

Research on Automatic Inspection of Spot Welding Using Ultrasonic Testing Methods

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ABSTRACT

This paper discusses research on inspection procedures and techniques for the identification of spot welding indentations ("spot indentations" below). The goal was to increase the reliability of ultrasonic testing methods by focusing on the procedures that are used by experienced inspectors.

A mechanism that is able to apply a uniform pushing force while optimizing the inclination of the probe with respect to the area being inspected has been developed. With this new system, the center of the spot indentation can be identified even when its outline is difficult to determine.

The system was fitted onto an industrial robot ("robot" below), and tested on the inspection of automotive parts. The results indicated that the system achieved the same level of accuracy as that of an experienced inspector.

1. Introduction

High-strength steel sheets are increasingly being used to respond to requirements for automotive weight savings. Spot welding is the preferred technique for joining these sheets; furthermore, 4000 to 5000 spot welds are used in each vehicle. Tensile shear strength, an indicator of spot weld strength, is shown to increase proportionally with the tensile shear strength of the base, high strength steel material. Both destructive and non-destructive inspection can be used to ensure spot weld quality. At present, the random application of chisel tests is the most common. However, as tensile strength increases, destructive chisel tests are beginning to require significantly more effort.

The main non-destructive inspection methods are radiography, ultrasonic testing, magnetic particle inspection, die penetrant and magnetic induction. As Table 1 shows, ultrasonic testing is the most applicable of the non-destructive tests employed to detect welding defects in thin sheets utilized in automotive applications⁽¹⁾. The use of ultrasonic testing as a non-destructive inspection method is particularly prevalent in Europe⁽²⁾. In Japan, non-destructive inspection per this method has aroused intense interest as a result of its successful application at companies capitalized by or involved in technological cooperation with overseas manufacturers.

Table 1 Applicability of nondestructive test methods in 6 mm sheets

Object	Metal steel	Nonferrous metal
Main nondestructive test methods		
(a) Radiographic test	Not applicable	Not applicable
(b) Ultrasonic flaw detection	Applicable	Applicable
(c) Magnetic inspection	Conditionally applicable	Not applicable
(d) Penetration test	Not applicable	Not applicable
(e) Magnetic induction test	Not applicable	Conditionally applicable

Presently, preparations are being made for full-scale introduction and use of this method. Most automotive manufacturers in Japan use automated spot welding, performed by six-axis robots. However, at this time, spot welds are still manually inspected using ultrasonic testing methods⁽³⁾. The authors of this paper conducted research on automating the process, focusing on the procedures incorporated by experienced inspectors to increase reliability

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through the introduction of a quantitative inspection method that is not reliant on the labor or experience of a human operator.

2. Judgment of a Nugget Using Ultrasonic Testing Methods

This section discusses comparative judgment using ultrasonic waveforms (termed “echo” below)⁽⁴⁾. The rough crystalline grains in a nugget of the type shown in Fig. 1 (a), which form a good spot weld, cause a fixed level of echo attenuation. This is judged as an appropriate waveform, and the nugget is therefore determined to be of passing quality. Cross-sections of actual nuggets were taken to verify these results. Figure 1 (b) shows the echo for a nugget smaller than the diameter of the probe. Here, an intermediate echo appears between the echoes from the back wall. As shown in Fig. 1 (c), when the nugget is thin (i.e., the spot weld is not thick enough), the level of attenuation is lower and attenuation takes longer than in Fig. 1 (a). When there is absolutely no weld between the two sheets, the echo is reflected only from the bottom of the upper sheet, as shown in Fig. 1 (d). All of these echoes, other than the pattern shown in Fig. 1 (a), are judged to be inappropriate. Ultrasonic testing is, therefore, a method that makes judgments on the basis of comparisons with an ideal standard echo.

3. Issues in Achieving Automation

3.1. Applying the Probe

Applying the probe effectively when inspecting spot welds using ultrasonic testing methods is a difficult operation that requires experience on the part of the inspector. The research team, therefore, decided to use a robot to study the method used by an experienced inspector so they could determine the reasons for this skill requirement, and outline the issues involved in automation.

