

Development of Resistance Spot Welding Simulation Technology

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ABSTRACT

A technology for simulating resistance spot welding process has been developed that is capable of predicting nugget diameter in automotive steel sheet weldments to determine the specifications of those weldments at an early stage and speed up setting welding conditions. An incrementally coupled analysis was performed for electrical, thermal and mechanical fields using a finite element code. The material properties relevant to this analysis were selected with reference to the phenomena occurring throughout the resistance spot welding process, and they can be predicted by using the chemical compositions and mechanical characteristics. Also, software was developed to aid entry of arbitrary steel sheet combination and welding condition. Verification tests of simulations indicated that nugget diameter was predicted with an accuracy of $\pm 5\%$. We expect that this simulation method will allow us to determine the specifications for automotive welded sheet combination at an earlier stage and reduce the time for setting welding conditions by approximately 45%.

1. Introduction

“Resistance spot welding process” means the welding of metal components by passing an electric current to the contact point of workpieces put between a pair of loaded electrode, and heating the contact point with a temperature higher than melting point locally by using heat generated from electric contact resistance of the interface between the components and Joule heat (resistance heat). Historically, this has been used for most of the welding in automotive manufacturing processes, where productivity and reliability are paramount. In recent years, however, it has become increasingly common to use high-strength steel sheets for body frame components to reduce weight and enhance crashworthiness⁽¹⁾. At the same time, there is increasing variety in the types of sheet

steel combinations welded by resistance spot welding. Thus, more efficient and quick identification of the optimal welding conditions for these sheet combinations is required. Conventionally, tensile tests, sectional inspections and other means have been used to set the welding conditions for such sheet combinations. However, the diversity of welded sheet combinations is increasing with the widening applicability of high-strength steel and the development time for automobiles is shortening. In the future, it will be harder to address these situations using those experimental methods only. Therefore, a technology for simulating resistance spot welding was developed that is capable of predicting nugget diameter in arbitrary automotive steel sheet weldments to determine the specifications of those weldments at an early stage and to speed up setting welding conditions.

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This report describes an outline of the simulation model and a method for defining material properties necessary for predicting nugget diameter. This also describes the development of more user-friendly software, and the benefits this package offers to automobile designers.

2. Setting Goals

Much research has been devoted to simulations of resistance spot welding processes, and there are several software packages on the market that offer such simulations^{(2) - (4)}. However, they are only capable of analyzing a limited number of steel types and sheet combinations because there are few kinds of the necessary material properties which are prepared by default. Therefore, goals for the following topics were designated so that welding conditions for general sheet combinations used in actual vehicles could be more easily set.

- (1) Simulation model: In order to reproduce actual resistance spot welding processes during complicated manufacturing procedures, it is necessary to perform coupled analysis of electrical, thermal and mechanical phenomena. Therefore, the simulation model must allow coupling of electrical, thermal and mechanical fields. At the same time, it must predict phase transformation temperatures and electrical, thermal and mechanical change of material properties in each steel type.
- (2) Applicable steels: Since a variety of steels are used in auto bodies now, from mild to high-strength steel, a key objective was to allow simulation of typical 270 – 980 MPa class steels in arbitrary sheet combinations and welding conditions. Galvaneal steels (GA steels) are used for automotive sheet products because of their corrosion resistance; it was also desirable to allow for the simulation of GA steels similar to uncoating steels.
- (3) Simulation accuracy: In consideration of joint strength of weldment, the nugget diameter was selected as the parameter for accuracy in this simulation. Generally, the optimal welding conditions for an automotive welded sheet combination are chosen on the basis of the range of electrical current, between the minimum current providing the necessary nugget diameter and the current that causes spatter. Figure 1 shows the relationship between welding current in two sheet combination with identical thickness and nugget diameter; in the low-current region, small differences

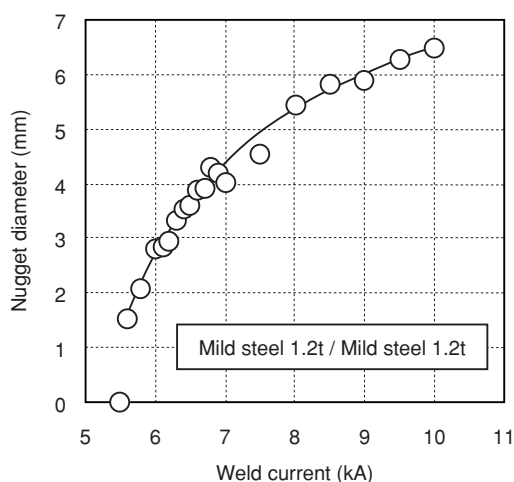


Fig. 1 Relationship between nugget and weld current

in welding current result in large changes in nugget diameter and there is considerable scatter in the measured diameters under otherwise apparently identical conditions. Accordingly, to verify the accuracy of this model, the nugget diameter range for this model was set between the necessary diameter and the diameter generated at the current that causes spattering.

