Residual stress determination in thick welded steel plates

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Abstract. Through thickness strain distribution of 50 mm thick welded ferritic steel (bcc) plate was studied using diffraction reflections 211 and 110 and neutron wavelengths of 1.55 and 2.39Å, respectively. Experimental results showed that for stress measurements in a possibly maximum thick weld, the different strain components should be measured with different reflections 211 and 110. The strains measured with these reflections for the same component are close. Since planes (211) and (110) of bcc ferrite have the same diffraction elastic constants the appropriate values of stresses could be derived from strains measured with reflections 211 and 110.

1. Introduction
Neutron diffraction method is widely used for strain measurements deep inside engineering structures and components [1]. Limitation of the path length is known to be about 60 mm in iron [2, 3], which corresponds to the plate thickness ~ 40mm. However, the ship building industry demands stress measurement in welded ferritic steel plates with thickness up to 80 mm now, and even more in future. The maximum available path length can be increased by using larger sampling (gauge) volume and/or longer measurement time. However, maximum size of the gauge volume is limited by the required spatial resolution. Increasing measurement time is not effective because intensity related to the diffracted peak exponentially decreases with neutrons path length through the material [1].

The more effective way for increasing available path length has been suggested and tested in ref. 4 based on the selection of the neutron wavelength corresponding to the local minimum of neutron total cross-section near the Bragg edges. The results showed that the available depth in steels can be remarkably increased by the use of focusing bent perfect crystal Si monochromators [5-8] and as well as selection of the proper neutron wavelength λ and hkl reflection for the measurements of the particular strain component. In ferritic steel (α-Fe, bcc structure) with a low texture, an instrument configuration using wavelength λ = 1.55Å and reflection 211 (2θs = 82.5°) is preferable for measuring normal (ND) strain components (reflection geometry, Figure 1c), while another configuration using wavelength λ = 2.39 Å and reflection 110 (2θs = 72.4°) is advantageous for measuring transverse (TD) and longitudinal (LD) strain components (transmission geometry, Figure 1d). Thus, it is necessary to measure different strain components with different reflections 110 and 211 for inferring stresses at the maximum possible depth in low textured ferritic steels.
Figure 1. a) Longitudinal (LD), transverse (TD), and normal (ND) directions in the welded plate; b) Schematic of the stress-free comb taken along the LD direction; c) Orientation of the plate for the measurement of the ND component in reflection geometry; d) Orientation of the plate for measurement of TD and LD components in transmission geometry.

In general, the calculation of stresses from strains measured with different hkl reflections can cause a misleading because the diffraction elastic constants and inter-granular strains are hkl-dependent. However, planes (211) and (110) of α-Fe (bcc) are known to have the same diffraction elastic constants calculated by the Kroner model: $E_{211,110} = 225.5$ GPa, $\nu_{211,110} = 0.28$ [1]. Furthermore, planes (211) and (110) are less sensitive to the inter-granular strains and evident inter-granular effects in ferritic steel weld could not be observed [9]. Therefore, one can expect that appropriate stresses can be derived from the strains measured with reflections 211 and 110.

In thick weld joints the microstructure and texture between the weld and base metal are different. A large grain size and strong texture are often formed in the weld [1]. The strong texture can considerably change intensity of the diffraction peak in a certain sample orientation and make a difficulty to measure the strain component along the particular principal direction. Moreover, texture differently affects intensity of different hkl reflections as well.

The instrument configuration with the wavelength $\lambda = 2.39$ Å and reflection 110 enabled us to measure all principal strain components in a 50 mm thick welded ferritic steel plate as reported in ref. 10. The TD component was measured much faster (~1 h) than ND component (~3 h) in the mid-thickness of the plate. Because of the strong texture in the weld a notable difference in the intensity of the 110 diffraction peak from the weld and base metal was observed for the same path length. In this work we performed the through-thickness scan of strains using the instrument configuration for the wavelength $\lambda = 1.55$ Å and 211 reflection in the weld of the same 50 mm thick welded ferritic steel plate. In low textured sample this configuration enables measurements of all principal strain components in 50 mm thick plate but it is particularly advantageous for the ND component [4].
The aim of this paper is to develop a guideline for the stress measurements in possibly maximum thick welded ferritic steel plate by comparing two instrument configurations, i.e., 110 and 211 reflections, for the measurements of the different strain components. Thus, the results will compare strain/stress components measured with both 110 and 211 reflections in the weld region.

