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Residual Stress Measurement of Welding Area by Neutron Diffraction Method

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Abstract

Resistance spot welding technique is extensively applied to join the body steel sheets in the manufacturing process for the automobile industry. It is known that the fatigue crack initiates occasionally inside of the spot-welded zone in this material, which is a serious issue of the fatigue life. Although this phenomenon is supposed to be related to internal residual stress, the actual residual stress distribution inside of the spot-welded zone is not clear up to now. In this study, a neutron diffraction residual stress measurement technique with well-defined sub-mm^3 square gauge volume is applied in order to clarify the internal three dimensional residual stress distribution just below the spot-welded part of the steel sheets.

1. Introduction

In order to understand the phenomenon of fatigue fracture of a steel structure, especially in its welded joints, understanding the residual stress distribution in welded joints is indispensable. In order to measure the residual stress distribution, a nondestructive method using X-rays, synchrotron radiation, or neutrons is generally applied. In the case of a steel material, not a light metal, ordinary X-rays can penetrate a few tens of μm at most. Synchrotron radiation—a high-energy X-ray—can penetrate several mm;[1] however, because of its lower angle of incidence, the measuring region elongates in one direction, calling for a larger gauge volume. Accordingly, neutron diffraction, which affords higher penetration, is considered a promising technique to measure residual stress in a region several mm deep from the surface of a steel material.

In contrast, in principle, it is difficult to narrow down the beam with the neutron diffraction method. To compensate for such difficulty, an incident slit is used. In one example, an incident slit with one direction narrowed down to 0.3 mm was used.[2] The other slit in the other direction was widened to ensure sufficient signal strength. The minimum gauge volume was about 1 mm^3.

Recently, the resistance spot welding technique, as well as nugget joints, is applied to the many parts of an automobile to join the body steel sheets. Fatigue is one of the problems of the spot welding technique. With the conventional method of measuring the residual stress in welded joints using a cut specimen, however, the problem of stress relief cannot be ignored. Ordinarily, in resistance spot welding, the steel sheets to be joined together are pressed from both sides. Therefore, any residual stress in the welded joints is expected to be anisotropic. In addition, there are cases in which a fatigue crack or stress propagation and diffusion occur in the nugget. For the reasons mentioned above, establishing a technique to measure the residual stress in local regions has been demanded.

Under such conditions, in the "Research on Basic Study of Steel Evaluation Technology Utilizing Neutrons," etc. which forms part of the Steel Research for Industry Reconstruction Project, equipment improvements required to increase the speed and improve the accuracy of residual stress measurement were discussed at the initiative

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of the Japan Atomic Energy Agency. As a result, a 0.5-mm radial collimator and one-dimensional neutron detector were introduced. In the present study, we attempted to measure the residual stress in a spot-welded zone using the neutron diffraction method and the newly introduced collimator and detector.

2. Measurement of Stress using Neutron Diffraction

Since neutrons carry no electrical charge, they do not interact with electrons in materials and can penetrate deep into any material. Neutrons penetrate even iron to a depth of several tens of mm. Therefore, they allow for nondestructive measurement of the strain in steel materials. In the measurement area of a material defined by incident slits and receiving slits as shown in **Fig. 1**, it is possible to determine the lattice plane spacing in a specific area by precisely measuring the Bragg diffraction from a particular crystalline lattice plane.

With the method of using neutrons to measure stress, it is possible to implement nondestructive measurement of the stress in a material. Therefore, it is widely used to measure the internal stress of welded joints. It should be noted, however, that utilizing neutron beams requires a large-scale facility. In Japan, it is necessary to use one of the research reactors (JRR-3, J-PARC, etc.) of the Japan Atomic Energy Agency (JAEA).

Stress measurement techniques that utilize neutron diffraction can largely be divided into angular dispersive and time-of-flight methods.

In the angular dispersive method (**Fig. 2**), a monochromator is used to obtain a neutron beam of a specific wavelength from a white neutron produced by a research reactor, etc. The neutron beam obtained is irradiated onto the specimen and the diffraction angle, 2θ, of the beam is measured. By so doing, the lattice plane spacing can be precisely measured. The JRR-3 reactor mentioned above is suitable for this method.

In the time-of-flight method (**Fig. 3**), a pulsed white neutron obtained by an accelerator, etc. is irradiated directly onto the specimen and the lattice plane spacing is measured from the time of flight of the neutron with the angle formed by the incident neutron beam at the fixed detectors. The J-PARC reactor mentioned above is suitable for this method.