The desired accuracy in prediction of nugget diameter was set at $\pm 5\%$, in consideration of the actual scatter in nugget diameter.

3. Simulation Model and Material Properties

3.1. Outline of Simulation Model

The 2-dimensional axially-symmetric finite element model (FEM) was used to simulate a pair of electrodes and the workpiece, consisting of two or more steel sheets (Fig. 2).

Electrical contact resistance in the interface is the dominant factor in the initial rise in temperature during resistance spot welding current; the generated heat generally depends on the temperature and pressure in the contacting interface⁽⁵⁾. These interface conditions change from moment to moment with the thermal conditions in the steel at the interface. As the materials are heated to higher temperatures, a solid/liquid phase change occurs, or a phase transformation in which the crystal structure of the steel changes, resulting in changes in mechanical characteristics, coefficient of liner expansion, or other material properties. Therefore, a simulation of resistance spot welding processes, including thermal changes of material properties and deformation processes accompanying temperature, must be based on a coupled analysis that accounts for metallurgical behavior. The framework presented in this report is illustrated in Fig. 3. It is based on a commercial nonlinear finite element code, and incorporates both a coupled electrical-thermal analysis for predicting temperature changes in steel sheets during current flow and a coupled thermal-mechanical analysis for predicting changes in mechanical characteristics with temperature rise in steel sheets. These analyses are repeated alternately with adequate small intervals in an incrementally coupled analysis method during the welding cycle, while considering changes in the material properties⁽⁶⁾. The electrical-thermal analysis is solved with contact information, such as contact area and pressure distribution, obtained from the previous thermal-mechanical analysis. Thermal history obtained from the electrical-thermal

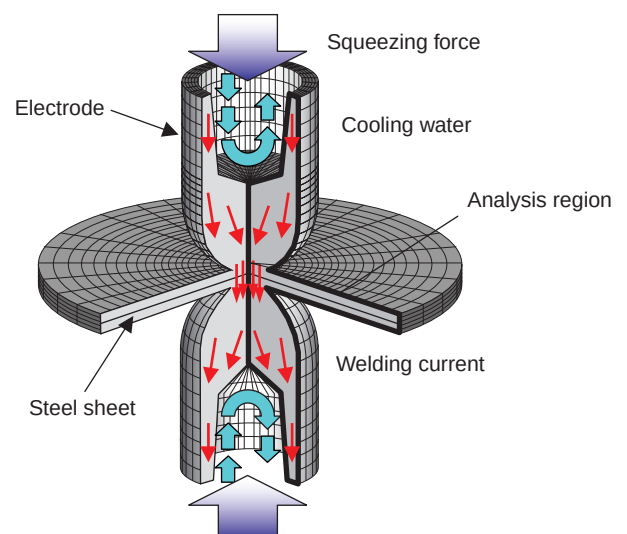


Fig. 2 Simulation model

analysis is then used as the input condition of the next thermal-mechanical analysis.

3.2. Material Properties

It was necessary to consider the changes in material properties of all applicable steels during the resistance spot welding process in order to obtain results that met the desired accuracy. Therefore the first investigation was into how to select and define the material properties necessary for this kind of simulation.

3.2.1. Selection of required material properties

As shown in Fig. 4, the resistance spot welding process was divided into three processes, (1) squeezing and turning on the current, (2) heating/melting, and (3) cooling, and the required material properties affecting each phenomenon were identified.

(1) Squeezing and turning on the current Resistance spot welding is initiated by putting workpieces between a pair of loaded fixed shaped electrode and activating the electrical current flow. Once current begins to flow, the material temperature begins to rise due to heating generated by electrical contact resistance and Joule heating. This changes the contact area and the contact pressure, important parameters in resistance spot welding heating behavior discussed below. Since these changes are caused by thermal distortion of the sheet with the temperature rise, it is necessary to define the changes in the material properties of the

steel, i.e., mechanical characteristics and the coefficient of liner expansion. Therefore, the stress-strain relationship (S-S property), accounting for temperature dependence, and the coefficient of liner expansion were selected for the required material properties during squeezing and turning on the current.

(2) Heating/temperature rise Heating during resistance spot welding process is caused by both electrical contact resistance and Joule heating.

Several models have been presented in the literature for contact resistance in the initial stage of current flow. This simulation employed the contact resistance model suggested by Babu et al⁽⁷⁾:

$$R_{CA} = (\rho_1 + \rho_2) \times \left[\frac{1}{4} \sqrt{\frac{\pi \sigma_y}{\eta P}} + \frac{3\pi}{16 \sqrt{\eta}} \right] \quad (1)$$

(R_{CA} , electrical contact resistance; ρ_1, ρ_2 , electrical resistivities of sheets 1 and 2; σ_y , yield stress; P , contact pressure; η , function of contact pressure P)

Joule heating occurring during exposure of a metal of a given resistance to a current over a given time can be expressed as in Eq. (2)⁽⁸⁾:

$$Q = R \times I^2 \times t \quad (2)$$

(Q , Joule heat; R , resistance; I , current; t , time)