2. Experiment

The two plates (600 mm long x 150 mm wide x 50 mm thick) of high-strength low-carbon steel plates with grain size of about 20 μm have been joined vertically using 1-pass 2-pole electro-gas welding technique. The details of base material and welding process are reported in [11]. The 600 mm long welded plate was cut across the welding direction and two pieces of dimension 300 mm x 300 mm x 50 mm were prepared. One piece (Plate 1, Fig. 1a) was used for the residual strain scanning and another one (Plate 2) was used for preparing reference “stress free” sample.

For getting the stress free reference spacing \(d_0\) a 4 mm thick through-thickness slice with dimensions 12 (LD) x 4 (TD) x 50 (ND) mm\(^3\) was machined out at the middle of the weld length from the Plate 2 by electro-discharge machining. A comb-like sample (Fig. 1b) was carefully machined from this slice with 4.7 mm wide “teeth” along the depth (ND) at the same locations where strains had been measured. The long (10 mm) axis of the “teeth” is parallel to the welding direction (LD) because no steep variation of \(d_0\) is expected in this direction [1]. It is supposed that “teeth” of the comb are free from the stress field.

The experiments were carried out by using the Residual Stress Instrument at HANARO reactor of Korea Atomic Energy Research Institute [8]. The bent perfect crystal Si(111) and Si(220) monochromators at take-off angles 2\(\theta\)\(_\text{M} = 45^\circ\) and 48° were used to provide neutrons with wavelength \(\lambda = 2.39\ \text{Å}\) and 1.55Å for measurement of diffraction peak (110) and (211) at scattering angle 2\(\theta\)\(_S = 72.4^\circ\), 82.5°, respectively. The section of the gauge volume in the diffraction plane was defined by 2 mm wide cadmium slits on incident and diffracted beams as shown in Figs. 1 b and 1 c. The height of the gauge volume (GV) was defined by the height of the incident beam as well. It was 20 mm for measurement of the ND or TD components (GV \(\sim 2 \times 2 \times 20 \text{ mm}^3\)) and 8 mm for the LD component (GV \(\sim 2 \times 2 \times 8 \text{ mm}^3\)). Through-thickness scan (at 9 depths from 5 mm from the top surfaces with 5 mm step) of diffraction peaks was conducted in the Specimen 1 at the middle of the weld centerline.

For the measurement of the comb the height of the incident slit was reduced to 2mm (GV \(\sim 2 \times 2 \times 2 \text{ mm}^3\)). For each component, in order to increase the number of reflecting grains, the comb was oscillated in the interval (±3°) along the diffractometer axes with 1° step and measured in seven rotations. The obtained seven diffraction peaks were summed for the peak analysis.

![Figure 2](image.png)

**Figure 2.** Diffraction peak measured at the mid-thickness (25 mm) and weld centerline by using a) (110) reflection and; b) (211) reflection in 50 mm thick ferritic steel weld plate.
3. Results and discussion

Figure 2 shows the diffraction peaks of the two configurations of the reflections, i.e., (110) and (211). Note that it was measured at the mid-thickness of the weld (25 mm depth) for different orientations of the plate. The result shows that the intensity of the 110 diffraction peak in the LD and TD sample orientations is higher than that of the ND orientation (see Fig. 2a). Meanwhile, the intensity of the 211 peak is higher for ND sample orientation than those of the LD and TD orientations (see Fig. 2b). Thus, for the investigation of the LD and TD strain components in a welded plate thicker than 50 mm using the 110 reflection is advantageous and on the other hand for ND components it is more suitable using 211 reflection.

