J Nondestruct Eval (2013) 32:286–293
DOI 10.1007/s10921-013-0181-0

Magnetic Nondestructive Test for Resistance Spot Welds Using Magnetic Flux Penetration and Eddy Current Methods

Keiji Tsukada · Kousuke Miyake · Daichi Harada ·
Kenji Sakai · Toshihiko Kiwa

Received: 15 October 2012 / Accepted: 13 May 2013

Abstract Resistance spot welding technologies are widely used in industry. A highly reliable monitoring method is needed to effectively weld and create a robust structure. We developed a combined technique using magnetic flux penetration and an eddy current test (ECT). The magnetic measuring system consists of a pair of magnetic probes having an induction coil and detection coil, a lock-in amplifier, a current source, and a personal computer. The magnetic flux penetration through both surfaces at the weld was measured at low frequency. The ECT was performed at each surface with multiple frequencies. The magnetic flux penetration method showed good correlation with the destructive shear test because of the change in permeability due to the formation of the nugget. The ECT method reflected the depth profile of the nugget and was effective for determining a defective product.

Keywords Spot weld · Magnetic flux · Eddy current test

1 Introduction

Resistance spot welding (RSW) technologies are widely used in industry. For example, a few thousand spot welds joining thin metal sheets such as steel or aluminum, are applied to assemble an automobile body. High reliability in the strength of spot welds is required because these joints are subject to variable loads. RSW is based on the resistance of the welded sheet material to a current flow that causes heating. The faying surface between the sheets is called the nugget and is formed by a melting and solidifying process. Nugget structure is a dominant factor in joining strength [1–3]. Many RSW parameters are involved in making appropriate nugget structures such as electrode force, weld current, weld time, hold time, and electrode diameter. The weld time is an easily controllable parameter because it is the time during which welding current is applied. The weld time is expressed by the number of cycles of AC current; one cycle is 1/50 of a second when a 50 Hz power line is used. However, even if the weld time is optimized, the nugget structure is changed by factors such as the welding position of the sheet and surface condition. Therefore, monitoring is important in ensuring the reliability of spot welds. The peel test is the standard for checking the strength and internal structure of a spot weld. However, this testing method is not applied to all products; it is a sampling test. To ensure all manufactured products are of high quality, a nondestructive testing method is desired. There have been many studies on nondestructive testing methods for spot welding such as ultrasonic [1, 4, 5], and radiographic methods [6]. Compared with the ultrasonic and radiographic methods, the magnetic method does not provide good morphology information; however, it is a convenient and low-cost method. Generally, there are two ways to perform magnetic-based testing; an eddy current test (ECT), which uses high frequency electromagnetic induction in conductive materials [7], and a magnetic flux leakage test (MFL), which uses the magnetic flux leakage from the specimen surface when a low frequency magnetic flux is induced [8]. Recently, we reported a nondestructive spot weld inspection method using MFL with a magnetoresistive sensor [9]. The nugget of a ferromagnetic material changes into a martensite structure due to rapid cooling. This causes a change in the material's permeability. Using the magnetic property change,

---

K. Tsukada (✉) · K. Miyake · D. Harada · K. Sakai · T. Kiwa
Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Kitaku, Okayama 700-8530, Japan
e-mail: tsukada@cc.okayama-u.ac.jp

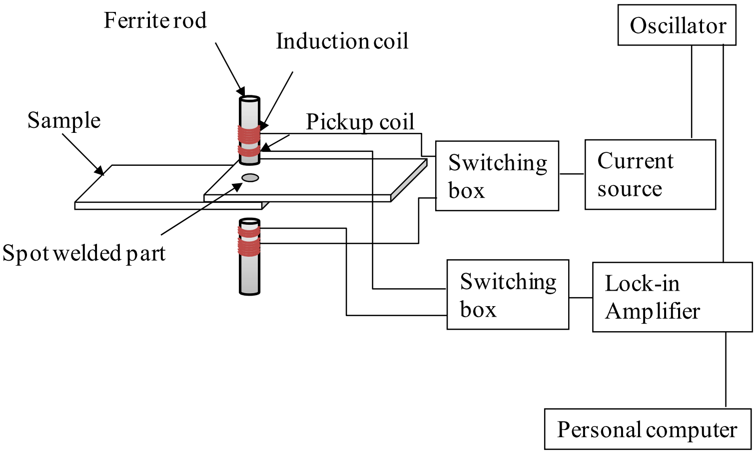

Fig. 1 Schematic diagram of the developed magnetic measuring system combining ECT and magnetic flux penetration methods