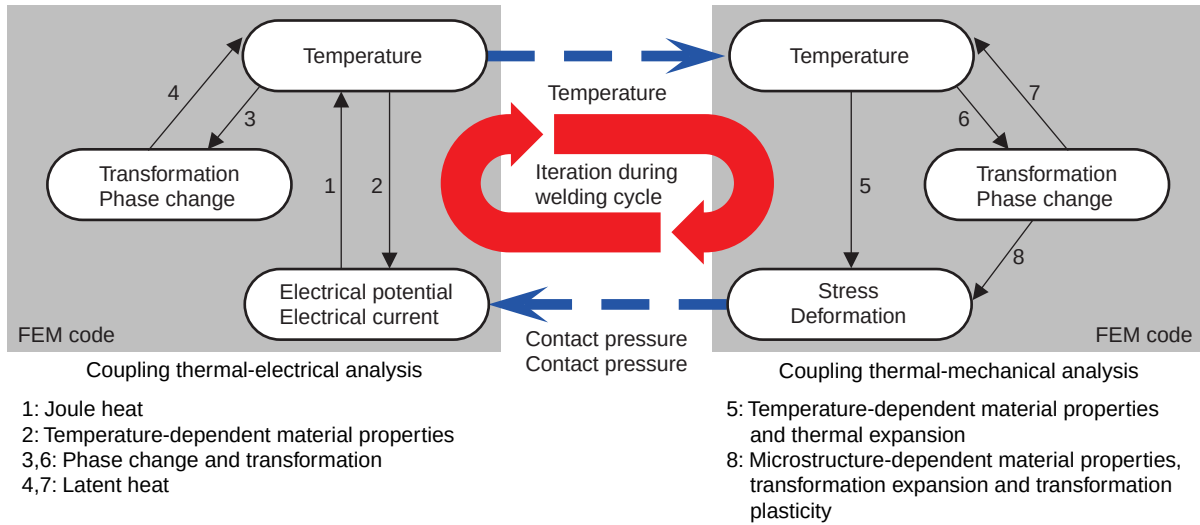


Fig. 3 Schematic illustration of the incrementally coupled electrical-thermal-mechanical analysis procedure

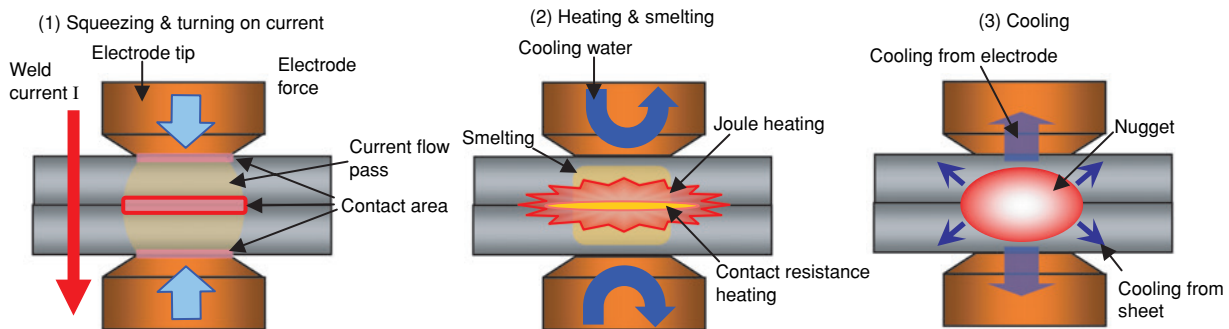


Fig. 4 Schematic explanation of the SPOT welding process

If Eq. (2) is rewritten in terms of electrical resistivity, which is one of the material properties of steel, and current density, which changes with rise in steel temperature, the Joule heat density can be expressed by Eq. (3):

$$q_v = \rho \times \delta^2 \times t \quad (3)$$

$$\rho = R \times \left(\frac{S}{l} \right), \quad \delta = \frac{I}{S}$$

(q_v , Joule heat per unit time, unit volume; ρ , electrical resistivity; δ , current density; t , welding time; S , contact area diameter; l , thickness)

As Eq. (4) shows, the relationship in resistance spot welding between heat generated during the welding time Δt and the temperature rise in the sheet steel is determined by the heat generated and the relationship between the specific heat of the material and its density.

$$\Delta\theta = \frac{q_v \Delta t}{(c \times D)} \quad (4)$$

($\Delta\theta$, temperature rise; c , specific heat; D , density)

Accordingly, because of the heat generated by electrical contact resistance, calculated in Eq. (1), the Joule heating calculated in Eq. (3) and the relationship between generated heat and temperature rise, shown in Eq. (4), the required material properties for heating and temperature rise phenomenon are electrical resistivity, yield stress, specific heat and density.

