Comparison of weld residual stress measurement results in low alloy welds between X-ray diffraction and stress relief methods

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Abstract. In this study, a comparison of weld residual stress measurements between the X-ray diffraction technique and the stress relief technique is performed with the focus on the effect of the thickness on the stress measurement results. As the difference in the thickness becomes smaller, the difference in the stress measurement results also becomes smaller. At the weld center, where the stress gradient is in the thickness direction, the difference in the thickness is not negligible. In other words, it is concluded that the X-ray diffraction method is advantageous because it can evaluate the unique stress generated only in the surface layer.

1. Introduction

It is important to ensure structural safety and reliability by extending the lifetime of welded structures. An appropriate design concerning the lifetime of a welded structure is a major issue in many industrial products, such as ships, bridges, construction machines, power plants, automobiles, and railway transport systems. For the lifetime assessment of a welded structure, welding-induced metallurgical changes and stress-strain fields should be taken into account. In particular, it is well known that the weld residual stress is an important factor for evaluating the structural soundness of a welded structure, because a variety of fractures, such as brittle fracture, fatigue fracture and corrosion fracture, can be assisted by the tensile residual stress. It is also important to modify the lifetime assessment of an in-service structure by considering age degradation, including corrosion, cracking, material deterioration, and redistribution of the residual stress. Therefore, the demand for a non-destructive measurement of the weld residual stress distribution is increasing.

Various measurement methods of the weld residual stress have been proposed: saw-cutting, center hole drilling (CHD), X-ray diffraction, neutron diffraction, instrumented indentation (IIT), and deep hole drilling (DHD). The X-ray diffraction method has been drawing attention as a non-destructive technique for measuring the residual stress in microscopic detail. However, the X-ray stress measurement result can be influenced by the microscopic characteristics at the surface layer because the depth of X-ray penetration is within several dozen micrometers. Since the weld zone has a heterogeneously distributed microscopic material structure and stress distribution, the difference and similarity of the stress measurement results...
between X-ray diffraction and the conventional stress relief method\textsuperscript{9,10,11} should be clarified to appropriately understand the X-ray stress measurement results.

In this study, a comparison of the stress measurement results between the X-ray diffraction method and the stress relief method is performed with the focus on the effect of the thickness. Based on the comparison results, the features of the X-ray stress measurement are discussed.

2. Experimental procedure

2.1. Welded specimens
In this experiment, the specimen is a plate of low alloy steel A533B. The dimensions of the plate are 100 mm in length, 100 mm in width, and 20 mm in thickness, as shown in Figure 1. The chemical composition of this low alloy steel is shown in Table 1. In mechanical property, the yield stress of the low alloy steel A533B is 497 MPa. To measure the residual stress due to welding, the machined layers on the surface at the center of the plate to be welded are removed by electrolytic polishing. In electrolytic polishing, the current density is set to 0.48 A/cm\textsuperscript{2} in 10 min, using 5\% perchlorate methanol.

In the experiment, bead-on-plate welding is performed on the center of the low alloy steel plate. The welding method is Gas Tungsten Arc (TIG) welding with 100\% Ar gas as the assist gas. The welding condition is shown in Table 2.

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| Table 1. Chemical composition of the low alloy steel used (mass\%). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C               | Si              | Mn              | P               | S               | Ni              | Cu              | Cr              | Mo              | Al              | Fe              |
| 0.12            | 0.26            | 1.43            | 0.06            | 0.02            | 0.53            | 0.02            | 0.01            | 0.51            | 0.038           | Bal.            |

| Table 2. Welding condition. |
|-----------------------------|------------------|
| Welding current (A)         | 200              |
| Welding speed (mm/s)        | 2                |
| Arc length (mm)             | 3                |
| Flow rate of shielding gas (L/min) | 15                |
2.2. Stress measurement using the stress relief method