a magnetic flux is induced between joined plates, and the magnetic flux leakage, with a tangential component parallel to the plate surface, is measured. The nondestructive magnetic flux leakage test showed good correlation with the destructive shear test. However, it was limited to two dimensional analyses. Skin depth was defined by the frequency of the applied magnetic field, permeability, and conductivity of the material. In the case of good conductive material or good permeable material, skin depth is shallow. Therefore, the ECT, which has a long history, is suitable and widely used for detection of surface or sub-surface flaws of a metal. The ECT provides depth information when it uses different frequencies. To investigate the depth profile of flaws, an ECT method using multiple frequencies or pulsed magnetic fields has been developed [10, 11]. We also reported depth profile analysis of flaws using pulses combining many frequencies [12]. To investigate the inside of the material, magnetic flux through the material is considered to be as suitable as magnetic resistance in a magnetic circuit. Magnetic flux penetration through the material is affected by permeability; this means a percentage of the magnetic property change in depth is reflected by the magnetic flux through the joined plates.

Therefore, we combined two techniques for surface depth profile analysis using an ECT and the magnetic property change by nugget formation using magnetic flux penetration from one surface to the opposite surface. We then investigated the correlation between these magnetic analyses and the strength of the spot weld.

2 Experimental

The developed magnetic measurement system for the RSW test has two modes: the ECT and the magnetic flux penetration mode. The test consists of a pair of magnetic sensor probes, a lock-in amplifier, a current source with a function generator, and a personal computer (Fig. 1). The sensor probe consists of a ferrite rod that is 4.8 mm in diameter, a pickup coil with 200 turns, and an induction coil with 50 turns. The pickup coil detects a penetrated magnetic field through a specimen in the magnetic flux penetration mode, and a generated magnetic field by the eddy current in the ECT mode. The detected magnetic field was analyzed to the magnetic strength R and phase θ by the lock-in amplifier. The specimen is sandwiched by a pair of sensor probes, and scanning is performed in 2 mm steps. The induction coils are operated at 5 mA with frequencies ranging from 100 Hz to 10 kHz in the ECT mode. The penetration mode operates at 0.1 A from 10, 50, and 100 Hz. In the ECT mode, only one sensor probe operated on each specimen surface. The induction and pickup coils operated on the upper surface first and were then operated on the lower surface. In the magnetic flux penetration mode, the induction coil was operated on the upper surface and the penetrated magnetic flux was measured by the pickup coil on the lower side and vice versa. The sample, which was 190 mm long and 50 mm wide, was joined by spot welding (Fig. 2) to a SECC-NP (SECC: Electrogalvanized Steel Sheet, NP: Chromate Free Phosphate Process) plate 120 mm long, 50 mm wide, and 1.2 mm thick. Samples with different spot welding conditions were prepared by altering the number of cycles (total weld time = cycles × 20 ms). Shorter weld times decrease heat generation, resulting in poor spot weld strength. Alternatively, excessive weld times produce faulty welds due to the expulsion of molten metal from the weld joint. Therefore, the optimization of weld times is necessary. Two samples were prepared under each condition for magnetic measurement and the shear test. For RSW, marginally different types of electrode tips were used for the upper and lower electrodes (Fig. 3); however, both electrodes had a diameter of 7 mm. Therefore, the upper and lower sides of the spot welds showed slightly different surface shapes. After magnetic measurement, the shear load test was performed to measure the strength of the weld.

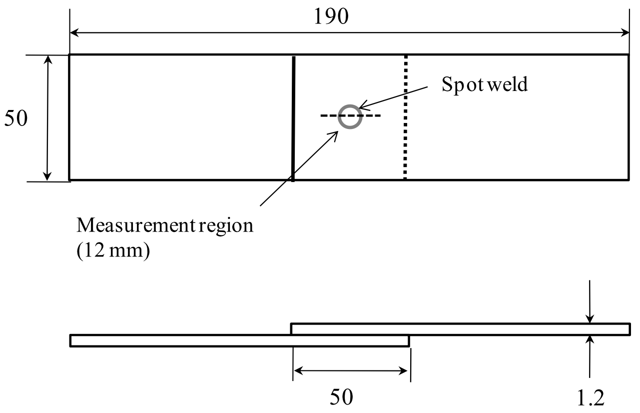

Fig. 2 Shape and dimensions of the spot welded specimen; scanning area is 12 mm with a 2 mm step

