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A Nondestructive Evaluation Method: Measuring the Fixed Strength of Spot-Welded Joint Points by Surface Electrical Resistivity

Destructive tests are generally applied to evaluate the fixed strength of spot-welding nuggets of zinc-plated steel (which is a widely used primary structural material for automobiles). These destructive tests, however, are expensive and time-consuming. This paper proposes a nondestructive method for evaluating the fixed strength of the welded joints using surface electrical resistance. A direct current nugget-tester and probes have been developed by the authors for this purpose. The proposed nondestructive method uses the relative decrease in surface electrical resistance, α . The proposed method also considers the effect of the corona bond. The nugget diameter is estimated by two factors: R_{Quota} , which is calculated from variation of resistance, and a constant that represents the area of the corona bond. Since the maximum tensile strength is correlated with the nugget diameter, it can be inferred from the estimated nugget diameter. When appropriate measuring conditions for the surface electrical resistance are chosen, the proposed method can effectively evaluate the fixed strength of the spot-welded joints even if the steel sheet is zinc-plated. [DOI: 10.1115/1.4007957]

Introduction

Spot-welding is one type of electrical resistance welding. Joule heating dissolves the work pieces at the applied spot. Since spot-welding is suitable for joining thin sheet metal, it is widely employed for manufacture of automobiles and appliances.

Two methods are widely used to evaluate the fixed strength of spot-welded joints: the tensile shear test and the peel test [1,2]. Owing to their destructive nature, these tests are expensive and time-consuming. Therefore, more convenient and less expensive alternatives are required, which would allow manufacturers to inspect all products and therefore reduce the uncertainty regarding product quality.

A nondestructive test is clearly one alternative. So far, a few studies have been presented on nondestructive tests [3–6]; those tests include the four-point probe method and several ultrasonic methods [7,8]. These methods, however, are not widely used. The testing methods may not be accurate enough for the manufacturers' requirements. Besides, they may not be practical for application in a production environment.

The present authors have proposed a nondestructive method in a previous paper [9,10]. To evaluate the fixed strength of spot-welded joints, the nondestructive method uses the direct current

difference in surface electrical resistance between a welded joint part and another nonwelded part, which is due to the difference in plate thickness between the welded joint part and the other nonwelded part. Specifically, the relative decrease in surface electrical resistance, α , is measured while considering the influence of a corona bond. Nugget diameter is estimated using R_{Quota} , which is calculated from variation of resistance and a constant representing the area of the corona bond. A nugget-tester and probes have been developed by the authors for this purpose.

The effectiveness of our method was confirmed by using uncoated sheet metal in our previous paper. In this present paper, we apply our method to spot-welds of zinc-plated steel sheet, and evaluate its effectiveness. When appropriate measuring conditions for the surface electrical resistance are selected, the test results indicate that the proposed method can effectively determine the fixed strength of the spot-welded joints even if the steel sheet is zinc-plated.

Measuring Surface Electrical Resistance Using the Four-Point Probe

By the four-point probe direct current difference method shown in Fig. 1, volume resistivity ρ is expressed as a function of plate thickness t , surface resistivity ρ_s , measured voltage V , and current I

$$\rho = \rho_s t = \frac{V}{I} t \frac{\pi}{\ln 2} f\left(\frac{t}{s}\right) \quad (1)$$

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Fig. 1 Surface electrical resistivity measurements using four-point probe method

where s is the electrode spacing; and $f(t/s)$ is the shape correction coefficient. When $s \gg t$, $f(t/s)$ becomes 1. By manipulating Eq. (1) [10], the apparent electrical resistance $R = V/I$ is expressed as shown in Eq. (2). f' is the reciprocal of the shape correction coefficient $f(t/s)$. Surface resistance is inversely proportional to plate thickness t . The ratio of thickness t and electrode spacing s also affects the surface resistance via the shape correction coefficient

$$R = \frac{V}{I} = \frac{\rho \ln 2}{t \pi} f' \left(\frac{t}{s} \right) = \frac{k}{t} f' \left(\frac{t}{s} \right) \quad (2)$$