When measuring stress using neutrons, the angle of Bragg diffraction from a particular crystalline lattice plane is measured first to accurately calculate the lattice plane spacing using Bragg's law

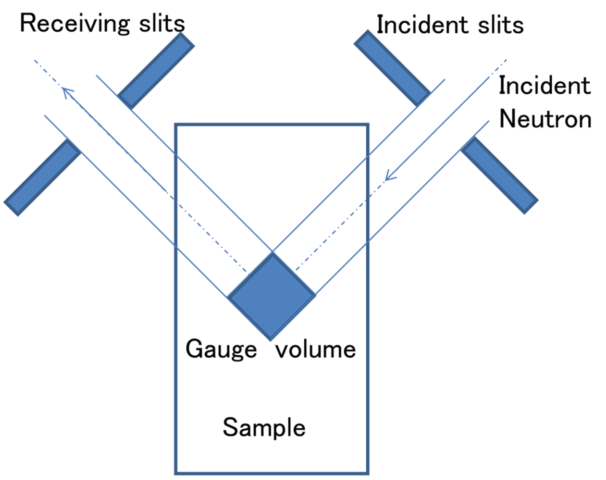

Fig. 1 Gauge volume in strain scanning method

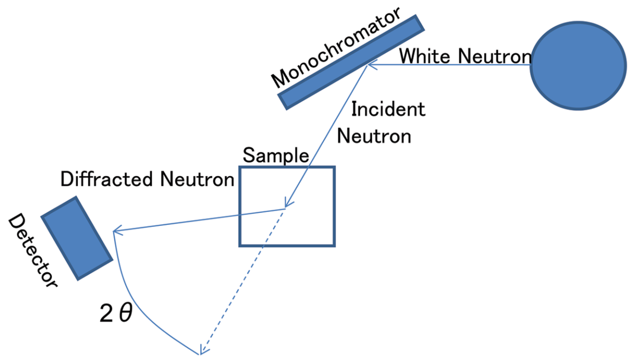

Fig. 2 Angular dispersive method

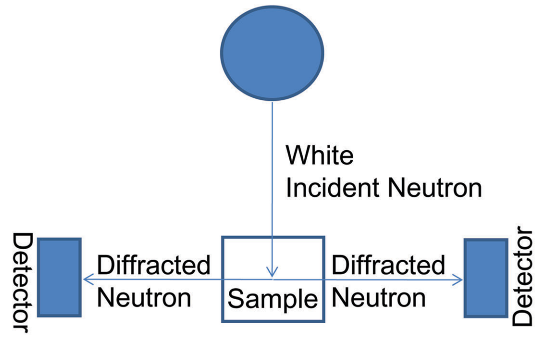

Fig. 3 Time-of-flight method

and then the stress and strain are calculated from the difference between the calculated lattice plane spacing and the lattice plane spacing under a stress-free condition.

3. Experimental Method

In the experiment, we performed nondestructive stress measurements by the neutron diffraction method using a diffractometer for residual stress analysis (RESA) at the JAEA. In the present study, we applied a one-dimensional position sensitive detector (PSD) that had been introduced to improve the precision and increase the speed of measurements in the Steel Research for Industry Reconstruction Project. For the purposes of stress measurement, α-Fe 211 diffraction was used. The wavelength, λ, of the neutron beam used was approximately 1.65Å and the diffraction angle, 2θ, was approximately 90°. A 0.5-mm × 0.5-mm slit was used as the incident slit, and a 0.5-mm radial collimator was used as the receiving slit. Under those measurement conditions, the gauge volume at the measuring position was set to be approximately 0.5 × 0.5 × 0.5 mm^3. As the steel material to be spot-welded, a 1.4-mm thick mild steel (JSC270E) sheet was used. The yield point (YP) and tensile strength (TS) of the sheet obtained by tension measurement were 139 MPa and 292 MPa, respectively. The spot welding conditions for the specimen are shown in **Table 1**.

Residual stress was measured in three directions, X, Y and Z, against the main axis of the material system and appropriate measuring points were set as required. For the three-way measurement at each of the measuring points, a Euler cradle was arranged in such a manner that once it is set, it permits obtaining different diffracted beams from the same position. With the beam intensity used in the

Table 1 Spot welding conditions

Electrode type	Electrode force	Welding current	Welding time	Hold time
DR6 ϕ -40R Cr-Cu	3.43kN	7.7kA	16cycles	10cycles (50cycles =1s)

present experiment, the measuring time was 100 minutes/point.

