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A magnetic flux leakage method using a magnetoresistive sensor for nondestructive evaluation of spot welds

Keiji Tsukada [a,*], Mitsuteru Yoshioka [a], Toshihiko Kiwa [a], Yoshinobu Hirano [b]

[a] Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Kitaku, Okayama 700-8530, Japan
[b] Ohashi Engineering Co. Ltd, 3-1-10 Omori-minami Ota-Ku, Tokyo 143-0013, Japan

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ABSTRACT

Spot welding is widely used for joining metal plates. However, a highly reliable monitoring method is needed to weld a robust structure. For this purpose, we developed a magnetic flux leakage (MFL) system using a magnetoresistive (MR) sensor for nondestructive spot-weld inspection. The magnetic flux is induced between two joined plates, and the magnetic flux leakage with a tangential component parallel to the plate surface is measured. A magnetic image at the spot-welding part is obtained by two-dimensional scanning. The connected diameter of the nugget and the maximum shear load are measured after the magnetic measurement to investigate their interrelationship. The results show that the nondestructive magnetic flux leakage test shows a good correlation with the destructive shear test.

1. Introduction

Spot welding is widely used in industry for joining metal plates. The overlapping metal plates are pressed together by two electrodes in opposite position, and an AC current is induced in the joint between the plates. In proportion to the resistance of the plate, the part in which the current flows is heated and locally melted. Finally, a nugget is produced at the faying part between the plates. The nugget formation affects the mechanical strength of the spot-welded part. Therefore, inspection of the welded part is very important to ensure the safety of the workpiece. A shear test is usually used to characterize the quality of spot welds. However, it is a destructive test, and so it is not applied to on-line monitoring. Even after a test sample is checked by the shear test, the strength of the spot weld of the actual structure under the same welding condition is not the same because of the current distribution, plate surface condition, etc. For example, while setting a second spot beneath a first-one, the current is not restricted to the second spot, one part of the current is also through the first spot. Therefore, the strength of the spot weld is changed by the distribution of the current. For this reason, a highly reliable on-line monitoring method is needed to ensure a robust structure. There have been many studies on nondestructive methods for spot welding, such as ultrasonic [1–4], radiographic [5], and infrared methods [6]. Although these methods are useful in industrial welding applications, they are costly and require human expertise. To efficiently inspect spot welds, a more convenient and low-cost method is desired.

Methods such as eddy current testing, or magnetic flux leakage testing (MFL), have a long history in nondestructive testing [7,8]. Recently, a magnetic method using a magnetic sensor instead of a search coil has been applied to not only surface flaws but also to deep flaws since it is a low-frequency operation with high performance and high sensitivity [9–15]. MFL, which is useful for ferromagnetic material structures, detects the magnetic flux leakage from the specimen surface when a magnetic flux is induced. By using a highly sensitive magnetic sensor, a low-magnetization operation that does not need a strong magnetic field to attain the saturation region of the *B*–*H* curve of a specimen can be realized [16]. In the past, however, MFL has only been applied to flaw detection. It is well known that the nugget part of the spot welds of ferromagnetic material changes into a martensite structure due to rapid cooling. This causes a permeability change of the material. In this study, we developed an MFL system using an magnetoresistive (MR) sensor to detect and show the magnetic change of the spot welds. We also investigate the relation between the magnetic measurement and the spot-weld strength.

2. Experimental

The MFL system developed in this study consists primarily of the following: sensor probe, lock-in amplifier, sensor circuits, current source for the induction coil, and a personal computer (Fig. 1). The sensor probe consists of a semicircular shaped yoke,

* Corresponding author. Tel./fax: +81 86 251 8129.
E-mail address: tsukada@cc.okayama-u.ac.jp (K. Tsukada).

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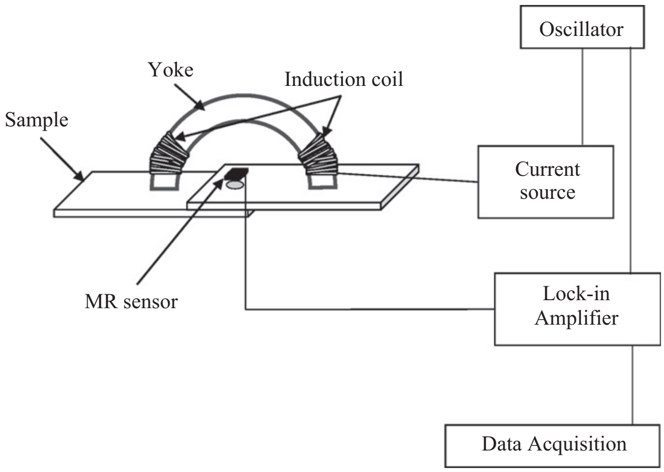

Fig. 1. Schematic diagram of the developed magnetic flux leakage testing system.