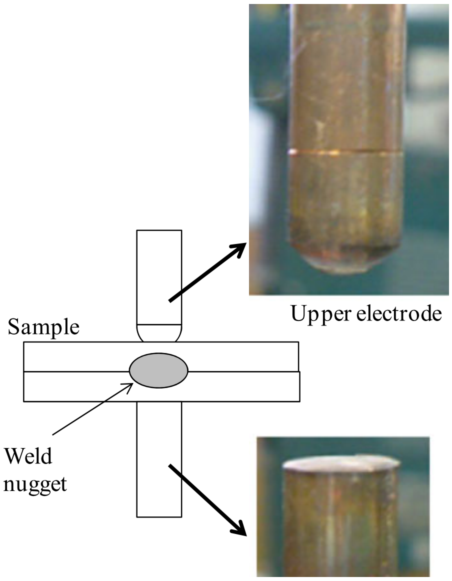

Fig. 3 Shapes of the upper and lower electrode

3 Results and Discussion

First, the magnetic flux penetration was measured from the welded section of the sample's upper surface. This meant that magnetic flux was induced by the upper surface induction coil and penetrated magnetic flux was measured by the lower surface pickup coil. The magnetic field distribution was provided by the scanning measurement. Figure 4 shows the magnetic field strength R curve of the samples at 10 Hz, and each curve displays a concave peak at the center of the weld. The curve decreased gradually as the number of cycles increased. It is thought that the magnetic property change is caused by nugget formation, and magnetic flux distribution becomes uniform with a wider nugget formation. To examine the change in the magnetic field strength of each curve, the peak value (ΔB) (Fig. 5) was extracted from each curve. The peak value was altered by the change in frequency; the relationship between the peak value in the magnetic field strength curve and the number of cycles at frequencies 10, 50, and 100 Hz are shown in Fig. 6. Peak values decreased as the number of cycles increased, as shown in Fig. 4. The correlation coefficients were −0.888, −0.896, and −0.897 at 10, 50, and 100 Hz, respectively. The relationship between the peak value in the magnetic field strength curve and cycle numbers, which were measured from the opposite direction, and the induction coil on the lower surface and the pickup coil on the upper surface were used (Fig. 7). The correlation coefficients are −0.930, −0.927, and −0.925 at 10, 50, and 100 Hz, respectively. For ideal measuring conditions, the penetration magnetic flux should be equal in both directions; however, there are some exceptions such as a difference in surface morphology and an asymmetric shape of the nugget. Absolute correlation coefficient value of 0.9 in the statistics obtained from both sides indicated a high correlative relationship between the magnetic strength change and the cycle time. Therefore, the magnetic flux penetration method is considered to be acceptable for evaluation of the spot weld.

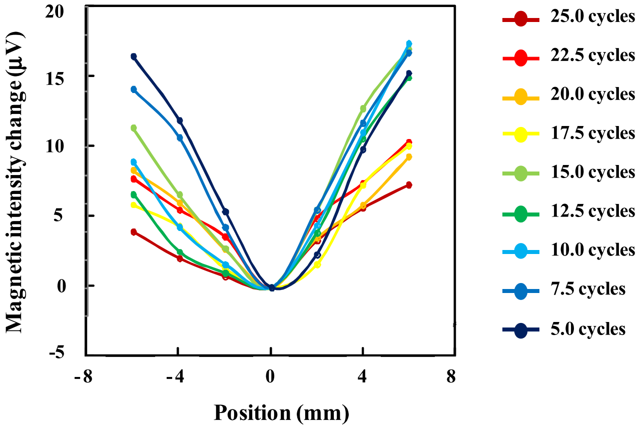

Fig. 4 Magnetic field curve at the weld using the magnetic flux penetration method at 10 Hz