As shown in Fig. 2, the thickness of the welded joint becomes

$$t_3 = t_1 + t_2$$

when two plates with thicknesses t_1 and t_2 are welded. R_1 is the surface resistance of the t_1 thickness plate, and R_2 is defined as the resistance of the welded joint. The relative decrease in resistance, α , is expressed as a function of plate thickness [11]

$$\alpha = \frac{R_1 - R_2}{R_1} = \left(\frac{f'_1}{t_1} - \frac{f'_2}{t_3} \right) / \frac{f'_1}{t_1} = 1 - \frac{t_1 f'_2}{t_3 f'_1} \quad (3)$$

The fixed strength of a spot-welded joint is proportional to nugget area and plate thickness. In general, an appropriate nugget diameter [12,13] for a particular plate thickness, t , is obtained from the equation

$$D = (\sim 4 - 6) \sqrt{t} \quad (4)$$

The Proposed Method and Its Mechanism. The proposed method nondestructively estimates nugget diameter from the distribution of surface resistance measured with the four-point probe.

Fig. 2 Relationship between the surface electrical resistivity and specimen thickness

Then, the maximum tensile strength of the welded joint is inferred from the estimated nugget diameter. As shown in Fig. 2, resistance is inversely related to plate thickness. Thus, the $t_3 = t_1 + t_2$ thickness welded joint shows lower resistance than the t_1 thickness nonwelded sheet. The surface resistance on an arbitrary straight line through the center of a welded joint is measured at 0.5 mm intervals to obtain the distribution of the resistance. The drop in resistance indicates the existence of the welded joint; the minimum resistance is at the center of the nugget.

The accuracy of the proposed method depends upon both plate thickness, t , and probe spacing, s , because measured resistance depends on these factors. Plate thickness is a fundamentally important factor. Since plate resistance decreases at a decreasing rate as plate thickness increases, it is very difficult to differentiate the surface resistance of thicker plates. This may be a limitation of the proposed method, and so we have also considered the range of conditions over which the proposed method is effective.

Searching for Optimal Conditions: Plate Thickness and Probe Spacing.

To clarify the effect of plate thickness, the surface electrical resistance was measured for seven cold-rolled steel sheet (SPCC) specimens of different thickness. Similarly, the distance between the inner voltage probes was altered during the experiment to clarify the influence of probe spacing. The distance between the inner voltage probes is changed from 1 mm to 7 mm in 1-mm intervals, while the distance between the outer and the inner probes (s_1 and s_2) remains at 1 mm. The area within 5 mm of the edge of the specimen is not included in the measurement because measurement error is more likely to occur in that area (limited electric current path at the edge of the specimen may cause higher electrical resistance).

Figure 3 shows the results. Surface electrical resistance decreases as the plate thickness increases. The tendency is true for all tested thicknesses from 0.5 mm to 3.2 mm. Using 1 mm thickness plate, the α values measured for different probe spacings, s_2 , are as follows: 63% decrease for $s_2 = 1$ mm; 67% decrease for 2 mm; 70% decrease for 3 mm; 72% for 4 mm; 73% for 5 mm; 74% decreases for 6 mm and 75% for 7 mm. For plate thicknesses over 2 mm, the surface resistance becomes almost constant, and is no longer influenced by probe spacing.

These results confirm that the wider probe spacing leads to greater difference in surface resistance. The problem with taking a wide probe spacing is that it causes loss of accuracy for measuring resistance in a small interval. A narrow voltage probe spacing gives an accurate measurement; however, the obtained resistance difference is low, and does not give enough variation to discriminate the spot-welding nuggets. Considering these test results, we have fixed the distance between s_1 and s_3 at 1 mm, and s_2 at 3 mm.

