Residual Stress Measurement on Welded Stainless Steel Specimen by Neutron Diffraction

M. J. Park, D.Y. Jang and H. D. Choi

Abstract

In this paper, the neutron diffraction is applied to the residual stress measurement on the 20mm-thick welded stainless steel plate (100° × 100mm²). The High Resolution Powder Diffractormeter of the Korea Atomic Research Institute The power of nuclear reactor was 24 MWt and the measured reflection in the 220 plane (2θ is 95° and wavelength is 1.8340 Å. The Poisson ratio of 0.265 and elastic constant of 211 GPa are applied to the calculation of stresses and strains. Three directional components such as normal, transverse, and longitudinal stresses are measured and the results show that the most of longitudinal stress is tensile and decreases, changing to compressive depending on the distance away from the welded spot. However, transverse component is changing from tensile to compressive along the depth of the welded point.

Key Words : Neutron, Diffraction, Residual stress, Welding

1. Introduction

Stainless steel is one of the principal materials being utilized in manufacturing critical parts of the modern power and the chemical plants due to the combination of appropriate mechanical properties and the high resistance to corrosion . Especially, it is one of the popular steels to be used in the piping systems of the nuclear power plants. Since most pipes are jointed through the welding, analysis of the characteristics of welding is very important for the stable operation of power plant. One of the important characteristics on the welded spot is residual stress.

The residual stress is generated in the structures as a result of an irregular elastic-plastic deformation during the fabrication processes such as welding, heat treatment, and mechanical processing or the creep and plastic deformation during the usage[1].

There are several factors attributed to the origin of residual stresses, tensile or compressive. The residual stress states are of two types [2,3]: macroscopic stresses and microscopic stresses. Macroscopic stresses or macrostresses, which extend over distances that are large relative to the grain size of the material, are of general interest in design and failure analysis. Macrostresses are tensor quantities, with magnitudes varying with direction at a single point in a body. The macrostress for a given location and directory is determined by measuring the strain in that direction at a single point. Macrostresses strain many crystals uniformly in the surface. This uniform distortion of the crystal lattice shifts the angular position of the diffraction peak selected for residual stress measurement. Microscopic stresses or microstresses are scalar properties of the sample, such as percent of cold work or hardness that are without direction and result from imperfections in the crystal lattice. Microstresses are associated with strains within the crystal lattice that traverse distance on the order of or less than the dimensions of the crystals. Microstresses vary from point to point within the crystal lattice, altering the lattice spacing and broadening the diffraction peak.

The residual stress, particularly tensile residual stress in the welded part, can be a very important factor to affect the reliability and integrity of the weld. The residual stress measurement on the welding is of the considerable value to the ability in predicting the weld strength under the static and dynamic conditions. It can be assumed that the main sources of residual stress are the prior thermos-mechanical processing of the plate and the subsequent

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welding process. The formation of tensile residual stress may result in an initiation of the fatigue cracks, stress corrosion cracking, or other types of fractures. It is important, therefore, to understand the distribution of residual stress in and near the welded spot [7,8,9].

Several methods are available for determining these stresses in destructive and nondestructive ways [1-6] including the X-ray diffraction, neutron diffraction, hole drilling, and the slicing or boring methods.

Nondestructive measurements by X-ray or neutron diffraction are popular and well-established techniques. Although stress measurement by X-ray diffraction is a well-established one, it is practically limited to near-surface stresses. Neutron diffraction permits non-destructive evaluation of lattice strain within the bulk of large specimens because it can penetrate more deeply into the steel specimens. In this research, the neutron diffraction is utilized to measure residual stresses in the welded stainless steel part.

There have been several experimental and computational studies of the welded austenitic steel plates by neutron diffraction [6-8].

Single-pass and multi-pass welding were measured by using neutron diffraction and residual stress distributions as well as stain were mapped out in the heat-affected zone of the welding. Most samples used in the past measurement had single V butt joint. No study on a double V butt joint has been reported. In this research, the austenitic stainless steel sample with a double V butt joint is utilized to measure residual stress distribution along the fusion line and, in and near the heat affected zone of the welding.

The neutron diffractometer of the Korean Atomic Energy Research Institute was utilized to map the three orthogonal components of the residual stress at the selected locations within the welding.

2. Experiments

The sample was prepared using two SUS304 stainless steel plates of sizes $100 \times 100 \times 200$ mm^3. As shown in Fig. 1, two plates with chamfers at the two edges of the one side of the plate were welded by using multiphase Tic-arc welding with current 130~140 A voltage 25~27 V, resulting in double V butt joints on the top and bottom of the welded plate. The nominal chemical composition and mechanical properties of the specimen are given in Table. 1 and 2.

