Inspection and Visualization Method for the Internal Structure of Spot-Welded Three-Steel Sheet Using Eddy Current Testing

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Abstract— **Spot-welding is widely used to assemble parts, such as those of vehicle bodies. To control the quality, safety and productivity of industrial products, a quick and accurate method of inspecting spot-weld is required. In our previous research, we reported an analysis method of examining the strength of spot welded parts by eddy current test (ETC) using a wide range of frequencies from high to low. In this paper, we report a method of analyzing the internal structure of a spot-weld. Magnetic field change showed a good correlation with the destructive shear test to check joint strength. The depth profile of the welded part was obtained by changing the skin depth using a wide range of frequencies. As the magnetic field strength at each frequency was not constant, they were normalized to create the depth profile. The two-dimensional depth profile was obtained by line scanning, and the three-dimensional depth profile was obtained by surface scanning. The three-dimensional internal structure of the welded part, which is nugget-shaped, was constructed from the volume rendering of the three-dimensional map, and it correlated with the shape obtained by cross-sectional observation.**

Keywords-eddy current testing (ECT); non-destructive testing; spot-welds; skin depth

I. Introduction

Spot-welding is widely used to assemble parts, such as vehicle bodies, where thin metal sheets are joined by thousands of spot-welds. In general, the quality of the spot-welds is evaluated by destructive testing of a selected sample. The correlation between weld strength and nugget size has already been established. To confirm nugget size, observation of a cross section is effective [1] [2] [3]. However, destructive testing methods are not applied to all products, and are costly and time consuming. To ensure that all spot-welded products are high quality, a nondestructive testing method is desired. The eddy current test (ETC) of the magnetic method is a convenient, low-cost nondestructive test. However, its application is limited to surface inspection because its high frequency has shallow skin depth penetration [4] [5] [6]. Recently, our group reported two methods: an eddy current test (ECT) using a wide range of frequencies and a magnetic flux leakage test (MFL) using detection of the magnetic flux leakage from the surface of the sample when a low frequency magnetic flux was induced [7] [8]. In this paper, we report a method of analyzing welded parts by ETC using a wide range of frequencies. A spot-welded three-layer steel sheet, which is the same as that used in a real automobile body, was used as the test sample.

Section II describes structure of sample and experimental procedure. Section III describes the result and discussion. Finally, Section IV addresses the conclusion.

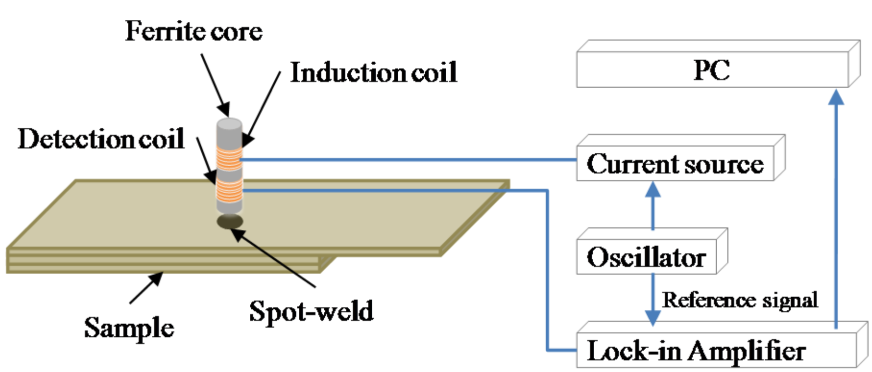

Figure 1. Measurement system for the internal structure of a spot-weld using eddy current testing

II. EXPERIMENTAL

As shown in Figure 1, the measurement system using ETC developed in this study consists of an oscillator, a current source for the induction coil, an induction coil and detection coil with ferrite core, a lock-in amplifier, X-Y stage, and a PC. These coils are composed of a ferrite core of 4.8 mm in diameter, a detection coil of 200 turns, and an induction coil of 50 turns. The pair of induction coil and detection coil with ferrite core is located near the sample surface. The induction coils are operated at 0.3 A (peak-to-peak) sine waveform generated from the current source with frequencies ranging from 100 Hz to 10 kHz.