Test Specimens

Specimens for the experiment are made from zinc-plated sheet metal (Galvanized steel sheet: EZNCEN), because it is widely used in automobile bodies. The EZNCEN sheets are cut into small

Fig. 3 Influence of electrode distance s_2 and specimen thickness, t , on surface resistance, R

Table 1 Chemical compositions of base metals (wt. %)

Elements	C	Mn	P	S	S-Al
Steel					
EZNCEN	0.0013	0.11	0.14	0.05	0.30

rectangles of 125 × 40 mm. Specimens were prepared from plates of five different thicknesses, t : 0.65, 0.9, 1.2, 1.4, and 1.8 mm. To make the specimens, two plates with same plate thickness were overlapped by 40 mm and spot-welded. The appropriate nugget size for each specimen was selected based on Eq. (4). Table 1 lists chemical composition of the specimens. Table 2 shows the welding conditions. Figure 4 depicts the size and shape of the specimens.

A pneumatic single-point spot-welding machine, with single-phase AC 150 kVA current capacity, was employed for processing the test specimens. Welding conditions, such as welding current, weld time, and hold time, are set by the controller on the machine. A load tester (CAS C1-5010) with 20 kN capacity was used to apply the electrode force. To ensure consistent welding conditions, electrode force was constantly monitored and adjusted if necessary. The electrode was an R type (dome shaped) Cr-Cu with tip diameter 6 mm.

Appropriate Weld Force and Weld Time (Cycle) for the Specimens. Using the $t = 1.4$ mm specimens depicted on Fig. 4, tensile shear tests were conducted. Through the tests, the effect of weld force and weld time on the zinc-plated sheet metal was considered. The test conditions were as follow. The tensile speed was 0.5 mm/min constant. Distance between the chucks was 100 mm. Room temperature was 24 °C.

Figure 5 shows the relationships between tensile shear strength and welding current obtained at several different weld forces and a constant welding time of 15 cycles. The tensile shear strength increases with increasing welding current, although no significant increase is observed for welding currents 9 kA and over. High welding current is likely to dissolve the zinc layer of the specimen and thus make the faying surface wider. This leads to a reduction in current density at the welding spot, which reduces the relative contribution of the higher welding currents. Figure 5 also shows that the tensile shear strength is increased by increasing the weld force from 2 kN to 2.5 kN. However, the tensile shear strength decreases when the weld force is increased from 2.5 kN to 3 kN.

Similar to the previous experiment, Fig. 6 shows the relationships between tensile shear strength and welding current obtained for various welding times while keeping the weld force constant at 2.5 kN. It indicates that tensile shear strength increases with increasing welding current. This is true until the weld time reaches 15 cycles; however, a significant increase is not observed at 20 or more cycles.

Appropriate Welding Current for the Specimens. To clarify the influence of the welding current on the fixed strength of welded joints, EZNCEN sheets were welded using five different currents: 6, 7, 8, 9, and 11 kA. Tensile shear tests were conducted to determine the effect of the welding current on the welded joint. The test conditions were same as the ones for weld force and weld time.

The relationships between the specimen elongation (in mm) and the loading force are presented in Fig. 7. Here, the plate thick-

Fig. 4 Specimen size and geometry **Fig. 5 Effect of welding current on tensile shear strength for different welding force (welding time 15 cycle, $t = 1.4$ mm)**

ness of the specimen is 0.9 mm. Figure 7 indicates clearly that the maximum tensile shear strength (F_{max}) increases as the welding current increases.

From these results, appropriate welding conditions for the zinc-plated sheet metal, EZNCEN, are 9 kA welding current, 2–2.5 kN weld force, and 10–15 cycles weld time. For our experiments, welding conditions were chosen as: 6–13 kA welding current, 2–3 kN weld force and 10–20 cycles weld time.