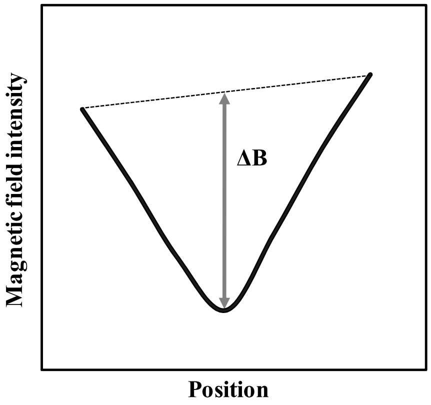

Fig. 5 Definition of the peak value (ΔB) of the magnetic field strength curve

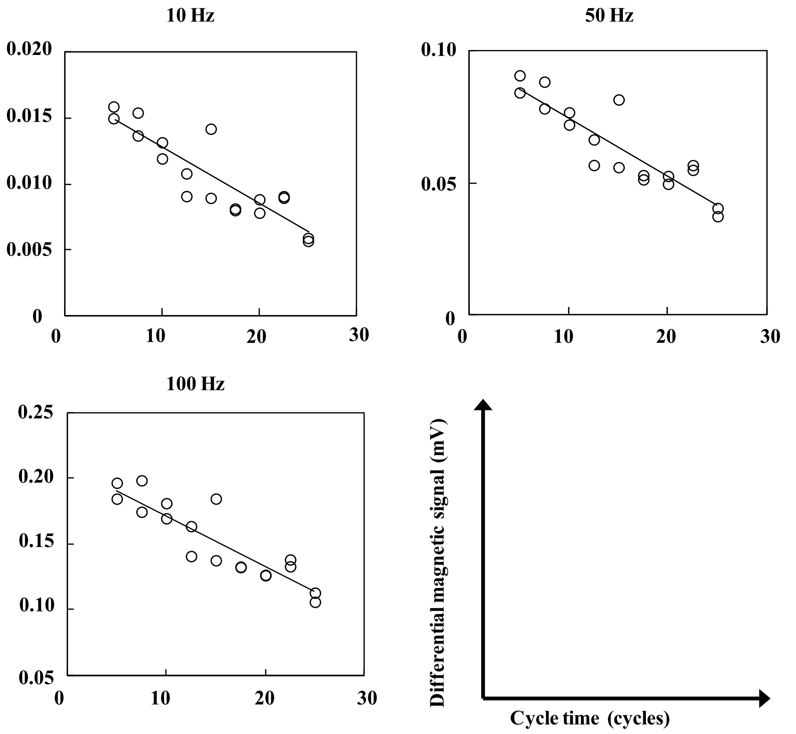

Fig. 6 Relationship between cycle time and peak value (ΔB) in the magnetic field strength curve measured from the upper surface at frequencies 10 Hz, 50 Hz, and 100 Hz

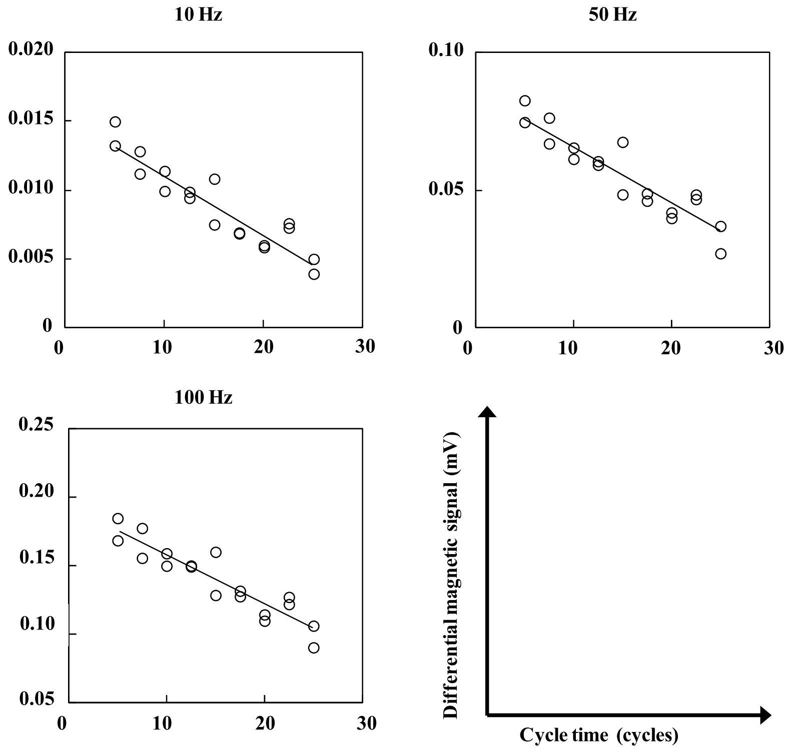

Fig. 7 Relationship between cycle time and peak value (ΔB) in the magnetic field strength curve measured from the lower surface at frequencies 10 Hz, 50 Hz, and 100 Hz

Next the correlation between shear strength and the magnetic field strength change was investigated (Figs. 8 and 9). Relative to an increase in the number of cycles, the diameter of the nugget formation increases due to increased heating power. Therefore, it is thought that a correlation between shear strength and the number of cycles exists. Figures 8 and 9 show a good correlation between shear strength and the change in magnetic field strength. The correlation coefficients were −0.953, −0.950, and −0.939 from the upper surface and −0.947, −0.942, and −0.922 from the lower