The measurement method in this study is shown below. The sine waveform that is generated by the oscillator is applied to the current source. An AC current of 0.3 A (peak-to-peak) was applied to the induction coil generating a magnetic field. The secondary magnetic field that occurred on the surface of the sample was measured using the detection coil. Then, the signal was detected as the magnetic field intensity and phase component by a lock-in amplifier. To obtain the magnetic field distribution above the spot weld, the detection coil scans two-dimensionally. Scanning is performed by a XY stage.

The samples used in this study were three spot-welded steel plates of Strength Steel (SS) (40 mm × 200 mm × 0.7 mm), High Tensile Strength Steel (HTSS) (40 mm x 120 mm x 1.2 mm), and High Tensile Strength Steel (HTSS) (40 mm x 120 mm x 1.2 mm), as shown in Figure 2. Several samples with different spot-weld conditions were prepared by changing the number of cycles (5, 10, 15, 20) for the total weld time. One cycle time is the inverse of the commercial power source frequency. Samples were classified as good quality products when the weld time was long. However, samples were classified as defective products when the weld time was insufficient. To observe the weld nugget structure, samples were cut by a cutting machine, and the cross section of the spot-weld part was observed by an optical microscope.

III. RESULTS AND DISCUSSION

First, we measured the magnetic field at the centerline of the welded part. Scanning was performed at 1-mm intervals by moving the induction and detection coil with ferrite core. Figure 3 illustrates the relation between the total weld time and the magnetic field strength measured at 10 kHz. According to the increments of cycle time, which means the increment of welding time, the magnetic field strength change around the weld position increased. The magnetic field change was considered to be caused by the difference in the nugget size leading to different permeability.

Next, the depth profile was imaged by the line scanned magnetic field change measured at several frequencies. The induction coils are operated in the frequency range from 10 Hz to 10 kHz. The results are shown in Figure 4. The magnetic field intensity at each frequency is not equal as explained by Faraday's law; therefore, the values obtained at each frequency was normalized. The value of the color scale in Figure 4 shows the normalized value that was the ratio of the magnetic field strength at each point and that at the non-weld position which is the average at both ends of measured area (position of 0 and 9 mm). Although the Y-axis in Figure 4 is frequency, this indicate the depth information. This is because the skin depth δ is defined as follows.

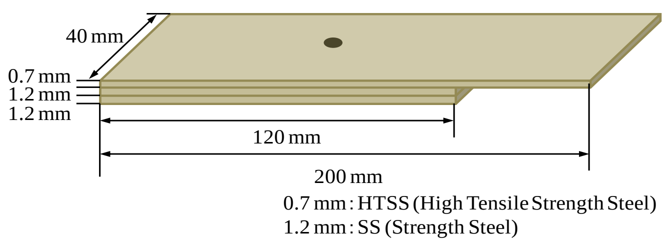

Figure 2. The test sample of spot-welded three-steel sheet.

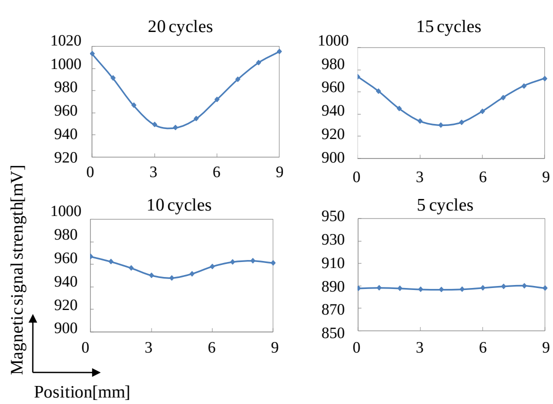

Figure 3. The relation between total weld time and the magnetic field strength measured at 10 kHz.

$$\delta = 1/\sqrt{\pi f \mu \sigma} \quad (1)$$

where μ is the permeability of the specimen and σ is the conductivity of the specimen. The δ is inversely proportional to the square root of the frequency *f*. This equation means that the magnetic field obtained by applying high frequency indicates the information near the surface and that obtained by applying low frequency indicates that information not only the surface but also inside in the specimen. The amount of change is low in the surface area which corresponds to the top of the image; the amount of change is large in the deep area which is at the bottom of the image. It indicates that a nugget with different permeability was generated inside the plates. In addition, as the cycle time and weld time decreased, the amount of change and size decreased. Therefore, the two dimensional mappings shown in Figure 4 represent the internal structure of spot weld.