(3) Cooling Fourier's principle, which describes a material body with temperature differences, predicts the amount of heat conducted over a unit time. As Eq. 5 shows, the principle depends on the material's thermal conductivity and temperature gradient.

$$q = -\lambda \cdot \text{grad}(T) \quad (5)$$

(q , heat flow rate; λ , thermal conductivity; $\text{grad}(T)$, temperature gradient)

Cooling by heat conduction in the workpiece and the electrode occurs simultaneously with heating generated by turning on the current during the resistance spot welding process. Therefore, thermal conductivity was selected as the required material property for the cooling process.

In view of the above results, six material properties were chosen for resistance spot welding process simulation: the stress and strain (S-S) property, the coefficient of linear expansion, electrical resistivity, specific heat, density and thermal conductivity.

3.2.2. Defining material properties

The thermal dependence of all the material properties listed in the previous section needs to be found, but measuring these parameters for all steel types would be an extremely complicated and time-consuming process. Therefore, it seemed necessary to estimate the material properties of each steel by using its mechanical characteristics at room temperature and its chemical compositions, which are relatively easily obtained, and other properties.

(1) S-S property It is important to account for temperature dependence of the properties of S-S. An approximation equation was investigated to use for standardized, simple definition of the properties.

At first, to understand the temperature dependence, changes in S-S property with temperature were measured. Figure 5-1 shows measured results in the S-S curve for mild steel and high-strength steel. Both steels showed declining strength with higher

temperatures, and there was almost no difference between the two at 800 °C. As a reason for this phenomenon, it is assumed that the effects of the chemical compositions and microstructures which keep the S-S properties at room temperature practically disappears

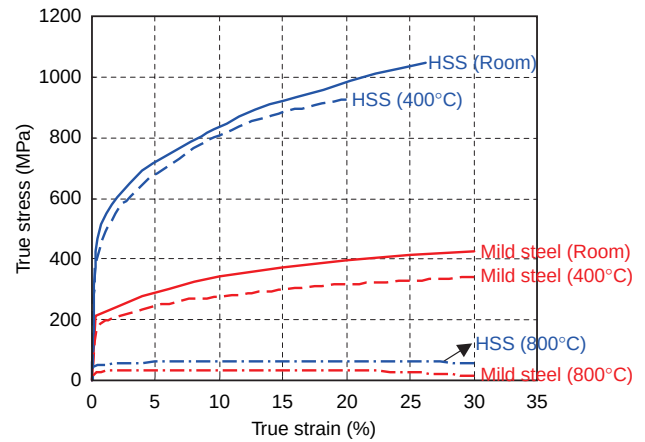


Fig. 5-1 S-S curve of mild steel and high-strength steel (HSS)

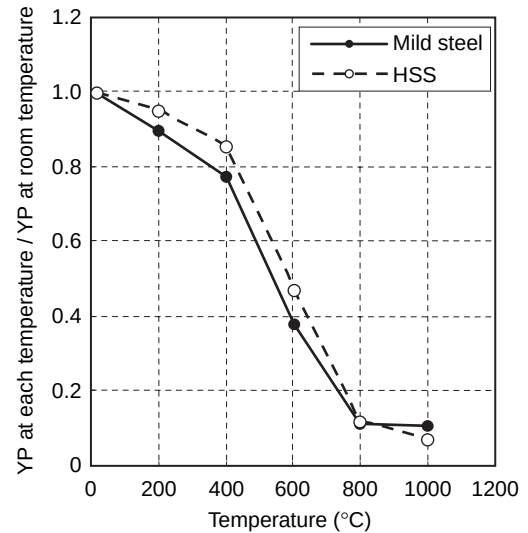


Fig. 5-2 Dependence of 0.2% proof stress on temperature

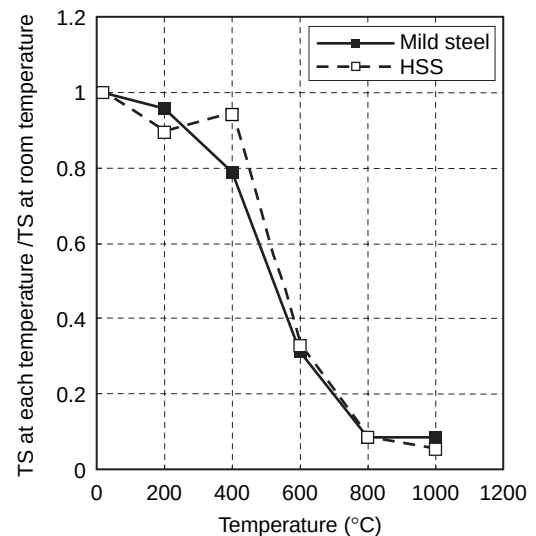


Fig. 5-3 Dependence of tensile strength on temperature

by grain growth and phase transformation in high temperature area.

Next, the temperature dependence of the tensile strength and yield strength were examined to standardize the temperature dependence of S-S property. As Figs. 5-2 and 5-3 show, both strengths were well represented by functions of temperature.