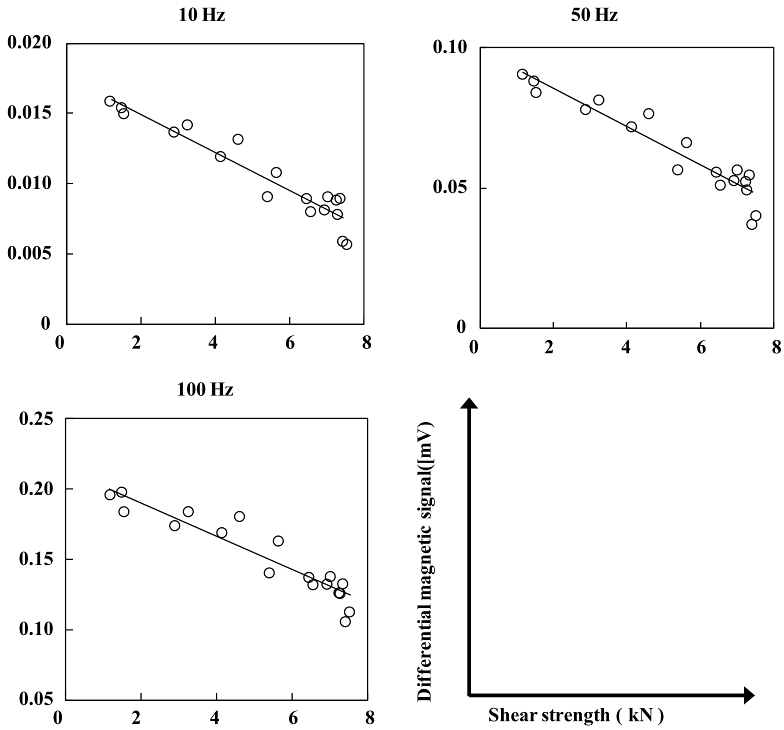

Fig. 8 Correlation between shear strength and peak value (ΔB) measured from the upper surface at frequencies 10 Hz, 50 Hz, and 100 Hz

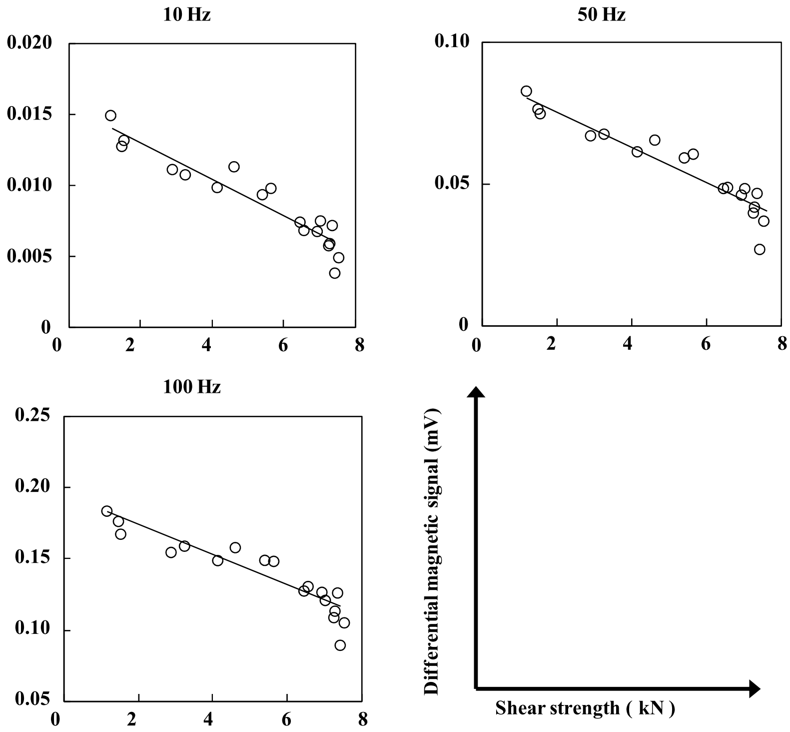

Fig. 9 Correlation between shear strength and peak value (ΔB) measured from the lower surface at frequencies 10 Hz, 50 Hz, and 100 Hz

surface, at 10, 50, and 100 Hz, respectively. The correlation coefficients from the upper surface were superior to those of the lower surface; however, there was no significant difference between either measurement direction.

We then investigated the spot welds using the ECT method. The magnetic field was induced by the induction coil, and the secondary magnetic field generated by the eddy current was detected by the pickup coil on the same surface; the measurement was performed on both surfaces. Scanning was performed at 2 mm intervals, which was the same as the conditions for the magnetic flux penetration measurement. Skin depth δ is expressed as

