on the change in resistance during welding. Next, analysis is conducted under the same conditions as those used in the experiment to obtain a history of  $F_c$ . From these results,  $F_c$  value at the spatter generation time is read to apply to Eq. (7) indicating the



Fig. 7 Contact force  $F_c$  in the simulation model



Fig. 8 Evaluation of parameter k in eq. (7) by plotting measured spatter time on the history of calculated  $F_C$ 

condition for spatter generation. Then, k for electrode force  $F_s$  is obtained.

Coefficient k by its nature should be affected by a welding machine difference or experimental variation. Despite that, in the experimental scope performed by us, the value was around 0.9 for any electrode force. Therefore, empirically, Eq. (7) for the spatter occurrence condition determination is further simplified as the following formula:

$$F_c = 0.1F_s \tag{9}$$

The validity verification for the spatter occurrence prediction model introduced as described above is explained in the next section.

### 2.4 Weld lobe prediction

In order to verify the validity of the spatter occurrence prediction model obtained as described in the previous section, a weld lobe was predicted. A weld lobe is a distribution chart of the nugget diameter when the horizonal axis is the current and the vertical axis is the electrode force or time period during which currents are applied. The chart indicates the appropriate welding condition range. The materials used for the study were three types of steels: Mild steel, 590-MPa DP steel, and 980-MPa DP steel. Welding of two 1.2 mmthick sheets was tested and analyzed. The conditions were varied with four levels of electrode force (1.47, 2.45, 3.43, and 4.41 kN) and with currents changed by 0.5 kA in the range from 3.0 to 11.0 kA. The time period of current application was 233 ms for all electrode force levels. The electrodes were of the DR type, the same as those described in 2.2.2.

Figure 9 shows charts of the weld lobes experimentally obtained for the three steel types, each compared with the weld lobe predicted through the analysis. The predicted weld lobes using solid lines were represented by regions surrounded by the contour line of the DN value of which the nugget diameter (DN) is  $4\sqrt{t}$  (*t*: sheet thickness) and the contour line of  $F_c$  value satisfies Eq. (9). For each steel type, the prediction weld lobe favorably agrees with the shaded experimental result. The validity of the spatter occurrence prediction model in this study was thus confirmed.

# **3.** Study on the Influence of Various Factors on the Spot Weldability at the Door Opening

**3.1 Analysis model and analysis conditions** Assuming spot welding at the door opening, an assembly consisting of three sheets of side panel outer (hereinafter referred to as

sisting of three sheets of side panel outer (hereinafter referred to as "SPO"), reinforcement (hereinafter referred to as "REINF"), and A pillar inner (hereinafter referred to as "APLR-INN") is considered in this chapter. Such a sheet assembly is regarded as one of the most difficult sections for spot welding in an automotive body due to the high sheet thickness ratio that is generally 4 or more. Another reason is that there is concern about sheet gaps caused by less-accurate press forming of the member or less-accurate assembling with other components, as well as the concern about current shunting caused by neighboring existing welding points.

Figure 10 shows the analysis model simulating the door opening, while **Table 1** shows the sheet assembly specification. In order to simplify the study, members should be straight. As shown in Fig. 10(a)(b), an 80-mm range in the longitudinal direction was determined as the analysis region due to the limited analysis scale. However, in order to consider the influence of current shunting due to the rigidity of the member or existing welding points on the weldability, the cross-section of the member is modeled in accordance with the actual vehicle body. In addition, as existing welding points, three 5-mm in diameter welding points were provided on the side of the



Fig. 9 Comparison of weldability lobes between measurement and predicted

front window and one on the flange in the same position as the welding point to be added for the study at intervals of 25 mm, as shown in Fig. 10(b). At the existing welding points, mesh vertices were shared in the range of a 5-mm in diameter circle to mechanically constrain the three sheets, while allowing currents to flow (current shunting). For the interfaces between the electrode and sheet and between sheets, mechanical contact conditions, contact heat, and electric resistance were defined. All displacements on the front window edge and out-of-plane displacement on the edge in the longitudinal direction were constrained as shown in Fig. 10(b).