Table 1 Chemical composition (%)

C	Si	Mn	P	S	Ni	Cr
0.08	1.00	2.00	0.040	0.03	8~10.5	18~20

Table 2 Mechanical properties

Tensile Strength, Ultimate(MPa)	Tensile Strength, Yield (MPa)	Elongation (%)
> 505	> 215	> 70

During welding, the plate was constrained by the tack welds at each corner. The Cartesian coordinate system is adopted for the strain components. It is assumed that the principal strain directions are along and perpendicular to the welding in the plane of the plate, and normal to it. The sample is assumed to be symmetrical with respect to the axes of X and Y. Strain measurements are conducted along three directions of longitudinal, normal, and transverse as in the one fourth of measuring section as shown in Fig. 2 [5-9].

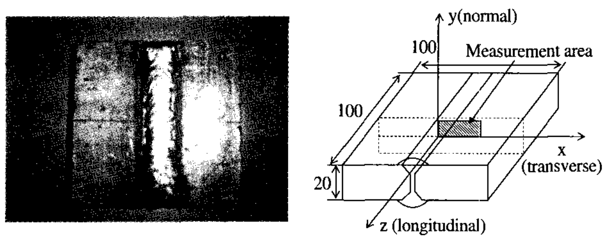

Fig. 1 Measured welding sample

The neutron diffraction experiments were carried out on the High Resolution Powder Diffractometer (HRPD) that is put into operations at the 24 MWt HANARO reactor in Korea Atomic Energy Research Institute (KAERI). The 220 reflection was selected since the diffraction elastic constants are close to the bulk values and the assessment of residual stress is simplified. The incident neutron beam is made monochromatic by diffraction from the 220 plane of a welding sample. The wavelength that was selected to give a scattering angle 2θ of 95° for the 220 plane, is 1.8340 Å. The narrow incident and receiving slits define the gauge volume within the specimen as shown in Fig. 2. The neutrons were counted in a position sensitive detector (PSD). For the accurate measurement, calibration was conducted by using standard samples from the VAMAS (The Versailles Project on Advanced Material and Standard)[1]. The calibration results showed 97% reliability.

The measurements of strain components along normal, transverse, and longitudinal directions were made by an alignment of the sample so that the corresponding direction was along the scattering vector as it is shown in Fig. 2 [2, 3]. The two 2mm wide slits in absorbing cadmium sheets were placed in the incident and scattered beams to define the gauge volume over which the strain is measured. The profiles of strain in the sample were measured by moving the sample through the gauge volume.

An appropriate translation and rotation of the sample controlled the precise location of the diffracting volume within the specimen. For the transverse and normal strain measurements the height of the incident slit was relaxed to 20mm since for this component, the slit averages along the length of the weld where the strain gradient is relatively low therein.

However, this was reduced to 4mm for the longitudinal measurements where the height of the slit averages along the transverse line, perpendicular to the weld of which a larger strain gradient is expected. The diffraction peak 220 ($2\theta_{220}$ 95°) was scanned. The peak centers, widths, and intensities were obtained by least square fittings a Gaussian line shape to the experimental data. The measurement took 5 to 10 minutes for normal and transverse strains and 2 to 3 hours for longitudinal strains. The typical error in strain was 30×10^{-6}. Normal and transverse strain distribution along the transverse and normal direction were measured with 2 mm step in the region between - 4 mm and 30 mm position in X direction and between 0 mm and 8 mm in Y direction. Distribution of longitudinal strain along transverse direction was measured with 2 mm step in the same region between - 4 mm and 30 mm position in X direction but for two depth: Y=0 mm and Y=6 mm.

The plate of $20 \times 50 \times 100$ mm^3 from the same material was studied to determine diffraction angle $2\theta_0$ corresponding to the stress-free material. Stresses were calculated using effective elastic diffraction constants E = 211 GPa and ν = 0.265 for 304L stainless steel for reflection 220.

Residual stresses are obtained from measurements of lattice strain by using the neutron diffraction. Since stress is a tensor, measurements are required in six orientations to completely determine the stress state at a point.