The lattice spacing ($d_{hkl}$) for different reflections can be compared on a common scale by comparing corresponding lattice parameters ($a_{hkl}$):

$$a_{hkl} = \sqrt{(h^2 + k^2 + l^2)}d_{hkl}.$$

The macro-strain in particular sample direction, corresponding to the macroscopic stresses field is given by

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^0}{d_{hkl}^0} = \frac{a_{hkl} - a_{hkl}^0}{a_{hkl}^0},$$

where $d_{hkl}^0 / a_{hkl}^0$ is lattice spacing/parameter of reference “stress free” comb for the particular direction. It is assumed that each “tooth” with dimensions 4 x 4.7 x 10 mm$^3$ does not hold macro-strains associated with the elastic macro-stresses. It may have micro-strains and effects of chemistry but they should be the same as in the bulk plate and will cancel out in the macro-strain calculation.

Figure 3a shows the variation of lattice parameter measured with reflections 110 ($a_{110}$) and 211 ($a_{211}$) as a function of depth from the top surface in the weld. It shows that the lattice parameters measured for ND and TD components smoothly change with the depth and discrepancy between parameters.
measured with 211 and 110 reflections in the most points is within the experimental error. For LD component the discrepancy is larger and there is a notable scatter in the measurement values. The micrographs showed that the average grain size in the weld is about 180 μm and this may be the source of the scatter for the LD component, which was measured with the smaller gauge volume. However, if consider the insignificant dependence of the lattice parameter with the depth the discrepancy between the smooth lines is smaller (~0.0005 Å) which corresponds to strain error ±10^-4 and it is acceptable for the most stress measurements. Close values of the lattice parameters measured with reflections 110 and 211 suggested that most probably the macro-strains and micro-strains (if latter exist) measured with 211 and 110 reflections are close. Therefore, appropriate stresses could be derived from the strain components measured with different reflections 211 and 110, if corresponding values of the reference lattice spacing $d_{211/110}^0$ have been measured.

Figure 3b shows the variation of the lattice parameters with depth in the comb measured with reflections 211 ($a_{211}^0$) and 110 ($a_{110}^0$). There is a fair amount of scatter in the measurements, much larger than experimental error. Relatively large grain size, possibly remained macro-stresses in “teeth” [10], and inter-granular micro-stresses can be the reason of the discrepancy (~0.0005Å) between the lattice parameters for the different directions and reflections. Further experiments with “stress free” samples are necessary.

Figure 4 compares the stresses derived from the strain components measured with i) one reflection 110 and ii) two reflections 110 (TD, LD) and 211 (ND). It shows that there is a good agreement between stresses measured with one and two reflections in most points. Notable (~50 MPa) difference in several points is mainly caused by difference between the two reflections in reference lattice spacing/parameter $d_0/a_0$ measured in the normal component. Obviously the agreement would be better if the ND component is also measured with the 110 reflection up to available depth and only in few points when the gauge volume is deep inside the sample near the mid-thickness should be measured with the reflection 211. Thus, for stress measurements in 50 mm thick (and more) welded ferritic steel plates the following procedure can be recommended: measurement of all TD and LD components along all depths, and ND component up to about 20 mm depth by using wavelength $\lambda =2.39$ Å and reflection 110; measurement of ND component in the rest deeper locations by using the wavelength $\lambda =1.55$Å and reflection 211.

![Figure 4](image-url)
Through-thickness variations of residual stresses along the weld centerline can be discussed. Figure 4 shows that the three profiles of components similarly fluctuate with a sine-wave like distribution. It can be observed in the previous results of residual stress measurements in thick components [12]. Compared to the previous results it shows a similar distribution. For example, the minimum longitudinal residual stress (σLD) located at the depth of 0.5–0.7, while the higher tensile σLD (up to 180 MPa) were observed close to the surfaces at the depth of 0.2–0.3 of the thickness from both sides. Since such a tensile σ can often initialize the transverse cracks in thick welds the location of the maximum tensile residual stress can be critical to the integrity of the final weld components.

4. Conclusions
The presented experiments showed that available thickness of welded ferritic steel plate for stress measurement can be increased by using two instrument configurations with the neutron wavelengths 2.39 and 1.55Å and corresponding reflections 110 and 211, respectively. Then, appropriate residual stresses can be obtained from the transformation of these strain components by using appropriate diffraction elastic constants.

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