(a) Analysis region and finite element mesh

(b) Model dimensions and position of existing welds

Fig. 10 Finite element model of a door opening

Table 1	Sheet combination
SPO	Mild steel / 0.8 mm
REINF	590 MPa-class steel / 1.0 mm
APLR-INN	590 MPa-class steel / 1.8 mm

Table 2	Welding	conditions
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Electrode force	3.5 kN
Weld time	22 cycles (60 Hz)
Weld current	7.0kA

The study on the influence of sheet gaps is described later. First, a DR type electrode with a tip diameter of 6 mm and a tip of R40 mm was vertically placed on the flange on the door opening side of the model without a sheet gap, and welding was analyzed under the conditions shown in **Table 2**. The welding center was determined in a position in the center of the flange in the longitudinal direction, 6 mm from the flange edge. In the following subsections, the influence of various factors on the weldability at the door opening is examined, while comparing the obtained analysis results with the analysis results of test coupons.

# 3.2 Influence of current shunting caused by existing welding points

Figure 11 shows a graph indicating nugget growth histories at the interfaces with sheets of the door opening model, compared with a history in the case of single-point welding of a 50 mm  $\times$  30 mm test coupon (Fig. 12) under the same conditions. These results show that the door opening model is slower in nugget formation, and that the final nugget diameter is considerably small. The main cause for the results is considered to be the influence of current shunting caused by existing welding points. Specifically, as is clear from the current time history at the welding point shown in Fig. 13, only 60 to 80% of the input currents of 7.0 kA flowed at the welding point on the door opening model. The current shunting can be understood from the contour chart of current density.

Figure 14 shows the current density distribution in the 5th cycle





Fig. 12 Finite element model of a coupon test piece

current input to the door opening model. From this result, the occurrence of current shunting can be confirmed at all modeled existing welding points. However, for the three points on the flange on the front window side, the amount of currents that were shunted was very small, with a large part of the entire shunting currents concen-



Fig. 13 Histories of current passing through the welding area



trating on the nearest welding points. Therefore, when examining the influence of current shunting on the weldability, the main focus should be placed on the nearest welding points.

## 3.3 Influence of the member's rigidity

Next, the influence of the rigidity of the member on the weldability is studied. When a test coupon is spot-welded, the steel sheet sustains out-of-plane deformation due to the electrode force, resulting in a gap (sheet separation) between the steel sheets. The size of a sheet separation influences the contact statuses at the interfaces, and varies depending on the welding conditions, electrode shapes, steel type, sheet thickness, etc. In addition, the shape of the material to be welded, meaning the rigidity of the member, is responsible for the size of a sheet separation as well. In particular, in a member with a closed cross-section structure like the door opening, the deformation during welding may be suppressed, showing weldability different from that of test coupons. In this section, the analysis results obtained from a test coupon model (Fig. 15) with the same sheet assembly and existing welding points as the door opening model are compared with the analysis results of the door opening model to examine the influence of the rigidity that a member has on the weldability.

Figure 16 shows a chart comparing nugget growth histories at the SPO-REINF interface between the door opening model and test coupon model. Whereas the nugget formation in the door opening model is slightly slower, the overall growth of the two nuggets show only a small difference. For the interface of REINF-APLR-INN as well, there was very little difference between the two. To determine the reason for this, the average current density of the weld area at the SPO-REINF interface was calculated to examine the difference



Fig. 15 Finite element model of a coupon test piece with an existing weld



Fig. 17 Mean current density

Weld time, cycle

between the two models. **Figure 17** shows the results. As the chart clearly shows, the average current density at the weld area directly involved in the nugget formation was almost equal to each other. The sheet assembly and the shape of the component dealt with in this study are considered to be the reason for no difference in the nugget formation between the two models.