Thus an approximation equation was constructed to obtain the temperature dependence of the S-S property using the yield and tensile strengths at room temperature and the temperature as variables, allowing above property values at room temperature only to be inserted into the basic equation to define the S-S property at high temperatures.

(2) Thermal conductivity Generally, most of thermal conduction of a metal is represented by the propagation of heat for free electrons. The thermal conductivity is affected by the thermal vibration of metal atoms and by the presence of alloying elements. Accordingly, the chemical compositions and temperature were selected as the variables, employing Miettinen's formula⁽⁹⁾, which allows different expressions for different crystal structures. The results of the investigation are shown in Fig. 6-1. The measured

values for mild steel were nearly the same as the calculated values, but the thermal conductivity in high-strength steel diverged greatly from the measurements below 800 °C.

The authors then considered that the error might have been due to the influence of alloying elements not included as terms in Miettinen's formula. An approximation equation for the thermal conductivity was constructed that included such influences. Figure 6-2 shows the verification results of that equation.

The new equation showed a good correlation with the measurements for all types of steel tested. It is now possible to define thermal conductivity simply by inputting the chemical composition and the temperature.

(3) Electrical resistivity Since thermal conduction by free electrons is the dominant factor in metals, it has been shown that the reciprocal relationship between thermal conductivity and electrical resistivity shown in Eq. (7) holds; this is called the Wiedemann-Franz Law (W-F Law)⁽¹⁰⁾.

$$\lambda \rho = L \cdot (T + 273) \quad (7)$$

$$L = 2.45 \times 10^{-8}$$

(λ , thermal conductivity; ρ , electrical resistivity; T , temperature; L , Lorentz number)

Thus, the W-F Law was investigated for its utility in formulating an approximation equation for electrical resistivity. Figure 7-1 shows the results. The W-F Law somewhat underestimated the electrical resistivity, especially in high-strength steels, and provided no clear difference between high-strength and mild steels. This was probably because under the W-F Law, dependence on alloying elements, which have effects on the movement of free electrons, is thought to be similar for both thermal conductivity and electrical resistivity. However, this is not necessarily true in steel sheet.

Therefore, the authors considered that other influential factors could be the presence of allowing elements in the steel sheet and the thermal vibration of atoms of the base material, since electrical resistance in metals occurs due to collisions of the free electrons with the atoms making up the metallic crystal. The allowing elements are chemical composition values of the steel sheet that can be expressed as C, Si, Mn, etc., and the thermal vibration of the base material atoms can be expressed as a function of

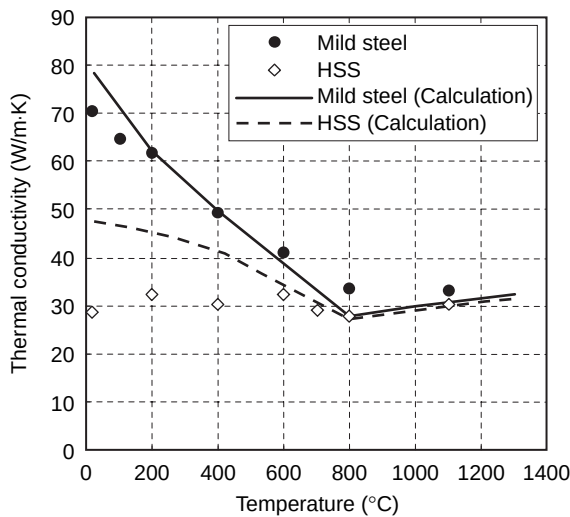


Fig. 6-1 Comparison of thermal conductivity between measurements and predictions by Miettinen's formula

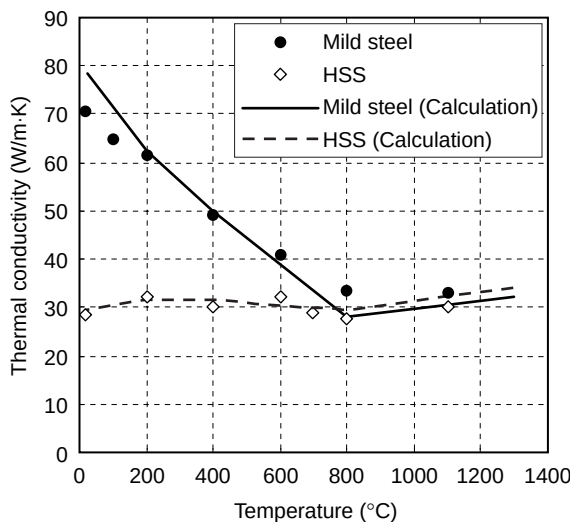


Fig. 6-2 Comparison of thermal conductivity between measurements and predictions by modified Miettinen's formula