The six-axis robot shown in Fig. 2 was used in tests in which the probe was applied to the center of spot indentations with weld

samples being fixed. After testing the allowance for angle of inclination [Fig. 3 (a)] and the allowance for offset [Fig. 3 (b)], the possibility of the robot reproducing the positioning shown in Fig. 3 (c) was verified. Results are shown in Table 2. The robot displayed an excellent ability to reproduce the target positioning with respect to a spot indentation, indicating sufficient ability to detect conformity and non-conformity. However, while the nugget was parallel to the sheet surface of the sample used in these tests, as shown in Fig. 4 (a), under actual work conditions, the angle of the welding gun, the inclination of the sheets, and the contact angle of the welding electrodes can produce a nugget that is on an angle with the sheet surface, as shown in Fig. 4 (b). To inspect the nugget



Fig. 2 Six-axis robot

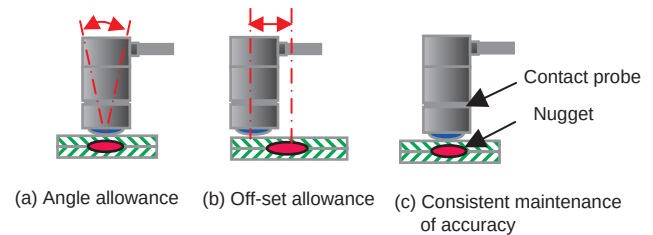


Fig. 3 Test of position and inclination

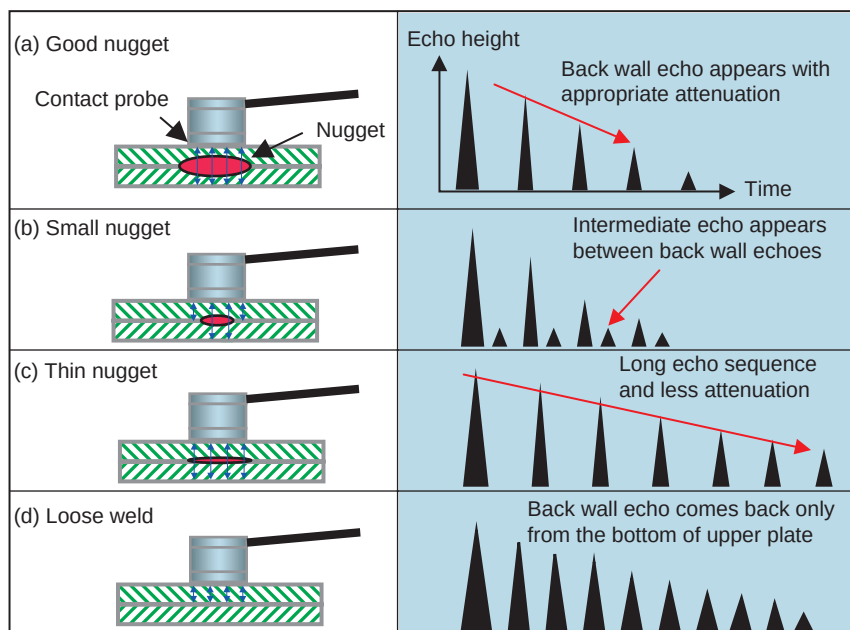


Fig. 1 Ultrasonic detection of spot welding

Table 2 Robot inspection test

Item	Result
(1) Angle allowance	$\pm 1^\circ$ below
(2) Off-set allowance	$\pm 1\text{mm}$
(3) Consistent maintenance of accuracy	Possible

under these conditions, the tip of the probe must be angled normally, relative to the nugget, as shown in Fig. 5. The levels of accuracy indicated in (1) and (2) in Table 2 are required. When the test described above was conducted on nuggets that were actually angled, no echoes were produced. In actual welding, the geometry of the sheets affects the formation sequences of the spot welds, and the nugget at each weld point might, therefore, have a minute inclination. An experienced inspector is able to alter the contact angle of the probe in response to the inclination of the sheets or the nugget, but the robot has difficulty in judging the inclination of the nugget between the steel sheets from the external appearance of the weld, and in adjusting the probe's orientation to allow contact with the nugget accordingly. This is a reason skill is required on the part of inspectors, and presents a significant issue in achieving automation.