Furthermore, focusing on the sheet separation, an obvious difference is found between the two models. For example, **Fig. 18** shows images of the cross-sections taken in the 5th cycle of current input, clearly showing that the sheet separation in the door opening model is smaller. This is very important when dealing with a coated steel



Fig. 18 Deformation and sheet separation with temperature distributions at 5 cycles on the cross section (a) Parallel to (b) Perpendicular to the longitudinal direction (upper: coupon TP model, lower: door opening model)



Fig. 19 Finite element models of single spot joint with gap

sheet. In other words, coating on the steel sheet surface is partially melted when currents are being applied; The sheet separation is filled with the molten coating, leading to an apparent increase in the diameter of the region where the currents are flowing. As a result, the current density at the weld area is lowered to render the nugget growth slower.<sup>3)</sup> Since this study only deals with bare steel sheets, no significant difference has been found in the weldability in the two analysis models. If the SPO was a coated steel sheet as in the case of actual vehicles, the difference in sheet separation due to the difference of member rigidity might have affected the weldability to no small extent.

#### 3.4 Influence of sheet gaps

When the influence of sheet gaps is evaluated in experiments, test coupons provided with gaps by inserting spacers between sheets are used in general. However, sheet gaps in a variety of forms can be contained in an actual vehicle body, and the evaluation using such test coupons can cover only a small part of the diverse sheet gaps.

For example, we assumed a case in which a test coupon model with supports provided at the interval of 50 mm and gaps of 1 mm as shown in **Fig. 19**(a) and the door opening model with the same gaps of 1 mm as shown in Fig. 19(b) were used. The two models were welded under the conditions shown in Table 2 to compare the nugget growth of the REINF-APLR-INN interface. The nugget growth histories of the test coupon model and door opening model significantly differed from each other as shown in **Fig. 20**. When compared with the result obtained using a no-gap test coupon, one of the two models was faster than it, while the other was slower in nugget growth; the weldability change tendency thus different from each other was shown. The reason for this is considered to be the difference in the way the gaps were provided, rendering the contact status at each interface different from each other, resulting in a dif-





ference in heating as shown in **Fig. 21**. In addition, if there is a coated steel sheet in the assembly, the influence of the sheet separation is present as well as described in 3.3. For this reason, the change in weldability is considered to be more complicated. As explained above, when the influence of sheet gaps on the weldability is studied, it is necessary to examine the exact situation in the case of an actual vehicle structure.

#### 4. Application to the Prediction of Fracture at Weld Areas for Dissimilar Material/Thickness Sheet Assemblies

#### 4.1 Tensile tests of spot-welded joints

The spot-welded joint tensile tests described in this chapter used five different sheet assemblies; a 270 MPa cold rolled steel sheet (hereinafter referred to as the "270 steel") that was 2.0 mm in thickness was used for one side, and for the other side sheets of various material and thickness were used. Table 3 shows the five sheet assemblies together with the tensile test results. The joint shapes were a tensile shear joint and an L-shaped joint as shown in Fig. 22. The target nugget diameter value at the weld area was  $4\sqrt{t}$  (t: Thickness on the sheet side). The tensile tests were performed under the static condition of 10 mm/min. The maximum load shown in Table 3 is the average value of the results of three tests. Fractures were defined into two types: One was those mainly constituted by shear at the center of the nugget (hereinafter referred to as the "nugget interface fracture"); and the other was those involving the nugget unplugging fracture (hereinafter referred to as the "unplugged fracture") resulted by crack growth around the nugget outer circumference. All frac-

 Table 3
 Combination of steel sheets for spot welded joints, and corresponding experimental joint strength

			TS joint		LT joint	
No.	Combination of steel sheets		Joint strength (MPa)	Fracture mode	Joint strength (MPa)	Fracture mode
A1	270-steel (2.0 t)	270-steel (1.2 t)	8.77	Shear	2.11	Pull out
A2	270-steel (2.0 t)	440-steel (1.2 t)	10.47	Shear	2.00	Pull out
A3	270-steel (2.0 t)	590-steel (1.2 t)	9.80	Shear	2.52	Pull out
A4	270-steel (2.0 t)	980-steel (1.2 t)	11.71	Shear	2.40	Pull out
A5	270-steel (2.0 t)	Boron-steel (1.2 t)	11.69	Shear	2.28	Pull out



Fig. 22 Tension test specimens of spot welded joint

tures sustained by the tensile shear joints were nugget interface fractures, while all fractures that the L-shaped joints underwent were unplugged fractures on the sheet side.

