General paper

Residual Stress Distribution in Carbon Steel Pipe Welded Joint Measured by Neutron Diffraction

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Abstract: In order to estimate crack growth behavior of fatigue and stress corrosion cracking in pipes, the residual stress distribution near the pipe weld region has to be measured through the wall thickness. Since the penetration depth of neutron is deep enough to pass through the thick pipe wall, the neutron diffraction technique for the residual stress measurement is effective for this purpose. At the first step the residual stress distribution near the weld region in a butt-welded carbon steel pipe was measured by the neutron diffraction. Significant stresses extended only to a distance of 30mm from the center of the weld. The major tensile stresses occurred in the hoop direction in the fusion and heat affected zones of the weldment, and they attained a level greater than 200MPa through the thickness. While the axial residual stress at the inside surface was 50MPa, the stress at the outside surface was -100MPa. The comparison of residual stress distributions measured by the neutron diffraction, the X-ray diffraction and the strain gauge method reveals that the neutron diffraction is the most effective for measuring the residual stress inside the structural components.

Key words: Neutron diffraction, Residual stress, Welded pipe joint, X-ray diffraction, Strain gauge method

1. INTRODUCTION

The X-ray diffraction technique widely used to accurately measure residual stress in various kinds of materials has been standardized by the Committee on X-ray Study for Deformation and Fracture of Solid of The Society of Materials Science, Japan [1]. Since the penetration depth of X-ray is only about 20 μ m from the surface, residual stresses inside the structure can not be measured. On the other hand, the penetration depth of neutron is sufficiently deep and the neutron diffraction technique is the only method available to non-destructively determine residual stresses inside weldments [2,3]. The neutron diffraction technique has also been applied to the stress distribution measurement at the fatigue crack tip of specimens under loaded and unloaded conditions [4].

Residual strains were measured in almost all of the previous studies on neutron diffraction. Residual stress distributions have to be measured to evaluate the fatigue strength of structural components. Elastic constants are needed to convert residual strains to residual stresses. Since elastic constants depend on diffraction planes, we have studied this dependency for ferritic steel [5]. Based on our research and previous studies, (211) lattice plane was recognized as the most appropriate plane for measuring residual stresses. The authors also examined the spatial distribution of residual stresses in a socket weld in which a short sleeve is aligned and welded to two tubes

[6]. The residual stress at the root of the weld metal in the socket welded joints was about 130MPa. This is about half of the estimated value from the fatigue test results of as-welded and stress-relieved socket joints.

To estimate the crack growth behaviors of fatigue and stress corrosion cracking in pipes, the residual stress distribution near the pipe weld region has to be measured through the wall thickness. Since the penetration depth of neutron is deep enough to pass through the thick pipe wall, the neutron diffraction technique can be used to measure the residual stress. In the first step of this process the residual stress distribution near the weld region in the butt-welded 100mm in diameter carbon steel pipe was measured by the neutron diffraction.

2. EXPERIMENTAL PROCEDURE

2.1. Neutron Diffraction Measurements

Neutron diffraction is a method for measuring the spacing, d , between the atomic planes of a crystal lattice. A neutron beam of a known wavelength λ is diffracted from its incident direction by a scattering angle 2θ according to Bragg's law,

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

By scanning a detector through a range of scattering angles, a profile of neutron counts versus 2θ is obtained, as

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Fig. 1. Typical raw data showing neutron counts versus scattering angle.

Fig. 2. Scattering geometries necessary for measurement of three components of lattice strain.

shown in Fig. 1. A Gaussian function is fitted to the raw data to obtain the mean scattering angle, also known as the lattice spacing. Typical precision of the mean scattering angle is $\pm 0.003^\circ$. The value of d in most engineering materials ranges from 0.1 nm to 0.3 nm. They are determined by Eq.(1) to a precision of about $\pm 1 \times 10^{-5}$ nm. Elastic strain, ϵ , is determined by comparing the measured value of d to the value measured in a suitable stress-free reference d_0 through the relation,

$$\epsilon = (d/d_0 - 1). \quad (2)$$

Actually, d_0 is measured in a small sample, which is cut from a similar structure of identical material and annealed for stress relief.