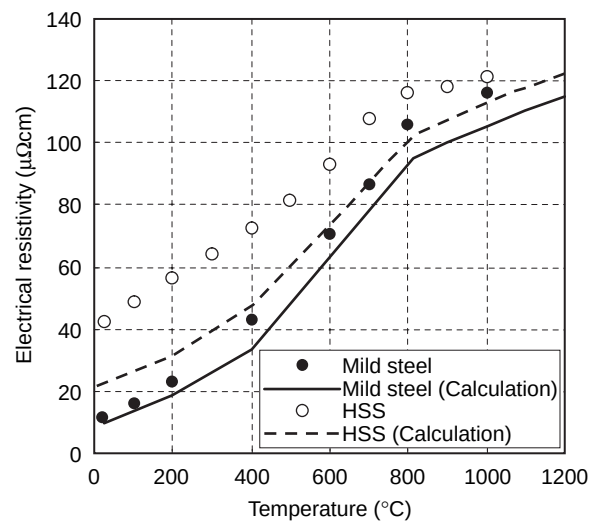


Fig. 7-1 Comparison of electrical resistivity between measurements and predictions by W-F Law

temperature. Accordingly, an approximation equation was constructed that was based on actual measured values and could express the differences between steel types. The results of the verification experiments using the equation are shown in Fig. 7-2. These had a better correlation with the measured values than the expression derived from the W-F Law and clearly distinguished between different steel types.

(4) **Specific heat** There are no organized data about the specific heats of different steels, leaving variations between steel types unclear, so changes in the specific heat with temperature were measured in various steels (Fig. 8). No differences between the types were found, so this parameter has been defined with identical values for every steel type.

(5) **Density and coefficient of linear expansion** The equation proposed by Jablonka et al.⁽¹¹⁾ is well established for density; it uses the carbon content and the temperature as parameters. However, the characteristics of steel sheets used in the automobiles are changed by adding C and numerous other elements as well as Si, Mn, so Miettinen's formula⁽⁹⁾ (Eqs. (8-1) – (8-3)), obtained by taking into account the influence of Si, Mn, Cr and Mo on Jablonka et al.'s expression, were employed.

(austenite)

$$\rho_r = 8099.79 - 0.506T + (-118.26 + 0.00739T)C_c - 68.24C_{Si} - 6.01C_{Mn} + 12.45C_{Mo} + (-7.59 + 3.422 \cdot 10^{-3}T - 5.388 \cdot 10^{-7}T^2 - 0.014271C_{Cr})C_{Cr} + (1.54 + 2.267 \cdot 10^{-3}T - 11.26 \cdot 10^{-7}T^2 + 0.062642C_{Ni})C_{Ni} \quad (8-1)$$

(ferrite)

$$\rho_a = 7875.96 - 0.297T - 5.62 \cdot 10^{-5}T^2 - 206.35 + 0.00778T + 1.472 \cdot 10^{-6}T^2 C_c - 36.86C_{Si} - 7.24C_{Mn} + 30.78C_{Mo} + (-8.58 + 1.229 \cdot 10^{-3}T + 0.852 \cdot 10^{-7}T^2 + 0.018376C_{Cr})C_{Cr} + (-0.22 - 0.470 \cdot 10^{-3}T - 1.855 \cdot 10^{-7}T^2 + 0.104608C_{Ni})C_{Ni} \quad (8-2)$$

(cementite)

$$\rho_c = 7686.45 - 0.0663T - 3.12 \cdot 10^{-4}T^2 \quad (8-3)$$

The coefficient of linear expansion can be obtained from changes in density using Eq. (9). There is no need to measure the relationship between temperature and elongation using the Formaster tester. This method was used because the density found in Eq. (8) could be inserted in Eq. (9) to take into account the influence of chemical constituents in the steel sheet.

$$\alpha(T) = \frac{1}{T - T_R} \left[3 \sqrt[3]{\frac{\rho(T_R)}{\rho(T)}} - 1 \right] \quad (9)$$

($\alpha(T)$, coefficient of linear expansion; T , arbitrary temperature; T_R , room temperature; $\rho(T)$, density at arbitrary temperature T ; $\rho(T_R)$, density at room temperature)

3.3. Influence of Coating Layer

Coating steel is used to confer protection against corrosion in automobiles, so it is necessary to include the effect of weldment coating in this simulation method.

Generally, a higher welding current is necessary for a coated steel than in an uncoated one to obtain any desired nugget diameter. This is mainly attributed to the fact that melting of coating occurs before melting of base metal due to the melting point of coating being lower than that of the steel. This enlarges the area turning on the electrical current, so Joule heating is spread over a greater volume of material, reducing the temperature gain. The simulation was programmed to reflect the expansion in the diameter of the area turning on the electrical current. As shown in Fig. 9, the simulation accurately reproduced the actual measured values in