#### 4.2 Creating the fracture prediction FEM analysis model

4.2.1 Overview of the analysis model

This section describes the development of the fracture prediction FEM analysis model capable of dealing with the dissimilar material/ thickness sheet assemblies. **Figure 23** shows the analysis mesh of the spot-welded area. The shapes of the nugget and the heat affected zone (HAZ) were obtained using a regression formula using the sheet thickness and nugget diameter as parameters. For the deformation resistance curve and the fracture limit of the base metal and HAZ, data for each area of the same material sheet assembly was used. For the nugget made up of two different materials, the data of the same material sheet assembly could not be used as-is. For the nugget data, ultra-small test piece tensile test results<sup>7</sup> were used. However, from the viewpoint of simplification and extensibility, the study described in this chapter used a linear mixing approximation formula and a prediction formula for the calculation.

4.2.2 Calculation method of the deformation resistance curve and fracture limit value

The deformation resistance curve was approximated by Ludwik's equation. As shown in Eq. (10), in the dissimilar material/ thickness sheet assembly, the flow stress of the nugget was calculated by multiplying Ludwik's equation of each material by the mixing ratio of the molten area (R<sub>(270)</sub>: 270 steel [2.0 t], R<sub>(other)</sub>: Mating sheet [1.2 t]). The fracture limit value was expressed by the Eq. (11) power function, and their constants a and b were obtained using Eq. (12) and Eq. (13) with chemical components as parameters. From a1 to a10 and from b1 to b10 of Eq. (12) and Eq. (13) are the constants derived using the least-squares method from the fracture limit value data on the five steel types obtained using the tensile test technology<sup>7)</sup> of ultra-small test pieces. Regarding the dissimilar material/ thickness sheet assembly, the chemical composition of the nugget was estimated from the mixing ratio of the molten area. Equation (14) is a calculation example of the C content. As described above, for a dissimilar material/thickness sheet assembly, the calculation method of the molten mixing ratio is important. In this chapter, the molten mixing ratio was obtained from the results of the sheet thickness ratio or spot welding simulation (nugget formation analysis). Then the deformation resistance curve and the fracture limit value calculated using respective methods were applied. Lastly, the prediction accuracy of the FEM analysis was compared.





Fig. 23 Finite element mesh of spot welded joint (different materials and thickness)

$\varepsilon_{\rm CR} = a \sigma_{\rm triax}^{\rm b}$	(11)
( $\varepsilon_{\rm CR}$ : Fracture strain, $\sigma_{\rm triax}$ : Stress triaxiality)	
$ a = 1 - a1 \cdot C - a2 \cdot Si - a3 \cdot Mn - a4 \cdot P - a5 \cdot S  - a6 \cdot Mo - a7 \cdot Cr - a8 \cdot B - a9 \cdot Ti - a10 \cdot Nb $	(12)
$\begin{split} b &= -0.5 - b1 \cdot C - b2 \cdot Si - b3 \cdot Mn - b4 \cdot P - b5 \cdot S \\ &- b6 \cdot Mo - b7 \cdot Cr - b8 \cdot B - b9 \cdot Ti - b10 \cdot Nb \end{split}$	(13)
(a1-a10, b1-b10: Constants)	

 $C = R_{(270)} \cdot C_{(270)} + R_{(other)} \cdot C_{(other)}$ (14) (C<sub>(270)</sub>: C content of 270C, C<sub>(other)</sub>: C content of the mating sheet)

4.2.3 Calculation using the thickness ratio

All joints subject to the evaluation were assemblies of the 270 steel (2.0 t) and mating sheets (1.2 t). Therefore, if the sheet thickness ratio is used,  $R_{(270)}=0.625$  and  $R_{(other)}=0.375$  were determined from Eq. (15) and Eq. (16).

$$R_{(270)} = \frac{2.0}{2.0 + 1.2} \tag{15}$$

$$R_{(other)} = \frac{1.2}{2.0 + 1.2}$$
(16)