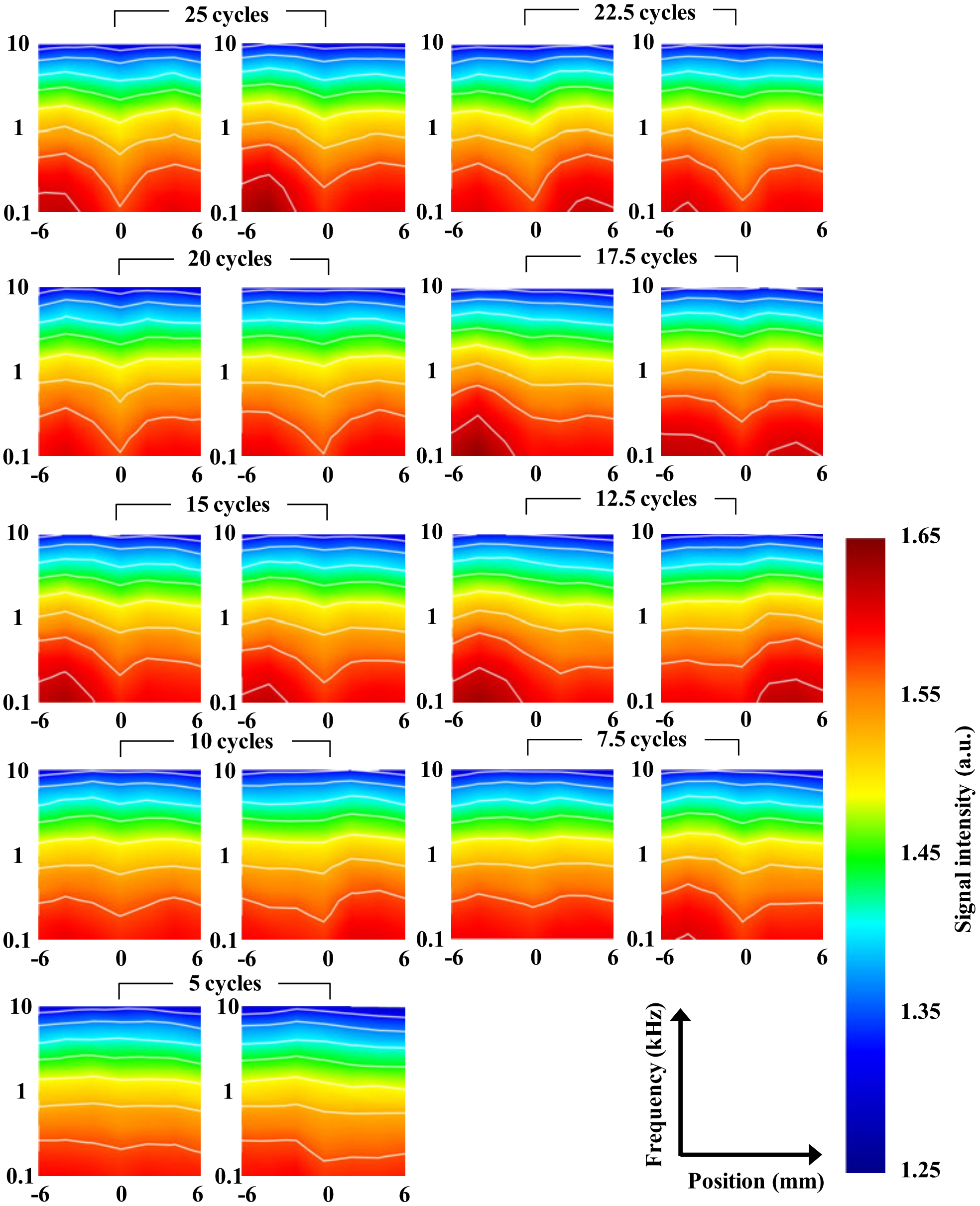

Fig. 10 Magnetic intensity map measured from the upper surface

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

where μ and σ are the permeability and conductivity of the sample, respectively. In the simplified condition with a flat surface, and magnetic and conductive parameters are uniform, the skin depth is inversely proportional to the square root of the induced frequency. Therefore, we can treat the frequency as the depth from the surface. Figures 10 and 11 show the relationship between frequency and magnetic field strength obtained by the ECT method, and can be treated as a depth profile. High frequency (y-axis) indicates a depth near the surface, and low frequency indicates a deeper depth within the sample. When the pickup coil was used for magnetic field detection, the sensitivity was increased by an increase in frequency. Therefore, magnetic field intensity in Figs. 10 and 11 were standardized by the magnetic field strength without reference to the sample. Figure 10 shows the measurement data from the upper surface, and Fig. 11 shows data from the lower surface. In addition, Fig. 10 shows, relative to an increase in the number of cycles, two peaks and strong magnetic field intensity at low frequencies. This was thought to be caused by nugget formation. After an adequate nugget was formed with a large number of cycles, the nugget has an expanded joint and uniform recrystallization area. The distance between the two peaks was approximately equal to the diameter of the welding electrode. Relative to a decrease in the number of cycles, the two peaks gradually disappeared, became asymmetrical, and finally became uniform with weak intensity. Figure 11, which