In the conventional stress relief method, the biaxial stresses, \( \sigma_x \) (longitudinal direction to the welding line) and \( \sigma_y \) (transverse direction to the welding line), are calculated using equations (1) and (2), which convert the relieved elastic strain in the specimen by saw-cutting to the original stress before saw-cutting.

\[
\sigma_x = \frac{2}{R} \cdot \frac{1}{1-\nu^2} E (\Delta \epsilon_x + \nu \cdot \Delta \epsilon_y) \tag{1}
\]

\[
\sigma_y = \frac{2}{R} \cdot \frac{1}{1-\nu^2} E (\Delta \epsilon_y + \nu \cdot \Delta \epsilon_x) \tag{2}
\]

where \( R \) is the gauge factor (2.08±1%), \( E \) is the mechanical Young’s modulus (229.9 GPa), and \( \nu \) is the mechanical Poisson’s ratio (0.272). The gauge length of the strain gauge used in the measurement experiment is 1 mm. The measurement locations are shown in Figure 2(a). The dimensions of the broken specimen are 10 mm in length, 10 mm in width, and 20 mm in thickness. To improve the measurement resolution of 5 mm in the transverse direction, two measurement lines with a 10 mm silt along the welding direction are determined because it is known that the weld residual stress is constant in the center of the specimen.

Furthermore, to compare the stress measurement results with the focus on the difference in thickness between the X-ray diffraction method and the stress relief method, the broken pieces are gradually cut into slices from a thickness of 20 mm to 3 mm. In the weld metal, broken pieces 3 mm in thickness are gradually reduced by mechanical polishing to thicknesses of 0.7 mm and 0.3 mm, as shown in Figure 2(b).

![Figure 2](image)

**Figure 2.** Measurement locations in the stress relief method. (a) Measurement locations, (b) Slices cut along the thickness.

2.3. Stress measurement using the X-ray diffraction method

2.3.1. \( \sin^2 \psi \) method\(^{12} \). For the biaxial stress measurement on the welded surface, the \( \sin^2 \psi \) method, which is recommended as the X-ray stress measurement standard, is used. Unless otherwise noted, the X-ray diffraction method in this paper corresponds to the \( \sin^2 \psi \) method. The X-ray stress measurement is performed by the fixed \( \psi \) method of the \( \psi \)-diffractometer method using an MSF (Rigaku Corporation). The X-ray beam size is set to 4×4 mm in consideration of the size of the coarse grains at the welded zone. The radiation source used is CrK\( \alpha \), the tube voltage is 30 kV, and the tube current is 10 mA. The scattering angle is determined by the half-value breadth method using the 211 reflection of \( \alpha \)-Fe. The \( \psi \) angles are 7 points equally spaced between 0 and 45 deg. The X-ray elastic constants are the Young’s modulus \( E_{211} \) of 249.5 GPa and the Poisson’s ratio \( \nu_{211} \) of 0.272. The measurement location is shown in Figure 3. The distance between each measurement location in the X-ray diffraction method is 5 mm, which is the same as that in the stress relief method.
2.3.2. 2D method\(^{13}\). The 2D method of D8 Discover with a GADDS (Bruker AXS Corporation) is used to obtain a more detailed residual stress distribution along the thickness of the cross section because the X-ray beam size can converge. It has been shown that the X-ray stress measurement results between the \(\sin^2\psi\) method and the 2D method are in good agreement\(^{14}\). The fluctuation angle is within \(\pm 4^\circ\) in the wavelength distribution direction (\(\omega\) direction in the diffractometer), so that reciprocal lattice points are on the Ewald sphere of \(K\alpha_1\) and \(K\alpha_2\). In addition, the 211 reflection of \(\alpha\)-Fe is used. The number of measurement locations is 21 points in 120 s per 1-Flame with varying \(\phi\) and \(\psi\). For the X-ray elastic constants, the Young’s modulus \(E_{211}\) is 249.5 GPa, and the Poisson’s ratio \(\nu_{211}\) is 0.272. Details of the measurement location in the 2D method are shown in Figure 4. As shown in Figure 4, the transverse component of the residual stress \(\sigma_y\) is evaluated along the thickness of the cross section using the specimen, which was cut out from the center of the welded plate.