3.2. Identification of Spot Indentations

Following the inspection method development discussed in the previous section, the following technology is required for automation of the inspection procedure; the spot indentation imaging and identification through binary image processing based on the morphology and color (hereafter called identification of spot indentations). Inspection becomes possible by identifying multiple spot indentations in sequence and positioning the probe at the center of each indentation. A method was tested using a CCD camera to image the spot indentation so that its center could be determined from its outline. In the case of normal steel, the color change produced by spot welding temperatures enabled the outline of the spot indentation to be clearly imaged, as shown in Fig. 6 (a), and its center could therefore be located immediately. However, as

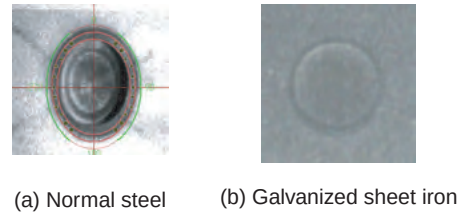


Fig. 6 Spot indentation image by CCD

Fig. 6 (b) shows, in the case of galvanized sheet iron, which is frequently used in automotive applications, the spot indentation could not be clearly imaged. This is assumed to be because the galvanized sheet iron does not change color, and the spot indentation is therefore not clearly visible, making it difficult to identify its outline. However, normal sheet steel and galvanized sheet iron are sometimes used together in automotive applications, and an inspection technology must therefore be able to identify spot indentations on both types of sheeting.

4. Experimental Verification

4.1. Study of Mechanism Response to Nugget Inclination

A mechanism was developed to enable the angle of probe inclination to be freely altered, allowing it to adopt arbitrary angles in relation to the surface of the spot indentation. This was done by applying a rocking motion in response to minute inclinations to the work surface, spot indentation and nugget. A standard robot could not reproduce the probe angles used by a human inspector, so an XY slider table and urethane rubber were, therefore, used at the end of the robot arm (Fig. 7). After the probe has made contact with the spot indentation, it inclines 3 deg. from perpendicular and describes a full circle, divided into 12 sections, around the indentation. A single spot indentation can be inspected in 6 seconds (Fig. 8).

Test pieces were prepared that would produce "good" echoes (echoes judged to be appropriate), and tests were conducted to study the mechanism response to the inclination of the work surface and the nugget. First, the test piece was fixed in place, and the inclination angle of the mechanism was freely altered in relation to it. Tests

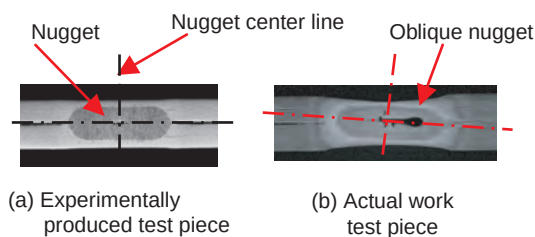


Fig. 4 Comparison of nugget test pieces

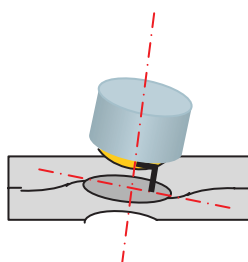


Fig. 5 Correct inclination of contact probe

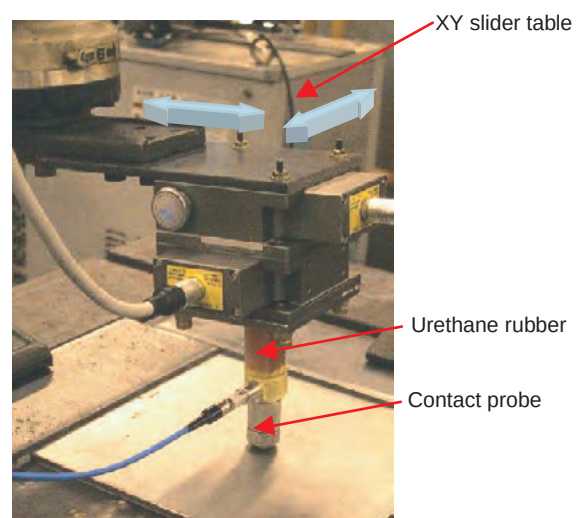


Fig. 7 Mechanism enabling response to change in nugget angle

were conducted to determine whether the developed probe-rocking motion enabled the nugget to be traced, and an appropriate echo could be produced. Results indicated that the desired echo was produced at an angle of inclination of 2 deg. (Fig. 9). The rocking mechanism was therefore judged to be able to respond to the angle of inclination of the work surface and the nugget. Next, to judge the performance of the mechanism in relation to the angle of inclination of the work surface, tests were conducted with the work inclined at angles of 45 and 90 deg. (Fig. 10). The same echo patterns were generated as when the probe was perpendicular to the work. These results indicated that automated inspection was possible even under conditions close to those found on actual production lines.

