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Residual Stress Measurements at HANARO Reactor

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하나로 원자로를 이용한 잔류 응력의 측정

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Abstract

Principles of residual stress measurements by neutron diffraction and the residual stress instrument installed at 30MWt HANARO reactor in KAERI are considered. In-depth residual stress distribution was measured in aluminum VAMAS round robin sample and welded stainless steel plate, which showed high ability of the instrument for the stress measurements in components.

Nomenclature

e : lattice strain
Q : scattering vector

1. Introduction

Many industrial components contain residual stresses caused by inhomogeneous plastic deformation during fabrication or inhomogeneous heat treatment, such as welding. These stresses can affect the component life in service as they may add to applied loads causing fatigue and failure. These stresses are also a key factor in the phenomenon known as stress corrosion. Consequently engineers have to allow for the presence of residual stresses in components.

Neutron diffraction can measure stress distribution non-destructively [1,2]. The principle advantage of the neutron method over the more conventional X-ray method is connected with the neutrons ability to penetrate into most materials, which enables the measurement of stress within the bulk of material at depths up to a few centimeters (~2.5 cm in steel), whereas the X-ray method can only be used to examine near-surface stress fields to a maximum depth of ~ 100 μm.

The major drawback of the neutron diffraction method is its need of intense neutron beams, available only at a medium or high-flux reactor. This limits its use to relatively small portable components with typical dimensions ~50-100cm. However it can be used to test the computer codes using model samples, and also test other portable techniques and calibrate these techniques for use in the factory or field.

The volume resolution of the material over which a neutron measurement is made (gauge volume) is normally $10mm^3$ which is much greater then the fraction of $1mm^3$ sampled in an X-ray experiment. However, such gauge volume is much less than the sampling volume in a conventional neutron powder diffraction experiment (~ $1cm^3$) and the intensity of scattered neutrons is low even at high flux neutron reactors. Position sensitive detector (PSD) is usually used to speed up data collection.

Residual stress measurements started at HANARO reactor (KAERI) in 1999 [3]. The ability of instrument considerably increased in 2000 when new PSD was put into operation [4]. In this work the early results are represented to demonstrate the ability of the instrument for residual stress measurements.

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2. Principles of method and HANARO instrument

The principles of strain measurements are shown schematically on Fig.1. The white neutron beam from the reactor is first monochromated to a chosen wavelength λ by Bragg reflection from a single crystal monochromator. The monochromator beam passes over the diffractometer axis or "sample axis" about which the detector rotates. The detector scans particular reflection (hkl) by counting neutrons scattered through an angle 2θ. Both the beam incident on the sample and the beam entering the detector are defined in area by horizontal and vertical aperture in a neutron absorbing cadmium masks. The gauge volume or volume sampled by the diffractometer is defined by the intersection of the incident and scattered beam as shown in Fig.1. The measured strain is averaged over the gauge volume. By moving the large sample through the gauge volume one can obtain the profile of strain in sample. The strain is determined using Bragg's law of diffraction, 2d sinθ = λ, which allows to determine the lattice spacing d appropriate to a particular reflection (hkl) averaged over a small sampling volume within the stressed material. If the strain-free lattice parameter, determined from unstrained sample of the same material, is d_0, the lattice strain $e = (d - d_0)/d_0$. It is given by $e = -\cot\theta \, \Delta\theta$, where Δθ is the small change in Bragg angle θ observed from the two samples when placed in a monochromatic beam of wavelength λ. In experiment the diffraction peak shift Δθ is measured. The direction in which strain e is measured is that of scattering vector **Q**, where $\mathbf{Q} = \mathbf{k}_1 - \mathbf{k}_0$, and $\mathbf{k}_1$, $\mathbf{k}_0$ are the incident and final neutron wave vectors. In general, to define the strain tensor at a point completely, measurements in six orientations are required. However, when the principal directions are known, measurements in these three directions will suffice. Stress is obtained from the measured strains using diffraction elastic constants.

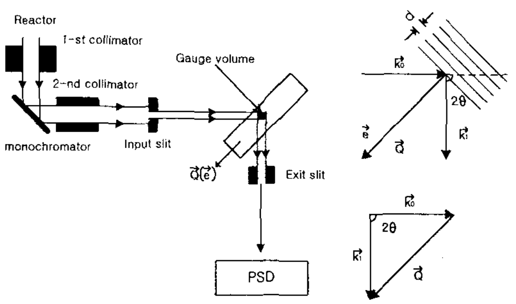


Fig. 1. Strain Measurement Schematic

The HANARO instrument for residual stress measurement (Fig. 2.) is assembled on the base of high resolution powder diffractometer (HRPD). One dimension PSD which has increased height of detecting volume (100mm) in comparison with conventional PSD(25mm) was designed and manufactured specially for residual stress measurements. Intensity of diffraction peak increased and measurement time decreased about 3.5 times. The germanium focusing monochromator with reflecting plane (331) at take-off angle 90° gives neutrons with wavelength 1.834 Å.