Strain components are measured in a direction that bisects the angle between the incident and diffracted neutron beams. To obtain values of strain in the principal directions of a tubular weldment, axial(A), radial(R) and hoop(H), the tube must be reoriented to place this bisector in the required direction, as shown in Fig.2. The incident and diffracted beams are shaped by slits in neutron-absorbing cadmium masks. Measurements are made only in the region of the intersection of these two beams, which is called the sampling volume.

With the three strain measurements at each location, residual stresses can be calculated through a generalized Hook's law,

$$\sigma_H = \frac{E}{(1+\nu)} [\epsilon_H + \frac{\nu}{(1-2\nu)} (\epsilon_H + \epsilon_R + \epsilon_A)] \quad (3)$$

where E is Young's modulus, ν is Poisson's ratio, and the subscripts indicate components of strain and stress. The radial, axial and hoop components of stress, σ_R , σ_A and σ_H , are obtained by cyclic permutation of the subscripts in Eq.(3).

The elastic constants E and ν , needed to convert the measured strain to the stress, depend on the hkl diffraction plane. Hayashi et al. revealed that the appropriate elastic constants were $E = 243 \pm 5$ GPa and $\nu = 0.28 \pm 0.01$ for strain determined from shifts in the 112 diffraction peak for ferritic steel weldments [5].

2.2. Neutron Diffraction Apparatus

An optical system near the diffractometer is shown in Fig. 3. The L3 neutron diffractometer at Chalk River Laboratories of National Research Council, Canada was configured to produce a neutron beam with a wavelength of 0.15951 nm by the 115 diffraction of a squeezed single

Fig. 3. Optical system near diffractometer.

Fig. 4. Appearance of butt-welded carbon steel pipe joint mounted on XZ- ω goniometer.

crystal germanium monochromator. Strains were determined from shifts in the angular position of the 112 diffraction peak, which occurred at a diffraction angle of about 85.7deg.

In order to measure axial, hoop and radial strains, both of incident and diffracted beams were shaped by slits in cadmium masks. For the measurements of axial and radial strain components, the sampling volume was 1.5mm $\times$ 1.5mm $\times$ 10mm, with the long dimension tangent to the curvature of the pipe. For the measurements of the hoop component of strain, the height of the sampling volume of 10mm was reduced to 2 mm to retain sufficient spatial resolution in the axial direction of the pipe. This was done to scan the gradient of the strain with the distance from the center of the weld. Since the angle between the incident and the diffracted beams was nearly 90deg, the intersection of the beams defined the sampling

Fig. 5. Shape and dimensions of butt-welded pipe

(a) Weld metal and base metal

(b) Heat affected zone

Fig. 6. Sampling positions of stress free sample.

volume that was nearly a rectangular prism.

A photograph of a butt-welded pipe mounted on the XZ ω -translator in an orientation suitable for measuring the hoop strain components is shown in Fig. 4. A rotary drive unit permits the automatic selection of circumferential positions for examination, while the linear translators permit the automatic selection of various depths and axial locations in the weldment. The welded pipe can be moved under computer control at a precision of ± 0.005 mm to scan the sampling volume throughout a two-dimensional slice through the wall of the weldment. Thus, a spatial map of strain is constructed.

2.3. Specimen

A measured butt-welded carbon steel pipe joint is shown in Fig. 5. The outer diameter of the pipe was 114.3mm, the inner diameter was 97.1mm and the pipe wall thickness was 8.6mm. The material was JIS STPT410. The weld groove shape was single V. The groove angle was 60 deg and the root opening was about 3mm. Welding was done by manual TIG (Tungsten Inert Gas) welding. The welding current was 110~120A and the voltage was 10~15V. Numbers of passes and layers were 4 and 4, respectively.