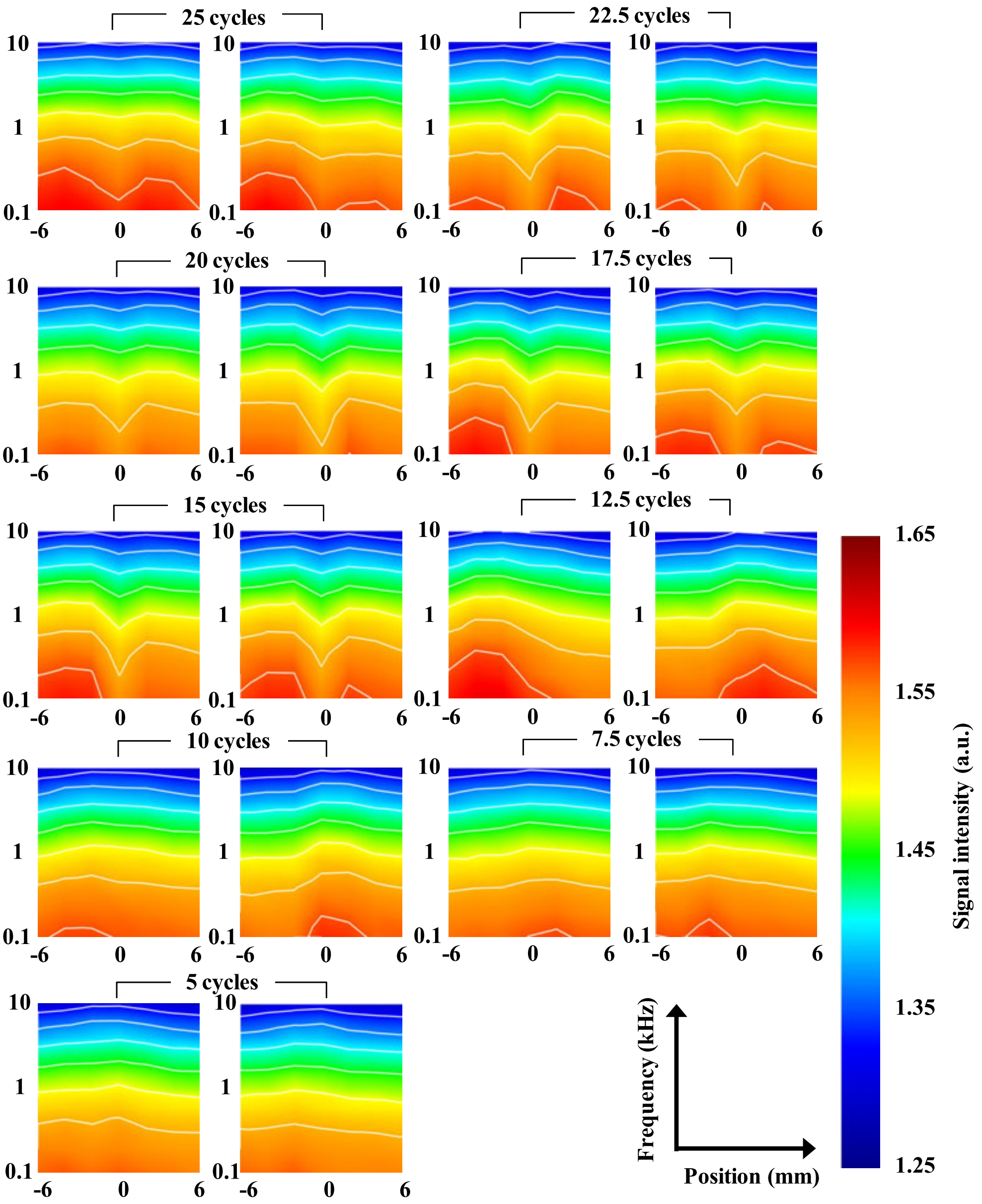

Fig. 11 Magnetic intensity map measured from the lower surface

shows measurements taken from the lower surface, shows properties similar to those shown in Fig. 10. Both figures show lower intensity and a single peak at a lower number of cycles. The difference between the results for the upper and lower surfaces is due to the difference in current distribution because of the configuration of the electrode tip. The top of the upper electrode is convex and the top of the lower electrode is flat; therefore, current flow was non uniform and concentrated at the upper electrode. The change in nugget shape was observed by cross-sectional microscopy (Fig. 12). The convex electrode tip produced concentrated current due to high pressure at the center point of the tip, and this extended the width of the melting area. On the other hand, the lower electrode's flat tip produced a more distributed current. Therefore, heating on the lower surface was less than that on the upper surface. This effect was evident at a lower number of cycles. The 7.5 cycle sample shows only an asymmetrical heat-affected region and a small recrystallization region, and the lower side has a convex downward single peak region. On the other hand, the 25.0 cycle sample shows a drum-like symmetrical shape and a clear recrystallization region surrounded by a heat-affected region. This symmetrical structure was caused by isotopic heat diffusion during melting and caused two peaks in the magnetic depth profiles, as shown in Figs. 10 and 11. As a result, the measured magnetic intensity maps show the nugget depth profiles. Therefore, the ECT measurement is considered effective for the evaluation of nugget formation.