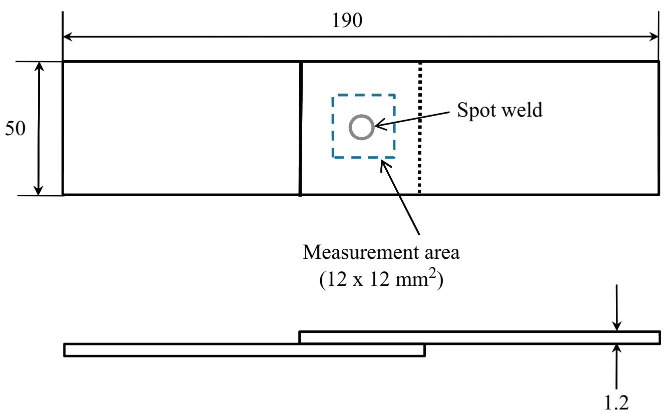

Fig. 2. Shape and dimensions of the welding spot specimen. Measurement area is 12 mm × 12 mm.

induction coils at both ends of the yoke, and an MR sensor. Two induction coils with 30 turns each are connected at both ends of the yoke, and an AC magnetic field is induced at each end of the two plates of the spot-welded sample. The MR sensor is installed at the center between the ends of the yoke, with a 5 mm lift-off from the sample surface. The MR sensor detects a magnetic field component parallel to both ends of the yoke. The induction coils are operated by a 0.5 A, 50 Hz sine waveform from the current source. The output voltage from the MR sensor is measured by a lock-in amplifier, which is synchronized with the frequency of the current source. To obtain the magnetic field distribution above the spot weld, the magnetic sensor probe scans two-dimensionally. Scanning is carried out in 2 mm steps. The sample, 190 mm in length and 50 mm in width, is joined to a SECC-NP (SECC: Electrogalvanized Steel Sheet, NP: Chromate Free Phosphate Process) plate 120 mm in length, 50 mm in width, and 1.2 mm in thickness by spot welding (Fig. 2). The composition of the SECC-NP plate is listed in Table 1. Samples with different spot-welding conditions are prepared by changing the number of cycles for the total weld time (4 cycles (80 ms), 8 cycles (160 ms), 16 cycles (320 ms), 20 cycles (400 ms)). Two samples are prepared under each condition for the magnetic measurement and the shear test. In addition, slightly different types of electrode tips for the upper electrode and lower electrode are used for welding (Fig. 3). The top of the upper electrode has a convex shape, and the top of the lower electrode has a flat shape. Therefore, the upper and lower sides of the spot welds show

Table 1
Chemical composition of the sample plate (SECC-NP) except Fe (mass %).

C	Si	Mn	P	S
0.04	0.01	0.18	0.013	0.012

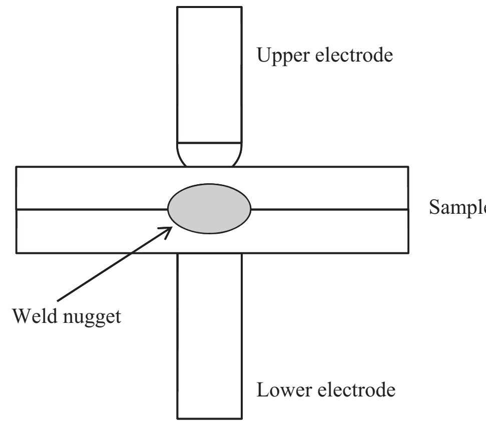

Fig. 3. Schematic diagram of the electrodes of the welding machine.

slightly different surface shapes. After the magnetic measurement, the shear load test is performed to measure the welding strength. To observe the weld nugget structure, other samples are prepared under the same conditions as those of the magnetically measured samples. The spot-welded samples for observation are cut by a cutting machine, and the cross section of the spot-welded part is observed by an optical microscope.

3. Results and discussion

The magnetic flux leakage was measured from the upper and lower sides of the welded part of the sample. An image of the magnetic field distribution is provided by the scanning measurement (Fig. 4). The contour maps of the upper side (Fig. 4(a)) and lower side (Fig. 4(b)) show different characteristics. The contour maps of the upper side are dependent on the welding condition. In contrast, the contour maps of the lower side show almost the same pattern and strength, even when the cycle time is changed. As the cycle time and weld time increase, the magnetic field strength increases in Fig. 4(a). This means that magnetic flux leakage gradually increases according to the increment of the cycle time. The nugget part has a martensite structure and consequently low permeability compared with the rest of the specimen. Therefore, the increment of the magnetic flux leakage indicates the growth of the nugget. The difference of the results of the upper and lower sides is presumed to be an effect of the electrode configuration. Because the top of the upper electrode has a convex shape and the top of the lower electrode has a flat shape, the current flow was not uniform and was more concentrated at the upper electrode side. Consequently, it was assumed to find a non-symmetric nugget shape. To investigate the change of the nugget shape in relation to the cycle time, cross-sectional macrographs were observed (Fig. 5). The 4-cycle sample shows only a non-symmetrical heat-affected region and no recrystallization region. This was due to poor heating. The heat-affected region was located near the upper surface, which resulted from the current concentration due to the shape of the upper electrode. In a comparison of the areas under both electrodes, the