Residual stresses were measured in the as-welded state at selected locations, especially near the weld. Small, approximately cube-shaped samples with dimensions of 5mm were also prepared for measurements of stress-free reference lattice spacing d_0 . These samples were cut from the base material, heat affected zone and fusion zone of a similar butt-welded pipe joint, as shown in Fig. 6. They were heat treated at 625 $^{\circ}$ C for 2 hours. Lattice spacings measured in these samples were used as d_0 in Eq.(2).

3. EXPERIMENTAL RESULTS

3.1. Residual Strain

The (211) lattice spacings of the stress free reference specimens were measured both before and after the residual strain measurements. The results were consistent within the precision of the measurement and were averaged to obtain values that best-represent the entire series of the strain measurements. The base metal and the heat affected zone specimens had the same lattice spacing, 0.11704nm. The fusion zone specimen had a higher lattice spacing, 0.11705nm. The stress free lattice spacings agree well with each other within the precision of the measurement. This means that the difference for the residual stress measurement is less than 30MPa.

The lattice strain distributions at various depths in the wall of a butt-welded pipe are shown in Figs. 7, 8 and 9. The residual strains were measured at the points of 1.0,

Fig. 7. Axial residual strains in a butt-welded pipe.

Fig. 8. Hoop residual strains in a butt-welded pipe.

Fig. 9. Radial residual strains in a butt-welded pipe.

2.32, 3.64, 4.96, 6.28 and 7.6mm from the outer surface and at the points of 0, 5.54, 7.0, 12.0 and 30mm from the weld center. Figures 7, 8 and 9 show the measured residual strains as functions of distance from the weld center and distance from the outside diameter of the pipe for axial, hoop and radial directions respectively. In all cases, the lattice strains are significant only at distances less than 30mm from the center of the weld. The axial residual strains are mostly compressive while those exhibit a through-thickness variation from -10.49×10^{-4} near the outside diameter to 0.77×10^{-4} near the inside diameter. This means that the residual strain depends on the depth. The minimum axial residual strain is about -10×10^{-4} at 7mm from the weld center. This means that the largest compressive residual strains occur near the heat affected zone. The axial residual strains take small tensile values at the heat affected zone near the inner surface.

The hoop strains are tensile, as shown in Fig. 8, reaching a maximum of $+8.46 \times 10^{-4}$ at the center of the weld metal. The residual strains near the heat affected zone take almost the same values as with the weld metal.

The radial residual strain distributions are mostly tensile, and always less than 5×10^{-4} , with a minor through-thickness variation, as shown in Fig. 9. There are a few through-thickness variations in the radial and hoop strains compared with the axial strains.

3.2. Residual Stress

Using Eq.(3), the residual strains are converted into the residual stresses. The axial, hoop and radial residual stress distributions along the axial direction of the pipe are shown in Figs. 10, 11 and 12 respectively. The stress patterns are similar to the strain patterns.

The axial stress in the weld metal exhibits about -100MPa at the outer surface and changes to a tension of +50MPa at the inner surface. The through-thickness variation of the axial stress ranges from a compression of

Fig. 10. Axial residual stresses in a butt-welded pipe.

Fig. 12. Radial residual stresses in a butt-welded pipe.

Fig. 11. Hoop residual stresses in a butt-welded pipe.

-270MPa near the outer diameter to a balancing tension of 70MPa near the inner diameter when it is measured near the heat affected zone about 6mm away from the weld center. The absolute values of the axial residual stress decreases with the distance from the weld center, and tend to reduce to zero at a distance of 30mm from the weld center.

The hoop stress exhibits the maximum of 250MPa at the middle of the weld metal, and decays to zero at a distance of 30 mm from the weld center.

Relatively high tensile radial stress was measured in the weld metal. However, it decreases to the compressive side near the heat affected zone, and increases a little bit away from the heat affected zone and decays gradually to zero at a distance of 30mm from the weld center.

In Fig. 13, the measured residual stresses are shown throughout a section of the weldment that extends from the inner to the outer diameter on the pipe, and from the

Fig. 13. Contour diagrams of the hoop, axial and radial components of residual stress.

weld center to a distance of 30mm in the axial direction. The dominant residual stress is in the hoop direction. The maximum tensile hoop stress of 200 ± 30 MPa is located at the mid thickness of the fusion zone. This stress value is close to the yield point of the material. The hoop stresses approach zero within 20mm from the weld center and change to compressive stress of -50MPa away from the weld center to balance the tensile stress at the weld metal. The hoop stress distributes nearly homogeneously in the wall thickness, as can be seen in Fig. 13.