4. Experimental Results

4.1 Cross-section structure

In the experiment, several samples which were spot-welded under the same conditions were used. Using one of those samples, we observed the cross-section of the joint by an optical microscope. As a result, it was confirmed that the joint consisted entirely of ferrite and contained neither martensite nor pearlite. The average grain size of the portion away from the heat-affected zone (HAZ) was 25 μm. **Fig. 4** shows an optical micrograph of a cross-section of a spot-welded joint. In the figure, columns A, B and C indicate the points of residual stress measurement of the neutron diffraction method.

4.2 Decision on lattice constant under stress-free condition

In the neutron diffraction method, a lattice constant under the stress-free condition is required when it comes to conducting triaxial stress analysis based on the measurement results for lattice plane spacings in three directions. Ordinarily, for a specimen prepared under the same conditions as the specimen measured, the lattice constant that is obtained with a coupon sample prepared by electrical discharge machining at the same point as the measuring point is used as the lattice constant under stress-free conditions.[3)] In the present study, this technique could not be used because the sample thickness was as small as 1.4 mm. Therefore, using the same steel sheet as used in the experiment, we prepared a specimen by subjecting it to vacuum annealing at 600℃ for one hour and decided the lattice constant by applying the X-ray diffraction method to that specimen. The lattice constant thus decided was used as lattice constant a_0 under stress-free conditions. The experimental results showed that a_0 was 2.865Å. The results of various studies indicate that the value of a_0 was considered valid.

4.3 Measurement of residual stress in spot-welded joint

Although the diffraction profile obtained by the neutron diffraction method was somewhat asymmetrical, probably because of problems with statistical precision, we determined the peak position by general-purpose Gaussian fitting. This should be performed with the utmost care since the precision with which the peak position is determined significantly influences the ultimate residual stress value. An example of a neutron diffraction profile is shown in **Fig. 5**.

$$\varepsilon_i = (a_i - a_0) / a_0 \qquad (i = X, Y, Z) \qquad (1)$$

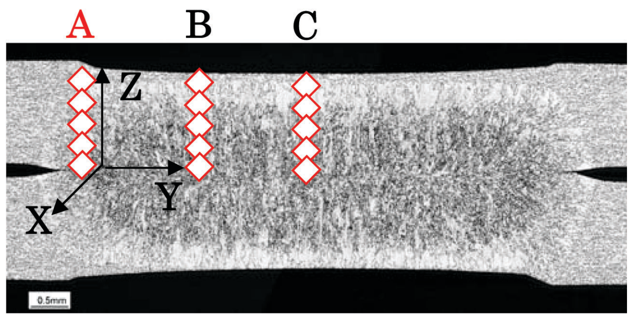

Fig. 4 Optical micrograph showing cross section of spot welding sheets

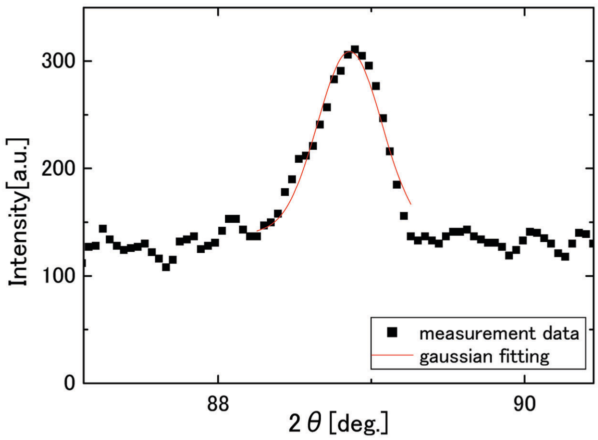

Fig. 5 Neutron diffraction profile of 211 diffraction

$$\sigma_i = E_{211} / (1 + \nu_{211}) \{ \varepsilon_i + \nu_{211} / (1 - 2\nu_{211}) (\varepsilon_Z + \varepsilon_Y + \varepsilon_X) \} \qquad (i = X, Y, Z) \qquad (2)$$

Using the lattice constant decided by the above method as the lattice constant under stress-free conditions, a_0, we conducted a strain and stress analysis using Equations (1) and (2) above. In Equation (2), E_{211} and ν_{211} denote Young's modulus and Poisson's ratio, respectively, for the 211 diffraction. We used 224 GPa as E_{211} and 0.276 as ν_{211}. In the above equations, ε and σ denote strain and stress, respectively.

Next, using Equation (2) above, we analyzed the stress distributions in three directions (X, Y, Z in Fig. 1) at each of the measuring points A, B and C. The analysis results are shown in **Figs. 6** (a), (b) and (c).