4.2.4 Use of spot welding simulation

With the welding conditions used in this experiment as input parameters, the molten area mixing ratio was calculated using this technology. Nugget volumes  $V_{\scriptscriptstyle (270)}$  and  $V_{\scriptscriptstyle (other)}$  respectively used the maximum liquid phase ratio during heating, and the nugget diameter was determined to be in a range with the maximum liquid phase of 0.8 or more. Molten area mixing ratios  $R_{_{\rm (270)}}$  and  $R_{_{\rm (other)}}$  were obtained using Eq. (17) and Eq. (18). Table 4 shows the nugget diameter and the molten area mixing ratio obtained from the nugget formation analysis. Figure 24 shows the cross-section of sheet assembly No. A4 weld joint and the nugget formation analysis result (liquid phase ratio distribution). The nugget diameter obtained as the analysis result corresponds to the target value ( $4\sqrt{t} = 4.38$  mm), and the molten area mixing ratio is considered to be a reasonable value. The molten area mixing ratio of sheet assembly Nos. A1 and A2 with the mating sheet (1.2 t) being 270 steel or 440 steel generally accorded with the case using the sheet thickness ratio.

Contrary to that, sheet assemblies Nos. A3, A4 and A5 showed different values from the case using the sheet thickness ratio. Since high tensile strength steel has a higher electricity resistivity at a temperature range between room temperature to  $1000^{\circ}$ C than mild steel, growth of the nugget is faster and the molten area mixing ratio is higher.<sup>1)</sup> The analysis result agreed with the tendency. When using hot stamp material for the mating sheet, the molten area mixing ratios R<sub>(270)</sub> and R<sub>(other)</sub> of sheet assembly No. A5 were almost equivalent.

$$R_{(270)} = \frac{V_{(270)}}{V_{(270)} + V_{(other)}}$$
(17)

$$R_{(other)} = \frac{V_{(other)}}{V_{(270)} + V_{(other)}}$$
(18)

4.2.5 Deformation resistance curve and fracture limit value of the nugget

With the sheet thickness ratio and through the spot welding simulation (nugget formation analysis), the molten area mixing ratios ( $R_{(270)}$  and  $R_{(other)}$ ) were calculated, respectively. Then using Eqs. (10) to (14), the deformation resistance curve and the fracture limit value of the nugget were obtained for each sheet assembly. As shown in Table 4, the molten area mixing ratios of Nos. A1 and A2 involved

Table 4 Comparison of spot weld simulated results

No.	Combination of steel sheets		Nugget diameter (mm)	Mixing ratio	
				R <sub>(270)</sub>	R <sub>(other)</sub>
A1	270-steel	270-steel	1 17	0.692	0.308
	(2.0t)	(1.2 t)	4.47		
12	270-steel	440-steel	4.50	0.630	0.370
A2	(2.0t)	(1.2 t)	4.50		
٨2	270-steel	590-steel	4.50	0.582	0.418
AJ	(2.0t)	(1.2 t)	4.50		
A.4	270-steel	980-steel	1 28	0.552	0.448
A4	(2.0t)	(1.2 t)	4.20		
۸.5	270-steel	Boron-steel	4.07	0.528	0.472
AS	(2.0t)	(1.2 t)	4.07		

0.0 0.8 1.0



(a) Experimental result (b) Analysis result (Distribution of liquid phase ratio)

Fig. 24 Tension test specimens of spot welded joint (unit: mm)



almost no difference between the spot welding simulation result and the calculation result using the steel thickness ratio. For this reason, the deformation resistance curve and the fracture limit line almost accorded with each other as well. Contrary to this, on the results of Nos. A3, A4 and A5, the difference in the molten area mixing ratio exercised influence; **Figure 25** shows a chart plotting their deformation resistance curves, while **Fig. 26** shows a chart plotting their fracture limit values. The solid lines and broken lines in gray are the calculation results using the sheet thickness ratio, and the solid lines and broken lines in black are the spot welding simulation results. The calculation results from the spot welding simulation of Nos. A3, A4 and A5 showed larger deformation resistance and lower ductility



Fig. 26 Spot weld fracture limit curves in FEM analysis model

for the fracture limit. As the strength of the mating sheet (1.2 t) was higher, such tendency became significant.