4. DISCUSSION

4.1. Residual Stress Measurement by X-ray Diffraction

The residual stresses in the butt-welded pipes were measured by the X-ray diffraction technique ($\text{Sin}^2\psi$ method) and the strain gauge method. After measurement of the residual stresses by the neutron diffraction, the residual stresses in the same pipe were non-destructively measured by the X-ray diffraction technique and destructively measured by the strain gauge method. In considering fatigue crack initiation and propagation or stress corrosion cracking, the axial stress is the most important. Thus the residual stresses were mainly measured in the axial direction and compared with the residual stresses measured by the neutron diffraction.

The residual stresses measured by X-ray diffraction are shown in Fig. 14. The residual stresses were measured every 90 deg in the circumferential direction. However, they distribute similarly along the axial direction of the pipe at all locations. At the weld center the residual stress is about -150MPa to -230MPa. It increases near the heat affected zone and reaches the highest compressive stress at about -320MPa to -450MPa, and then it rapidly decays to zero at about 30mm from the weld center.

4.2. Residual Stress Measurement by Strain Gauge

After the residual stress measurement by X-ray diffraction, the macroscopic residual stresses on the surface were measured by the strain gauge method, destructively. Near the weld metal the strain-concentration type gauges were affixed to measure the detailed residual stress distributions. In each strain-concentration gauge five small gauges are simultaneously installed. The gauge length was 1mm and the spacing was 2mm. Single-strain gauges were affixed more than 20 mm away from the weld

Fig. 14. Axial residual stress on outer surface measured by X-ray diffraction.

Fig. 15. Axial residual stress on outer surface measured by strain gauges.

Fig. 16. Axial residual stress on inner surface measured by strain gauges.

center. The strain gauges were affixed both on the outer and inner surfaces, and at every 90 deg in the circumferential direction. The residual stress distributions measured by the strain gauges are shown in Figs. 15 and 16. Each symbol indicates the raw residual stress at each circumferential and axial location, and the solid lines give averaged values at each axial location. In Fig. 15, the residual stress at the weld center is compressive and about -200MPa. The compressive residual stress increases slightly in the heat affected zone, and reaches the maximum value of about -300MPa. It rapidly decreases with the increase in the distance from the weld center and decays to zero at about 30mm. In some locations, the residual stresses are tensile away from the weld for balancing the compressive stress near the weld.

The residual stress distribution on the inner surface is approximately reversed from that of the outer surface. The residual stress at the weld center is tensile and the mean value is about 150MPa. However, the scattering bands are slightly wide near the weld metal in this case. The maximum tensile stress is greater than 250MPa. The residual stress increases slightly in the heat affected zone, and reaches the maximum value of about 180MPa. It rapidly decreases with increasing distance from the weld center in the base metal and decays to zero at about 20mm. It turns to compressive from 20mm to 60mm, and is almost zero more than 60mm away from the weld center.

4.3. Comparison of Axial Residual Stress Measurement

The comparison of the residual stress measured by the neutron diffraction, X-ray diffraction and the strain gauge method is shown in Fig. 17. Since only the residual stress on the outer surface can be measured by the X-ray diffraction, the comparison of the residual stress on the outer surface is shown in Fig.17. Here the residual stresses measured by the X-ray diffraction and the strain gauge method reveals the average value measured at 4 points in the circumferential direction.

While the residual stresses measured by the X-ray diffraction give the stresses of extremely shallow surface layer of about 20 μm in depth, and those measured by the strain gauge give the average value near the surface, the residual stresses measured by the neutron diffraction give the average value of about 1.5mm in depth 1mm beneath the surface. Thus the residual stresses on the surface are extrapolated through the polynomial approximation of the through-thickness residual stress distributions measured by the neutron diffraction. Although small differences

Fig. 17. Comparison of residual stresses measured by neutron diffraction, X-ray diffraction and strain gauge.

can be seen in the absolute values of the residual stress, the residual stresses measured by the neutron diffraction, X-ray diffraction and the strain gauge method, agree well. This means that the residual stresses inside the structure can be provided by the neutron diffraction.