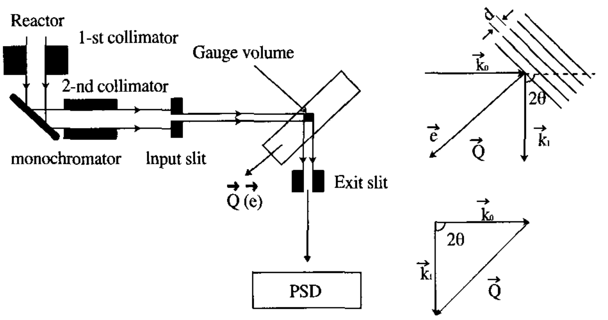

Fig. 2 Strain measurement schematic

However when the principle directions are known, three orientations are sufficient. Neutron diffraction measurements use lattice spacing as a strain gauge. They are obtained from Bragg's law [3].

$$n \cdot \lambda = 2d \cdot \sin\theta \quad (1)$$

Where n is an integer, λ is the wavelength of the radiation, d is the lattice spacing, and θ is the diffraction angle corresponding to a particular hkl reflecting plane. Strain is measured in the direction of the scattering vector Q that bisects the incident and diffracted beams.

In order to satisfy Eq. 1, any change in lattice spacing $\Delta d = d - d_0$, where d_0 is the unstrained lattice spacing, will result in a change in λ or θ and strain ε is given by

$$\varepsilon = \frac{d - d_0}{d_0} \quad (2)$$

For the welding sample, because of symmetry the principal directions coincide, with the normal, transverse and radial directions, so that measurements of strain in these orientations only are needed to completely define the stress tensor at a point. In order to obtain adequate resolution a suitable small 'gauge volume', as Fig. 1 in which the measurements are made, must be defined.

To make measurements it is necessary to precisely position and aligns the sample to be examined in the diffractometer. The spatial resolution of a neutron measurement depends on the dimensions of the apertures masking the beam as well as on the angle between the incident and diffracted beams. When the principal directions coincide with the coordinate directions normal, transverse and axial and the material is isotropic with a Young's modulus E and Poisson's ratio-ν, the principal stresses are obtained from

• Normal direction :

$$\sigma_{11} = \frac{E}{(1+\nu)}\left[\varepsilon_{11} + \frac{\nu}{1-2\nu}(\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33})\right]$$

• Transverse direction :

$$\sigma_{22} = \frac{E}{(1+\nu)}\left[\varepsilon_{22} + \frac{\nu}{1-2\nu}(\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33})\right] \qquad (3)$$

• Longitudinal direction :

$$\sigma_{33} = \frac{E}{(1+\nu)}\left[\varepsilon_{33} + \frac{\nu}{1-2\nu}(\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33})\right]$$

3. Results and discussion

The microstructure features of the heat-affected zone, base metal, and fusion zone are shown in Figs. 3b, 3c, and 3d, respectively. Fig. 3a shows a photomicrograph of the transverse section of weld. The bright part is the fusion zone with the deposit weld layers. The dark part is the base metal. Because of the solid state transformation from austenite to martensite during welding, which occurs after solidification, the grain structure of the fusion zone is distinctly visible with dark line patterns.

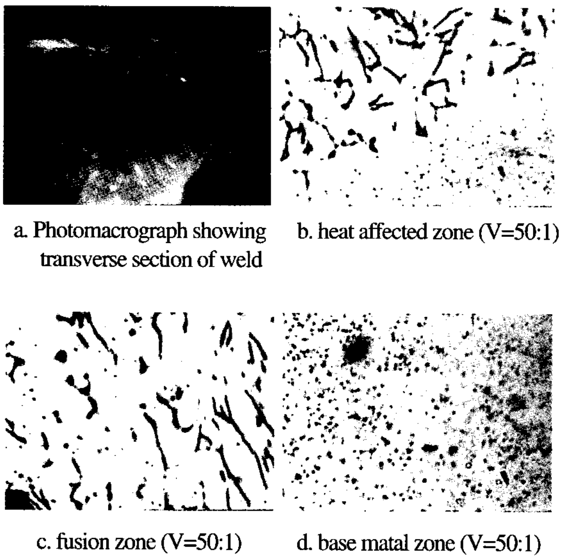

Fig. 3 Typical microstructures each zone

The variation of residual stresses for the three principal directions, normal, longitudinal, and transverse stresses, are shown in Fig. 4. These stresses are obtained by applying measured residual strains to Eq. 1 & 2. The normal and transverse components are compressive in the zone around the centerline and in the subsurface of the weld. They become tensile with the distance away from the centerline. The transverse stress becomes tensile close to the surface in the weld center zone. However, the normal component is compressive, falling off with the distance close to the surface. Both components become zero at about 26mm from the weld center. Nonetheless, the longitudinal component is tensile around the weld center as with the maximum distance of 6 mm from the weld center. It eventually becomes zero and compressive in the distance about 14 mm away from the center. When we compare the three components along the distance away from the centerline (X direction) in the plane located at the same depth (Y = 0 mm), the normal component