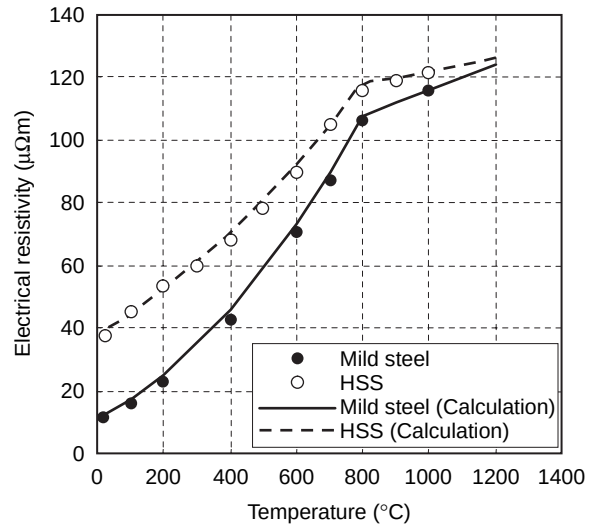


Fig. 7-2 Comparison of electrical resistivity between measurements and predictions using our modified equations

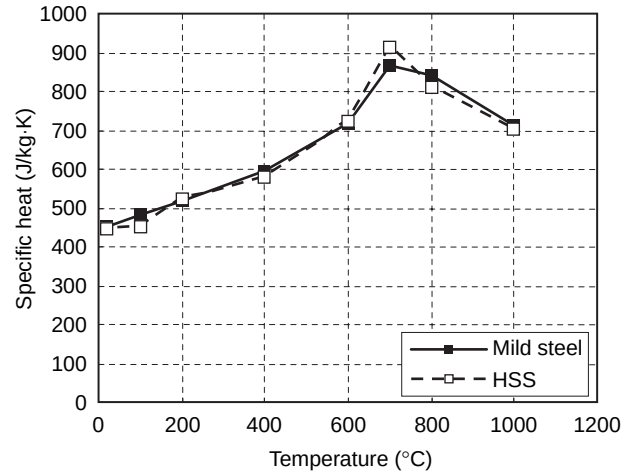


Fig. 8 Relationship between temperature and actual specific heat

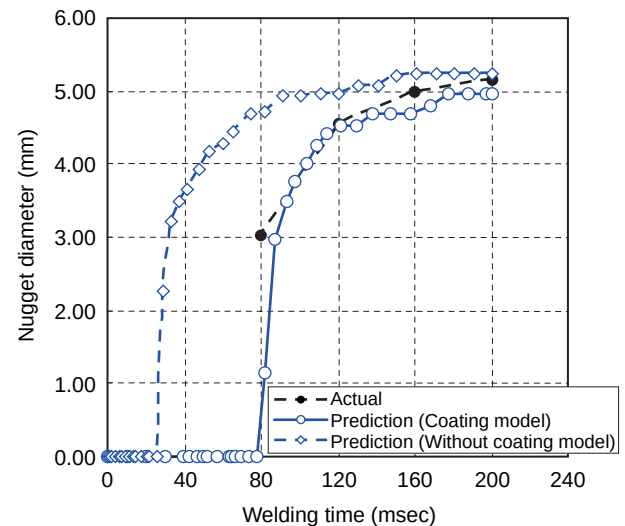
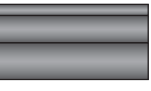


Fig. 9 Verification result of coating model

Table 1 Material properties of two-sheet combination

Sheet combination	Material	t mm	Mechanical properties		
			YP MPa	TS MPa	EI MPa
	HSS	1.6	432	811	27
	HSS	1.6	432	811	27

Table 2 Material properties of three-sheet combination

Sheet combination	Material	t mm	Mechanical properties		
			YP MPa	TS MPa	EI MPa
	Mild steel	0.7	138	305	49
	HSS	1.6	463	832	26
	HSS	2.0	568	631	18

the initial stage of nugget diameter. Sheet combinations of coated steel can be analyzed as well as those of uncoated steel with this model.

4. Development of Software

In order to execute this simulation, the user must create the model, set the boundary conditions and enter material properties and welding conditions for the arbitrary weldment sheet combination and electrode shape. Academic and practical expertise in FEM analysis, metallurgy and other areas is necessary to directly create the entry file for analysis in a commercial nonlinear FEM code, so a user-friendly interface was developed to ease use of this software.

It has been simplified so that anyone can use it; users need no special expertise to input weldment information, such as steel type and sheet thickness, or welding conditions such as pressure, welding time and welding current, to carry out an analysis. This software will be extremely effective in speeding up the process of analyzing weldments.

5. Verifying Simulation Accuracy

This software was used to simulate two assemblies, one of two sheets with the same thickness (Table 1), and the other of three sheets of differing thickness (Table 2). The accuracy of the simulations was examined and the results are provided in Figs. 10, 11-1 and 11-2. Both cases showed good correlation between the calculated values and the measured values. The nugget diameter was predicted with good accuracy.

The above results indicate that this simulation method accurately predicts nugget diameters in automotive sheet combinations in the initial stage. It also satisfies the objective of accuracy within $\pm 5\%$.