Nugget Testing Method

The fixed strength of spot-welds was measured via the tensile shear test and used to evaluate the effects of different welding conditions. The capacity of the monoaxial tensile tester was up to 20 kN, and tensile speed was 0.5 mm/min. The authors developed the direct current nugget tester (Fig. 8) and probes to measure the surface electrical resistance. The nugget tester is connected to the linear symmetric probes. The distance between the electric current electrodes is 5 mm. Similarly, the distance between voltage electrodes is 3 mm. The probes are set to touch the specimen surface at constant pressure (0.3 N) using springs mounted inside. The probe is made of SK steel with 6 mm diameter tips. The tips are tetrahedral, and covered with rhodium plating. To monitor the electrical resistance, R , 1 ampere current is applied for 0.5 s, and the voltage at that moment is measured. The repeatability of the nugget tester is $\pm 1.0 \mu\Omega$.

Table 2 Welding conditions used in this study

Condition	Welding current (kA)	Electrode force (kN)	Squeeze time (cycle)	Welding time (cycle)	Holding time (cycle)
Steel					
EZNCEN	6–13	2–3	30	10–20	10

Fig. 6 Effect of welding current on tensile shear strength for different welding times (electrode force 2.5 kN, $t = 1.4$ mm)

Fig. 7 Relationship between the shear strength and elongation ($t = 0.9$ mm)

Experimental Results and Discussion

Effects of Zinc Plating and Plate Gauge on Surface Electrical Resistance. Setting the probe spacings as $s_1 = s_3 = 1$ mm and $s_2 = 3$ mm, the distribution of surface electric resistance was obtained by measuring the resistance at 0.5 mm intervals along an arbitrary straight line that goes through the center of the welded joint. The welded current was set as 8 kA for these cases. Figure 9 presents several examples of the surface current distribution. Here, the surface current distributions of plated and nonplated specimens are presented together to clarify the effect of zinc plating. The 40- μ m zinc plating layer was removed from the specimens to create the nonplated specimens. No significant

differences were seen in surface current resistance between the zinc-plated and the nonplated samples. In both cases, surface current resistance decreased as plate thickness decreased.

The maximum and minimum resistance values were collected from the distributions of all samples, and then those values were plotted against their plate thickness. Because the surface electrical resistance is the highest at the thinnest part and lowest at the thickest part, the maximum resistance, $R_{\max}$, is the value obtained from the part where no influence of welding is found, and the minimum resistance, $R_{\min}$, is the value obtained at the center of the nuggets.

Figure 10 depicts the results. Similar to the results from SPCC specimens, both the values of $R_{\max}$ and $R_{\min}$ present inversely proportional relationships to plate thickness. Plate thickness of the welded joint part is defined as " $t = t_3 = t_1 + t_2$." Detection sensitivity, which is defined as the likelihood of successfully detecting the nugget diameter, decreases as the welded joint thickness increases. Detection sensitivity of the thinner plates is higher because the variation in the electric surface current is greater. Surface electrical resistance of the zinc-plated samples is around 4% lower than that of the nonplated samples. This decrease in surface resistance can be explained by the thickness added by applying the zinc plating.

Effect of Nugget Size on the Tensile Shear Strength. The nuggets' size depends on the welding current and the specimen thickness. The nugget size gets larger as welding current gets higher. To confirm the relationship between nugget size and maximum tensile shear strength, the diameter of the nuggets " D " is measured after the tensile shear test, as shown in Fig. 11. The tensile shear strength value, $F_{\max}$, increases as the nugget diameter increases. They are almost proportional, and match the results from the previous study by Okuda [14]. The results can be approximated by the equation

$$F_{\max} = 2.03D - 5.14$$

Figure 12 shows specimens after the tensile shear tests. The results indicate that the nugget processed using a 6 kA electric current may be too small to give sufficient strength to the joint. Fracture occurred inside the nugget. As the nugget size gets larger, fracture is initiated from circumference of the nugget; this is known as plug type fracture.