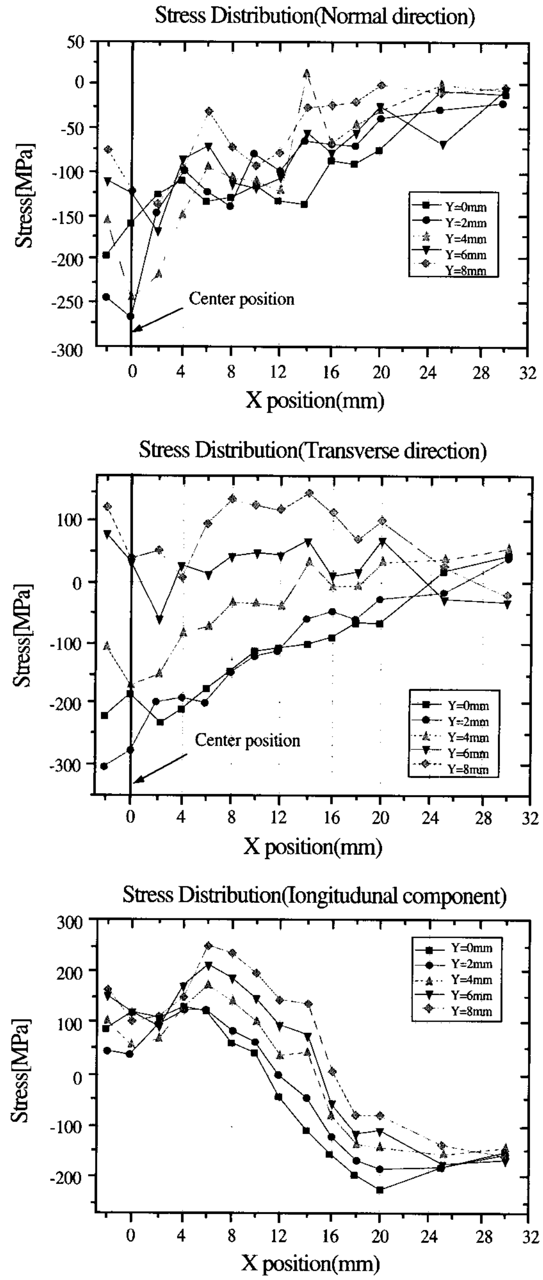

Fig. 4 The stress distribution in welded SUS304 plate

becomes balanced with the other two components. This may be caused by the welding geometry of this sample. Since the top and bottom surfaces of this sample are welded, the shrinkage effect can be balanced out.

The physical phenomena that cause residual stresses, such as thermal gradients and plastic yield, are often directional and coupled to stresses in parallel directions. There could be three possible physical phenomena that contribute to the final stress state of the welded plate. First, shrinkage effect is caused by the weld metal solidification on the top of a solid substrate such as base metal or previously deposited weld layers. The resultant stresses are generated parallel to the line of the weld. It is the longest dimension for shrinkage. Shrinkage effects also exist in the direction perpendicular to the long dimension of the weld since the core of the weld will solidify and contract slowly that the surface, resulting in triaxial tension in the fusion zone. Second, temperature gradients between outside and inside of the plate can generate thermal stresses that vary through the thickness. Third, the phase transformation from austenite to martensite is associated with volume change during cooling from high temperature. These three mechanisms could be the sources to the residual stresses. The longitudinal shrinkage of the fusion zone may be the main source of the longitudinal components of stress. The fusion and heat-affected zone are constrained by the unyielded portions of the base metal plate, resulting in a state of residual tension and the base plate left in the compression. Closer to the fusion zone, the other geometric effects and yielding mechanism may create more complex residual stress patterns.

4. Conclusion

The neutron diffraction provided us a way to understand the residual stress fields that develops during the welding. The large scale features of the spatial distribution of residual stresses can be explained by the thermal shrinkage of the fusion zone and the individual welding passes, and the through thickness temperatime gradients that exist during cooling of the welding. More research should be conducted for the complete mapping of the stress variations along the length of the plate.

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