The analysis results shown in Fig. 6 (a) reveal that in the vicinity of point A at which a fatigue fracture occurred, the shorter the distance to the center, the greater the residual tensile stress became. This result is considered valid as a result of the spot welding. Concerning the direction of crack propagation, although the crack propagated in the Z direction initially, the direction of propagation changed occasionally. This is considered due, in part, to the presence of a compressive force along the way as shown in Fig. 6 (a).

In the vicinity of points B and C, it was confirmed that the residual stress was a tensile stress at every measurement point. From Figs. 6 (a), (b) and (c), it appears that at any point in the vicinity of A, B and C, the X, Y and Z stresses show nearly the same distribution in the direction of depth and do not demonstrate anisotropy.

In contrast, since the steel sheets to be spot-welded are pressed from both sides, it can reasonably be considered that the residual stresses in the welded joints experience anisotropy. However, spot welding is a complicated process involving expansion by heating, shrinkage by cooling, and expansion by transformation, etc. Moreover, considerable difficulty is involved in predicting residual stresses by calculation. Therefore, it is difficult to discuss their actual conditions.

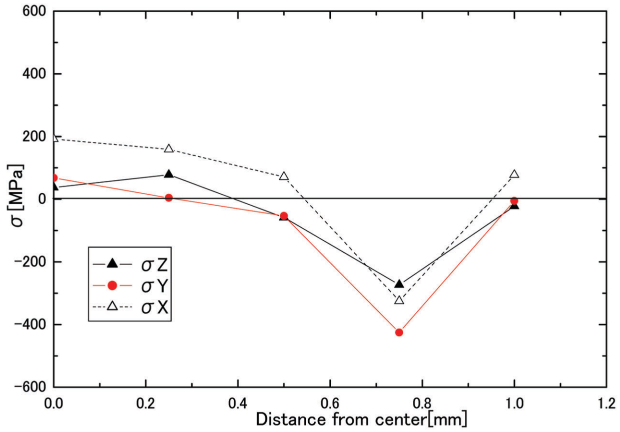

Fig. 6 (a) Resial stress distributon from fusion line to surface at Point A

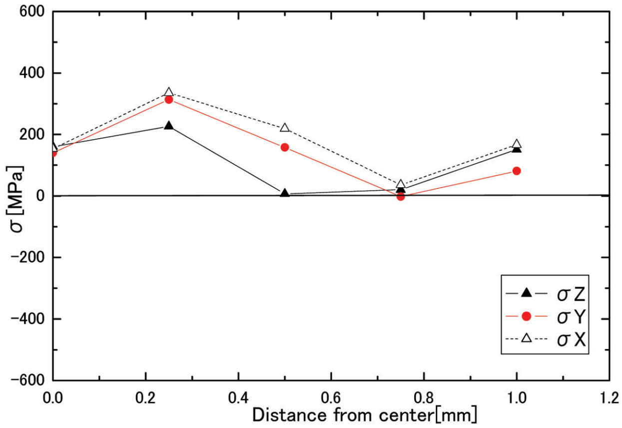

Fig. 6 (b) Resial stress distributon from fusion line to surface at Point B

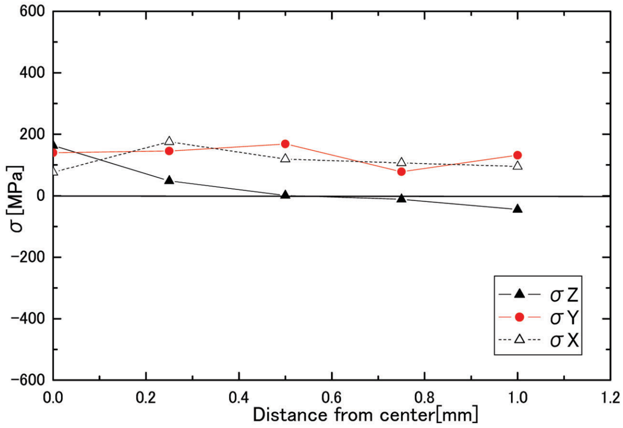

Fig. 6 (c) Resial stress distributon from fusion line to surface at Point C

5. Conclusion

Using the neutron diffraction method, we studied technology to measure the residual stress distribution in spot-welded joints and achieved a spatial resolution of 0.5 mm through improvements to the detection system, etc. In addition, we confirmed that in the region where a fatigue fracture occurred, tensile stress accounted for the majority of the residual stress. In the future, we would like to verify the validity of our measurement system and study in detail the residual stress distribution in spot-welded joints through a study of FEM calculations based on measured values and through measurements of specimens prepared under different conditions.

References

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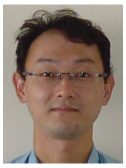

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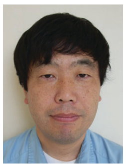

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