4.2. Identification of Spot Indentations on Normal Sheet Steel and Galvanized Sheet Iron

A technology was developed to identify spot indentations in both normal sheet steel and galvanized sheet iron. To enable CCD

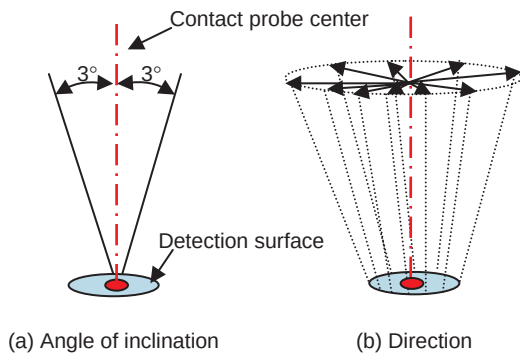


Fig. 8 Angle of inclination and direction

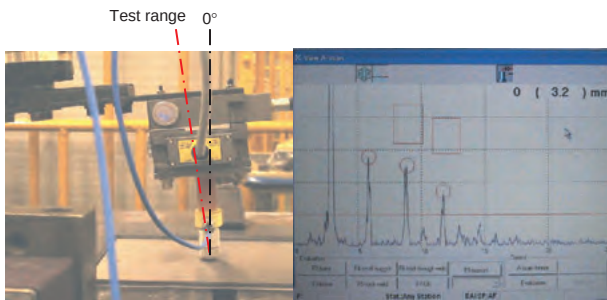


Fig. 9 Test : Change in nugget angle

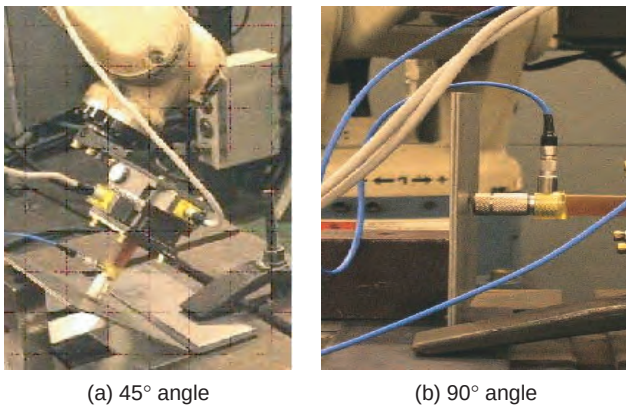


Fig. 10 Test : Change in inclination of work piece

camera imaging to accurately identify the outline of a spot indentation that does not change color, the angle of the illumination source (a red LED) and camera were adjusted to produce a shadow and a reflection of slight spot indentations on the surface of the galvanized sheet iron (Fig. 11). Orientation angles of between 5 and 30 deg. for the LED and between 30 and 60 deg. for the camera were tested (Fig. 12).

These tests indicated that the combination of the LED and the camera produced images that allowed the center of the spot indentation to be identified (Fig. 13). The center of a spot

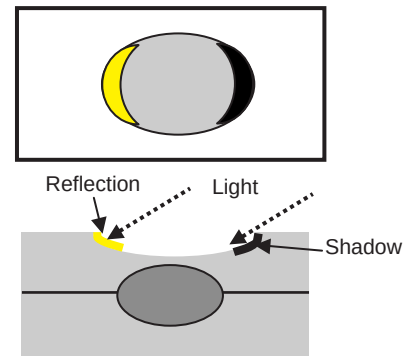


Fig. 11 Method of imaging of spot indentation outline

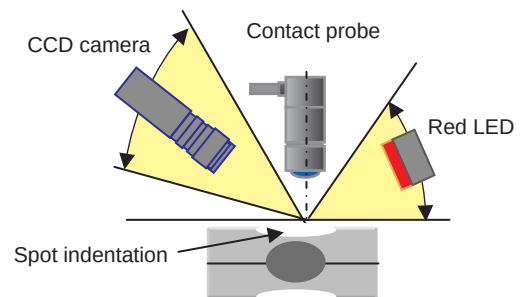


Fig. 12 Imaging test



Fig. 13 Imaging equipment

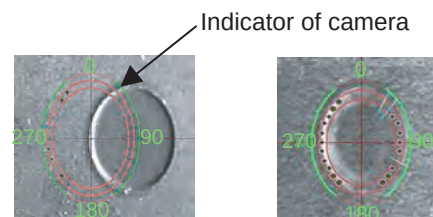


Fig. 14 Identification of spot indentation by developed system

indentation could be identified when this mechanism was fitted to a robot arm and operated at a feed rate of 300 mm/sec (Fig. 14). These trials demonstrated that the new system was able to identify a spot indentation regardless of the material.