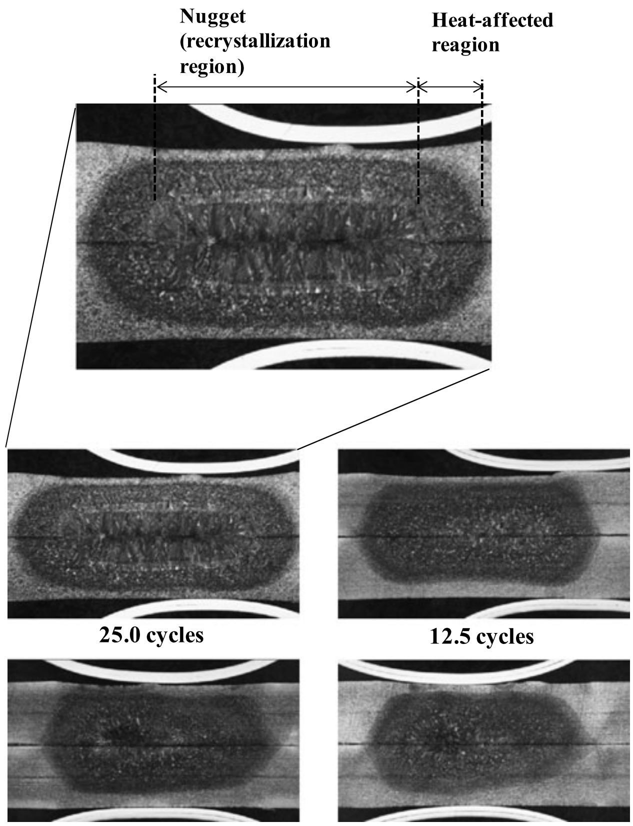

Fig. 12 Macrograph of cross-sectional spot welds exhibiting the dependence on cycle time

4 Conclusions

We developed a method for spot weld evaluation by combining multiple frequency magnetic flux penetration and the ECT method. The scanned magnetic flux change, particularly at low frequency, exhibited good correlation with shear strength testing. In addition, the change reflected the extent of change in the generated nugget's magnetic properties. Furthermore, the depth profile of the nugget was estimated by the characteristics of the scanned magnetic curve as measured by the ECT. Therefore, the combined technique is expected to be an easy and convenient method for on-line measuring and monitoring of spot welds.

References

1. Hall, E.T., Crecraft, D.I.: Bonded joints and non-destructive testing. Nondestruct. Test. **4**, 181–191 (1971)
2. Aslanlar, S.: The effect of nucleus size on mechanical properties in electrical resistance spot welding of sheets used in automotive industry. Mater. Des. **27**, 125–131 (2006)
3. Vural, M., Akkus, A., Eryurek, B.: Effect of welding nugget diameter on the fatigue strength of the resistance spot welded joints of different steel sheets. J. Mater. Process. Technol. **176**, 127–132 (2006)
4. Goglio, L., Rossetto, M.: Ultrasonic testing of adhesive bonds of thin metal sheets. Nondestruct. Test. Eval. Int. **32**, 323–331 (1999)
5. Blomme, E., Bulcaen, D., Declercq, F.: Recent observations with air-coupled NDE in the frequency range of 650 kHz to 1.2 MHz. Ultrasonics **40**, 153–157 (2002)
6. Liao, T.W., Li, Y.: An automated radiographic NDT system for weld inspection. Nondestruct. Test. Eval. Int. **31**, 183–192 (1998)
7. Auld, B.A., Moulder, J.C.: Review of advances in quantitative eddy current nondestructive evaluation. J. Nondestruct. Eval. **18**, 3–36 (1999)
8. Tsukada, K., Yoshioka, M., Kawasaki, Y., Kiwa, T.: Detection of back-side pit on a ferrous plate by magnetic flux leakage method with analyzing magnetic field vector. Nondestruct. Test. Eval. Int. **43**, 323–328 (2010)
9. Tsukada, K., Yoshioka, M., Kiwa, T., Hirano, Y.: A magnetic flux leakage method using a magnetoresistive sensor for nondestructive evaluation of spot welds. Nondestruct. Test. Eval. Int. **44**, 101–105 (2011)
10. Chady, T., Enokizono, M.: Multi-frequency exciting and spectrogram-based ECT method. J. Magn. Magn. Mater. **215–216**, 700–703 (2000)
11. Lebrun, B., Jayet, Y., Baboux, J.C.: Pulsed eddy current signal analysis: application to the experimental detection and characterization of deep flaws in highly conductive materials. Nondestruct. Test. Eval. Int. **30**, 163–170 (1997)
12. Kiwa, T., Kawata, T., Yamada, H., Tsukada, K.: Fourier-transformed eddy current technique to visualize cross-sections of conductive materials. Nondestruct. Test. Eval. Int. **40**, 363–367 (2007)