4.4. Mechanism of Residual Stress Formation

The residual stress distribution in the butt-welded pipe caused by the welding is very complex compared with simple butt-welded plates. Accordingly, the residual stresses have been analyzed using the elasto-plastic FEM analysis [6].

The residual stress distribution in the butt-welded pipe could be caused by the combination of following three mechanisms. Figure 18 (a) manifests the residual stress caused by the pipe configuration. In the figure symbols of + and - with circle indicate tensile and compressive residual stress respectively. When the pipe is butt-welded, the weld portion is shrunk both in the axial and circumferential directions. However, since both ends of the pipe are not restrained, the axial expansion and shrinkage do not cause an axial residual stress. On the other hand, most of the shrinkage of the pipe at the weld portion occurs when the deposited metal is solidified. This shrinkage introduces a tensile residual hoop stress homogeneously throughout the pipe wall thickness in the weld metal, bal-

(a) Residual hoop stress caused by cylindrical shape

(b) Balance between initial and later welding

(c) Circumferential shrinkage

Fig. 18. Mechanism of expansion and shrinkage due to welding.

Table 1. Estimation of residual stress caused by several mechanisms.

Residual stress Causing source	Inner surface		Outer surface	
	σ_A	σ_H	σ_A	σ_H
Fig.18(a)	~ 0	++	~ 0	++
Fig.18(b)	-	-	+	+
Fig.18(c)	++	~ 0	--	-
Total	+	+	-	++

anced by compressive residual hoop stress away from the weld metal.

Figure 18 (b) shows the residual stress due to the sequence of welding. For the simplicity, two layer welding is assumed. Since the formerly welded inner side layer is previously solidified, it becomes a constraint against the later welded outer side layer. Thus the residual stress in the inner side is compressive, while the residual stress in the outer side is tensile both in the axial and circumferential directions.

Figure 18 (c) indicates the residual stress generated by the secondary bending deformation resulting from the circumferential shrinkage. Since the circumferential shrinkage squeezes the inside of the pipe in the radial direction, the pipe at the weld metal is bent in the axial-radial plane. This bending deformation causes tensile residual stress at the inner surface and compressive residual stress at the outer surface near the weld metal. The residual stress measurement of the butt-welded pipe by the strain gauges and the finite element analysis clarified that the axial residual stress caused by the squeezed deformation is dominant [7,8]. The axial residual stress seems to be mainly ruled by this bending deformation.

The estimation of the residual stress caused by the above three mechanisms is summarized in Table 1. Radial residual stresses are small and are not evaluated. The residual stress causing sources correspond to Fig. 18 (a), (b) and (c). Symbols + and - mean the absolute value of the residual stress small and symbols ++ and -- mean large magnitudes. According to the mechanisms shown in Fig. 18 and the above explanation, the hoop residual stresses are relatively high tensile both at inner and outer surface. The axial residual stresses are tensile at the inner

surface and compressive at the outer surface, but the absolute values of them are not so large compared with the hoop residual stresses. Accordingly, the residual stresses in the butt-welded pipe joint can be explained by the above mentioned mechanisms.

5. SUMMARY

Neutron diffraction non-destructively provides a detailed map of residual stresses in the butt-welded 100mm in diameter carbon steel pipe. Significant stresses extended only to a distance of 30mm from the center of the weld. The major tensile stresses occurred in the hoop direction in the fusion and heat affected zones of the weldment, and they attained a level greater than 200MPa through the thickness. While the axial residual stress at the inside surface was 40MPa, the stress at the outside surface was -100MPa.

The residual stress distributions measured by the neutron diffraction technique, the X-ray diffraction technique, and the strain gauge method closely agree with each other. The neutron diffraction technique is the most effective for measuring residual stress inside structural components.

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