\[\text{Figure 3. Measurement location for the X-ray diffraction method.}\]

\[\text{Figure 4. Measurement locations on the cross section thickness.}\]

3. Experimental results and discussion
A comparison of the weld residual stress measurement results between the X-ray diffraction method and the stress relief method is shown in Figure 5. The weld metal is within 3 mm from the center line, the HAZ (Heat-Affected-Zone) is within 3 mm to 5 mm, and the base metal is more than 5 mm from the center line. In the base metal (especially more than 15 mm from the center line), the results are in good agreement. However, an obvious difference appears at the weld center. To discuss the effect of the difference in the thickness on the stress measurement results, broken pieces are gradually cut into slices from a thickness of 20 mm to 3 mm. As shown in Figure 6, the stress measurement results in the base metal are not influenced by the thickness (thickness of the broken pieces), whereas the stress measurement results at the weld center are obviously influenced by the thickness. The results at the weld center are not yet in good agreement.

A broken piece 3 mm in thickness, which is removed from the weld center, is then reduced gradually by mechanical polishing to 0.7 mm and 0.3 mm in thicknesses. The stress measurement results are shown in Figure 7. This figure shows that as the thickness of the broken piece becomes thinner, the difference in the measurement results between the X-ray diffraction method and the stress relief method becomes smaller. It is considered that the X-ray stress measurement result is in good
agreement with that of the stress relief method using the specimen of the same thickness between the X-ray diffraction method and the stress relief method.

To discuss the difference in the measurement results shown only at the weld center, the stress distribution along the thickness is measured by the X-ray diffraction method (2D method) on the cross section thickness, as shown in Figure 4. The measurement results of the transverse component of the weld residual stress at the weld center and the base metal are shown in Figures 8(a) and (b), respectively. The measurement result at the point $z = 0$, which is measured using the $\sin^2\psi$ method, is also shown together. At the base metal, no gradient of the stress distribution is shown, whereas an obvious gradient of the stress distribution is shown at the weld center. It is considered that the change of the measured transverse stress from 0 to compressive when the thickness changes from 20 mm to 6 mm, as shown in Figure 6(b), is due to the existence of compressive stresses at the area from the bottom surface (20 mm) to 6 mm, as shown in Figure 8(a). It is concluded that this gradient of stress distribution along the thickness causes the difference in the measurement results at the weld center due to the thickness (thickness of the broken pieces). A drastic change of the stress from compressive to tensile is shown very close to the top surface only at the weld center. This tends to be shown only in the low carbon steel in which the phase transformation occurs. It is considered that the drastic change of the stress is possibly influenced by local re-distribution of the stress due to very rapid cooling only in the thin layer at the surface and the phase transformation. Thus, using the X-ray diffraction method, the unique stress generated only in the surface layer can be evaluated.

![Figure 5](image5.png)

**Figure 5.** Comparison of the residual stress between the stress relief method and the X-ray diffraction method. (a) Longitudinal component, (b) Transverse component.

![Figure 6](image6.png)

**Figure 6.** Effect of the thickness on measured residual stress when broken pieces are cut into slices 3 mm in thickness. (a) Longitudinal component, (b) Transverse component.
4. Conclusions
By comparing the weld residual stress measurement results of the X-ray diffraction method and the stress relief method, it is shown that the effects of the thickness on the stress measurement results are not negligible when a stress gradient exists along the thickness. As the difference in the thickness becomes smaller, the difference in the stress measurement results also becomes smaller. In particular, at the weld center, the difference in the stress measurement results between the X-ray diffraction method and the stress relief method tends to become larger, because a stress gradient exists along the thickness. Using the X-ray diffraction method, the unique stress generated only in the surface layer can be evaluated.

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