5. Component Trials

The layout of the system, which tests the knowledge obtained from the experiment mentioned above using actual parts, is shown in Fig. 15. Figure 16 shows the operational flowchart of the system. A test piece was prepared with 20 spot indentations in a

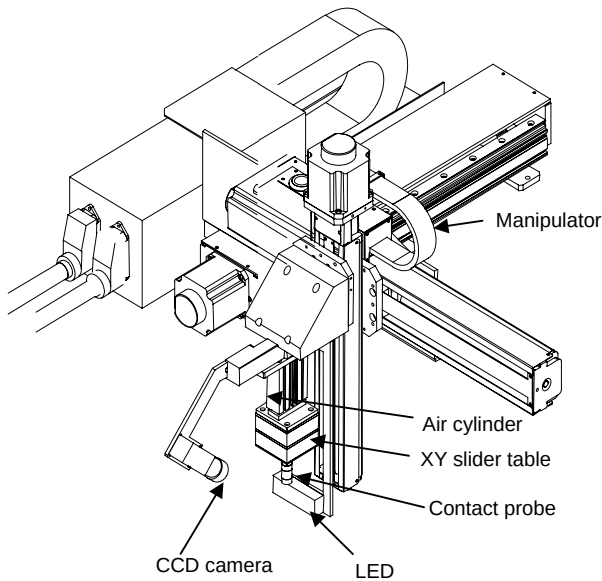


Fig. 15 Developed automatic ultrasonic flaw detection system

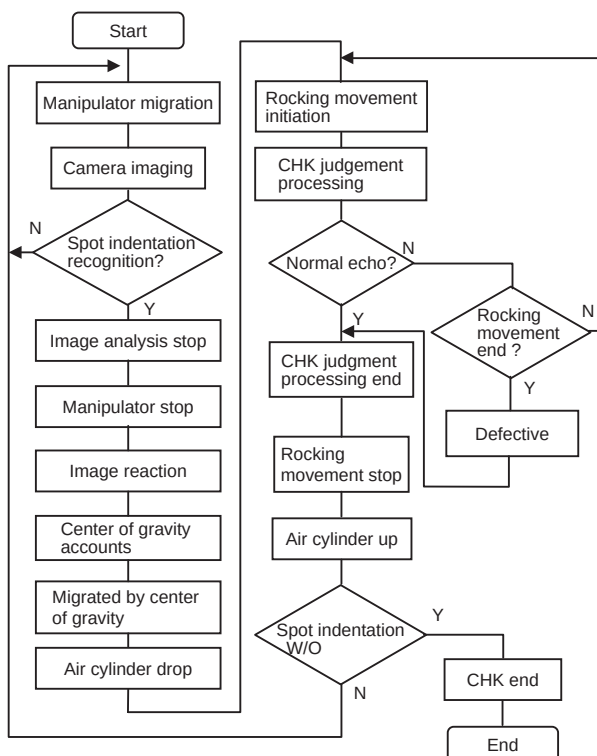


Fig. 16 Operational flowchart of developed system

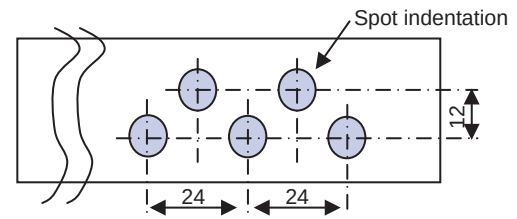
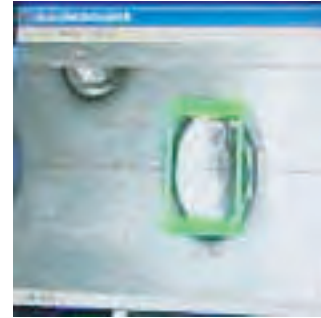