6. Effectiveness in Application

Two of the benefits expected in applying this simulation method in vehicle body development are the ability to do early investigations of welded sheet combinations and to speed the determination of welding conditions. At present, specifications and welding conditions are determined on an experimental basis using tensile tests and sectional macro inspections, which require a lot of time. This simulation allows the numerical calculation of

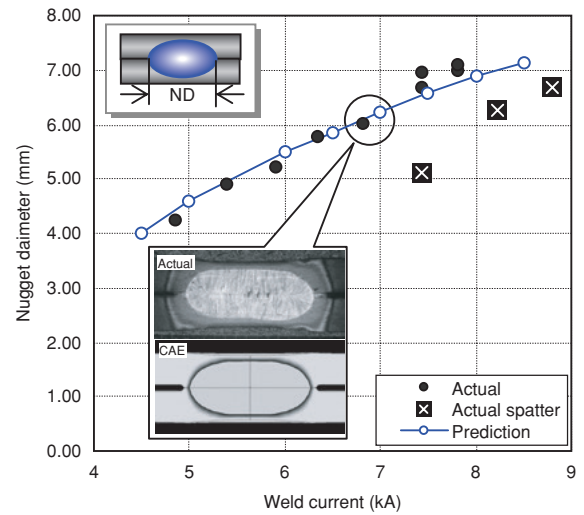


Fig. 10 Comparison of actual nugget diameter and predicted nugget diameter (two-sheet combination)

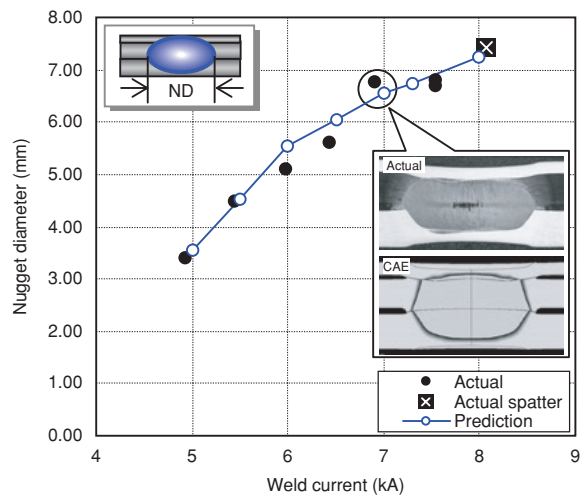


Fig. 11-1 Relationship between welding current and nugget diameter in actual sheet combination

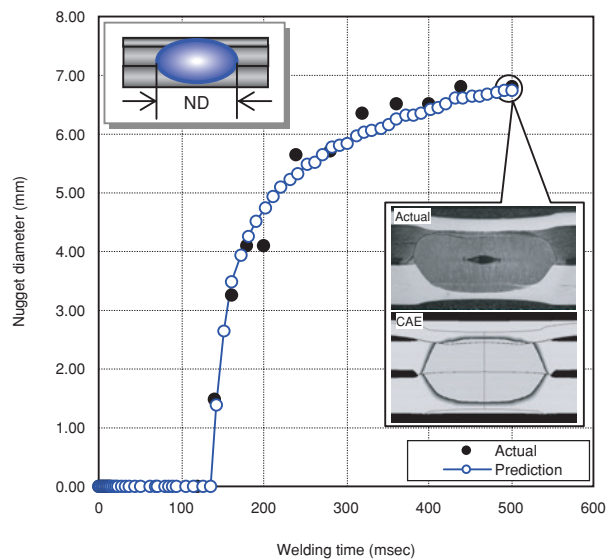


Fig. 11-2 Relationship between welding time and nugget diameter in actual sheet combination

weldability of automotive welded sheet combinations on the PC and early investigation of specifications. It may also allow for eliminating measurements of nugget diameters during sectional inspections, which would result in up to a 45% reduction in time.

7. Conclusion

A technology for simulating resistance spot welding using incrementally coupled analysis of electrical, thermal and mechanical fields has been developed to predict resistance spot welding conditions for automotive welded sheet combinations.

- (1) The required material properties for incrementally coupled analysis of electrical, thermal and mechanical fields were selected. A model equation capable of predicting the material properties based on chemical components and mechanical characteristics was constructed.
- (2) The simulation model was able to simulate the influence of galvanneal coating.
- (3) Software was developed allowing easy data input of arbitrary steel sheet weldments and welding conditions. No specialized expertise is necessary to quickly obtain analytical results.
- (4) The simulation model met the accuracy goal for predicting nugget generation processes in automotive weldments.
- (5) As a result of using this simulation, it is possible to investigate weldment specifications on the PC, and a total time savings of about 45% is anticipated for setting welding conditions.

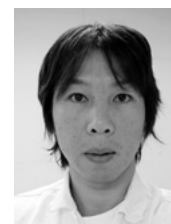
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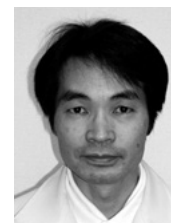
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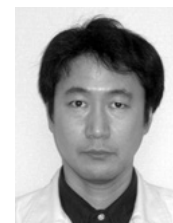
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