### 4.3 Analysis result

**Figure 27** shows bar charts indicating the comparison results between the experimentally measured joint strength and the joint strength calculated through the FEM analysis. For the FEM analysis results, further comparison between the analysis result of the deformation resistance curve and fracture limit value of the nugget using the sheet thickness ratio (hereinafter referred to as "analysis result (1)") and the analysis result of the same (hereinafter referred to as "analysis result (2)") using the spot welding simulation was conducted.

While analysis result (1) showed favorable accord with the experimental results regarding the tensile shear joint, regarding the Lshaped joint, the difference from the experimental results increased as the mating sheet (1.2 t) strength became higher; With sheet assemblies Nos. A4 and A5, the difference from the experimental results reached 10% or more. In analysis result (2), even the L-shaped joint result showed a less than 10% difference from the experimental results. Compared with analysis result (1), the prediction accuracy improvement effect for sheet assemblies Nos. A4 and A5 was significant. The fracture forms in both analysis results (1) and (2) were the same as that in the experimental results. As an example, Fig. 28 comparatively shows sheet assembly No. A4 in cross-section photographs taken during the experiment and in simulation images of analysis result (2). On the tensile shear joint, a fracture occurred at the nugget interface; on the L-shaped joint, the fracture that occurred was an unplugged fracture. If the mating sheet (1.2 t)strength was high, the fracture started inside the nugget. This was reproduced in the FEM analysis. The results above indicate that the material characteristic values at the molten area of a dissimilar material/thickness sheet assembly that includes a high tensile strength steel sheet greatly affect the prediction accuracy, making it important to choose a suitable estimation method.

### 5. Conclusion

In this paper, we described the initiatives to develop a highly accurate spot welding FEM analysis system based on an incrementally coupled analysis method between the electric, temperature, and stress fields considering the phase change and phase transformation. The technology achieved high accuracy prediction of the nugget growth for any sheet assembly under any welding conditions. In addition, the technology actually considered melting and evaporation



(b) Experimental results

Fig. 28 Comparison of fracture mode (No. A4)

of the coating, and predicted spatter occurrence involving the molten metal being spattered from inside as well. This has allowed the theoretical examination of the weld lobe of an actual sheet assembly including a coated steel sheet. Since the studies were started with single-spot welding of test coupons as the evaluation subject, axial symmetry models were mainly examined. However, due to the need for considering current shunting, sheet gaps, electrode axial misalignment, etc., the study subject was switched to 3D models.

As an example, the spot welding simulation technology was applied to the member geometry modelling a door opening. An examination method of the influence of current shunting, the rigidity of members, and sheet gaps on weldability was proposed; the method involved a comparison of the results from single point welding of test coupons. Furthermore, as application to the evaluation of weld area strength, the deformation resistance and fracture limit value were calculated from the molten area mixing ratio of the nugget obtained through the spot welding simulation. This was able to contribute to an accuracy improvement of fracture prediction FEM analysis modelling of dissimilar material/thickness sheet assemblies.

Along with the progress in strength improvement of automotive

steel sheets, sheet assemblies are becoming more complicated, making it more difficult to determine the spot welding conditions. In addition, since it is becoming increasingly important to study the welding mechanism under disturbance conditions such as sheet gaps, electrode axial misalignment, etc., expectations for the effect of the use of the analysis technology are increasing.

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Hideki UEDA Senior Researcher Materials Reliability Research Lab. Steel Research Laboratories 1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891



Manabu FUKUMOTO Senior Manager Research Administration Dept. R & D Planning Div.



Hiroki FUJIMOTO Senior Manager, Dr. Eng. Research Planning Dept. Steel Research Laboratories



Kazuo OKAMURA Fellow, Doctor (Energy Science) R & D Laboratories



Shota KIKUCHI Researcher Materials Reliability Research Lab. Steel Research Laboratories



Eisuke NAKAYAMA Senior Manager, Dr. Eng. Research Planning Dept. Steel Research Laboratories



Tohru OKADA Senior Manager Human Resources Div.



Masanori YASUYAMA Chief Researcher Welding & Joining Research Lab. Steel Research Laboratories