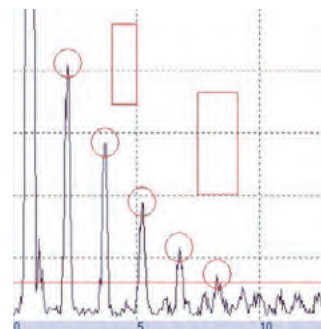
Fig. 17 Test piece



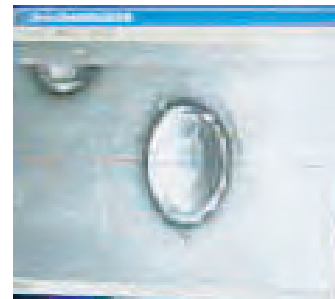
(a) Identify spot indentation



(b) Contact probe drop



(c) Back wall echo



(d) Identify next spot indentation

Fig. 18 Test results

zigzag die center distance, enabling the system to conduct a continuous inspection for flaws (Fig. 17), and test was conducted. Results showed that the system was able to image a spot indentation using the CCD camera and identify its center [Fig. 18 (a)]. Following this, it was able to contact the center of the indentation with the probe [Fig. 18 (b)] and trace the nugget by means of the probe's rocking motion, enabling an echo to be obtained [Fig. 18 (c)]. The system was able then to lift the probe and image the next spot indentation [Fig. 18 (d)]. The system repeated this process to detect all 20 of the spot indentations on the test piece. From these results, it was confirmed that the new system was effective in enabling automatic ultrasonic inspections of spot welds.

The system was fitted to a six-axis robot in combination with an automatic copying mechanism using a laser sensor (Fig. 19) and tested on a real component (Fig. 20). The results showed that the system was able to image spot indentations sequentially and produce echo patterns with simple teaching, indicating that the probe had traced the nugget.

These results clearly indicate that the system can be applied to real automotive parts.

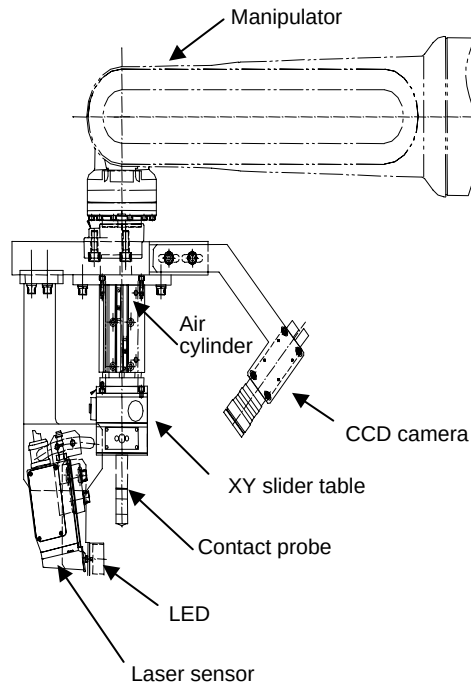
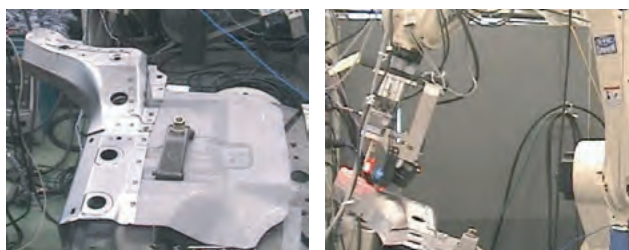


Fig. 19 Developed automatic ultrasonic flaw detection system fitted on six-axis robot



(a) Body component

(b) Test by developed system

Fig. 20 Application of developed system

6. Conclusion

Research was conducted on a technology for automated ultrasonic inspection of spot welds. The following are the significant findings of this research that suggest the possibility of automation in the future:

- (1) The research demonstrated that automated inspection was possible, even when the nugget was angled, if the probe was positioned at the center of the spot indentation and a rocking motion was used.
- (2) Even when working with materials such as galvanized sheet iron and stainless steel, on which it is difficult to identify spot indentations, the system was able to identify the outline and determine the center of indentations via CCD images of the shadows and reflections they produce, enabling automatic application of the probe to their centers.
- (3) A system was developed using the mechanisms in (1) and (2) with an industrial robot. The results of tests to identify a sequence of spot indentations indicate that this system can be used in automated ultrasonic inspection of spot welds.

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