To create a three-dimensional mapping of internal structure, we measured the magnetic field at the area of 10×10 mm around the weld in the frequency range from 10 Hz to 10 kHz. Surface scanning was performed at 1-mm intervals. To obtain volume rendering of the nugget, an arbitrary threshold of normalized value was set at 0.94 and this threshold was adopted for each two-dimensional image. The measured result of three-dimensional image is shown in Figure 5. The measurement positions are *x* and *y* axis and *z* axis shows the frequency. The three-dimensional depth profile denotes the shape of the welds and its size depended on the cycle time. Thus, this three-dimensional image reflects the shape change inside the spot weld caused by different cycle times and non-destructive evaluation of internal structure for spot weld is proposed.

IV. CONCLUSION

We developed an analysis and visualization method for the internal structure of a spot-weld by ECT. The depth profile of the welded part was obtained by usage of multiple frequencies. Furthermore, a three-dimensional nugget shape was constructed by volume rendering of the three-dimensional depth profile. The magnetically measured data is correlated with the optically observed structure.

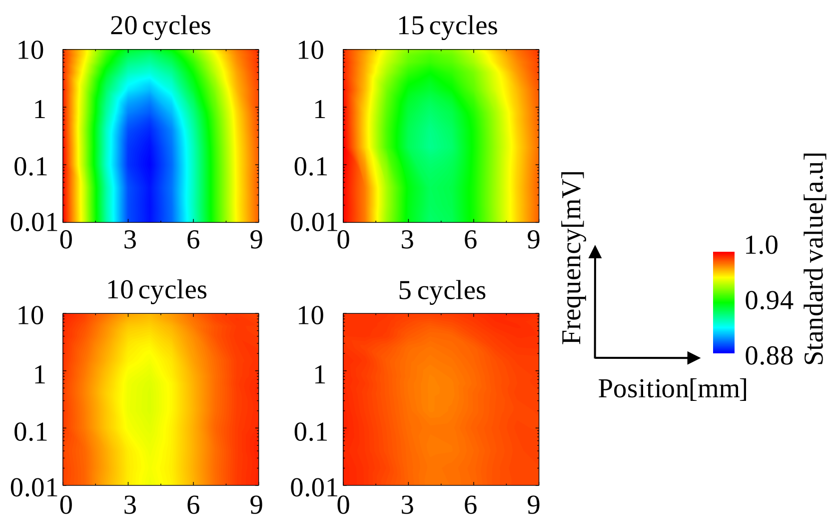

Figure 4. Mapping of the measured magnetic field strength at frequencies from 10 Hz to 10 kHz.

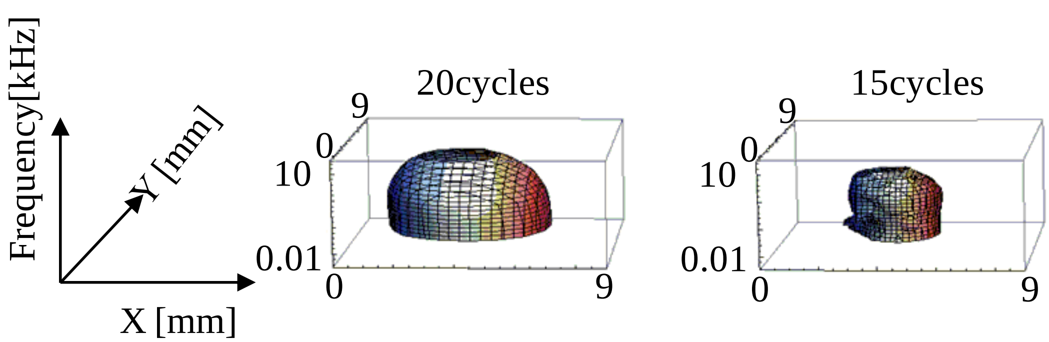

Figure 5. Volume rendered shape of the nugget inside the welded part.

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