Figure 13 is a typical cross section of a welded joint. The nugget and the corona bond formed around the nugget are observed. By investigating samples after testing, we found that the nugget and the corona bond each occupy almost 50% of the area of the welded joint. When we take the corona bond size into consideration, the effective nugget diameter, D_{eff} , is defined by the full

Fig. 8 Apparatus for measurement of nugget

Fig. 9 Example of the surface electrical resistance distribution in the normal welding condition

width at half maximum where $R = R_{\text{Quota}}$, as shown in Fig. 14. R_{Quota} is given by

$$R_{\text{Quota}} = 0.5(R_{\text{max}} - R_{\text{min}}) + R_{\text{min}} \quad (5)$$

Estimated Nugget Diameter and Its Relationship With Maximum Tensile Shear Strength. The distributions of the surface electrical resistance of the welded specimens were measured

with the direct current nugget tester. Based on the R_{Quota} values derived from Eq. (5), the effective nugget diameters, D_{eff} , were estimated from the distributions. Then the tensile shear strengths of the specimens were measured. After the test, the nugget diameter was measured, and compared with the estimated diameter.

Figure 15 depicts the estimated nugget diameter and its corresponding maximum tensile shear strength, F_{max} , obtained experimentally. Similarly, Fig. 15 depicts the measured nugget diameter

Fig. 10 Relationship between the thickness and surface electrical resistivity

Fig. 11 Relationship between the tensile shear force $F_{\max}$ and the measured nugget diameter D

and its corresponding maximum tensile shear strength, $F_{\max}$. For sheet gauges of $t = 0.65, 0.9$, or 1.2 mm, there is a proportional relationship between the estimated nugget diameter and the maximum tensile strength $F_{\max}$. Furthermore, the estimated nugget diameter for each specimen is almost identical to the measured one. As sheet thickness becomes greater than 1.4 mm, the estimated nugget diameter tends to be smaller than the measured diameter. There is no longer a correlation between the estimated nugget diameter and the maximum tensile shear strength. The measured diameter and $F_{\max}$ exhibit good correlation for the entire range of gauges tested.

The straight line on the graph (Fig. 15) represents the expected maximum tensile shear strength calculated from the estimated nugget diameter and the corresponding actual $F_{\max}$. Data from

Fig. 12 Example of specimen shape after shear tests ($t = 1.4$ mm)

Fig. 13 Cross section of nugget

Fig. 14 Surface electrical resistance distribution

sheet thicknesses over 1.4 mm are not included. The estimated $F_{\max}$ fits well with the experimental values.

The method is effective, although it is limited by the plate thickness. The maximum tensile shear strength $F_{\max}$ is derived from the effective diameter D_{eff} , which is calculated from R_{Quota} . R_{Quota} is obtained from the variation of surface resistance and the constant to account for the area of the corona bond. The developed nugget tester effectively measures the distribution of the surface electrical resistance and can be used to evaluate the fixed strength of spot-welded joints in thinner gauge plates. Although these experiments have tested joints between two plates of the same thickness, we have previously shown that the method is also effective for uncoated plates of somewhat different thicknesses (for example a weld between a 0.5 mm plate and a 2 mm plate) [9]. The method should also be applicable to welds between two zinc-plated sheets of different thickness.

Fig. 15 Relationship between the tensile shear force $F_{\max}$ and the estimated nugget diameter D_{eff}

Conclusions

To nondestructively estimate the fixed strength of spot-welded joints between metal sheets, the authors have developed a nugget tester. The method as well as the tester's effectiveness have been evaluated by testing zinc-plated specimens of various sheet thicknesses. We have found the following:

- (1) There is an almost proportional relationship between the maximum tensile shear strength $F_{\max}$ and the effective nugget diameter D_{eff} , which is estimated from R_{Quota} . R_{Quota} is calculated from the variation of surface resistance and a constant that accounts for the relative area of the corona bond.

- (2) The range of effectiveness of the proposed method has been determined. The proposed method estimates nugget size in spot-welded joints accurately when the sheet thickness is 1.4 mm or less.
- (3) Thus, we have confirmed the effectiveness of our direct current nugget tester.

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