Fig. 2. The instrument for residual stress measurement

The X-Y-Z translator table allowing to move the sample with accuracy up to 0.025mm is mounted on the diffractometer sample table.

3. Aluminum VAMAS round robin sample

In order to test our instrument for residual stress measurements the VAMAS round robin test of Aluminum standard sample was carried out. The VAMAS (Versailles Project on Advanced Material and Standards) was organized to standardize residual stress measurements by neutron diffraction. The specimen (Fig.3) was made from aluminum alloy Al7075 and consisted of a ring and a plug which had been joined in a way that mutual constraint occurred. The ring had been expanded by heating and plug had been contracted by cooling in liquid nitrogen. Then the ring was fitted on the plug and sample was brought to room temperature. At room temperature both the ring and the plug should have residual stress. From the same aluminum plate which had been used for the ring-and-plug sample another plug of diameter Ø25mm and height 50mm was prepared to measure scattering angle $2\theta_0$ for the stress-free material.

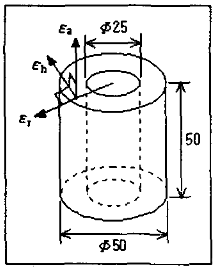
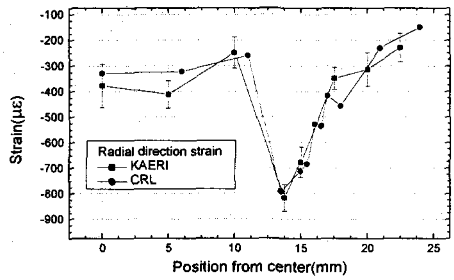
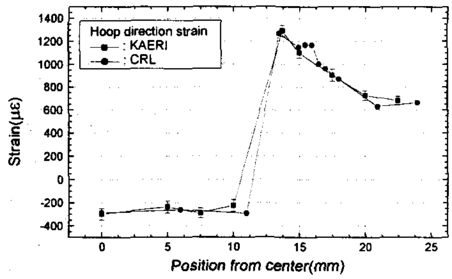


Fig. 3. Schematic of VAMAS round robin sample

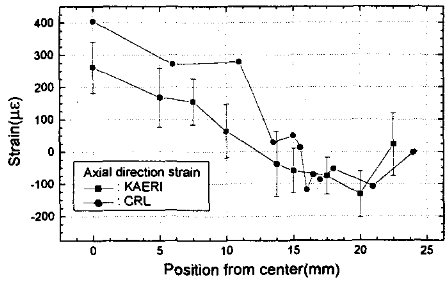
Measurement of strain was carried out at 8 points along radius at the distances from the sample axis : 0, 5, 7.5, 10, 13.75, 15, 20 and 22.5mm at a height 12.5mm from the base. At every point the strain was measured in three principle directions : radial, hoop and axial. The reflection (311) was used to measure radial and hoop component and reflection (220) to measure axial component.



(a) radial direction



(b) hoop direction



(c) axial direction

Fig. 4. Strain distribution in VAMAS sample

Our results (Fig. 4.) were in good agreement with the results obtained for the same sample in Chalk River Laboratory (Canada) and in JAERI (Japan). The results of determined stress components in comparison with ones predicted by the theory are given in Fig. 5. In agreement with the theory the radial and hoop components in the plug are close and compressive. In the ring near the plug-ring boundary the radial component is compressive while the hoop component is tensile. In contrast with the prediction of the theory the axial component differ from zero though its value is low.

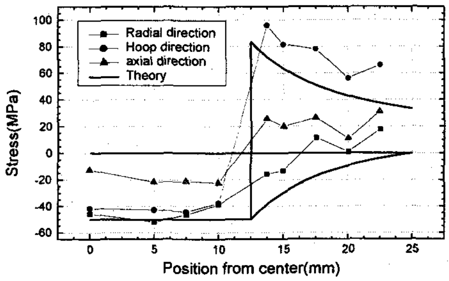


Fig. 5. Stress distribution in VAMAS sample

4. Ceramic matrix composite VAMAS round robin sample

Ceramic matrix composite sample consisted of Al_2O_3 matrix and 25vol% of SiC. Stress-free samples of hot pressed Al_2O_3 and powder SiC were also prepared to measure unstressed value of spacing d_0.

Samples of Al_2O_3 and composite Al_2O_3+25%SiC were prepared in form of disc with diameter Ø30mm and

3mm thick. The samples were inserted in hole of Ø30mm in sample holder made from 3mm thick aluminum plate 60x135mm^2 as shown on Fig.6. Unstressed SiC sample was prepared from SiC powder which was put in the hole in sample holder between two thin vanadium foils stuck to the aluminum plate faces.

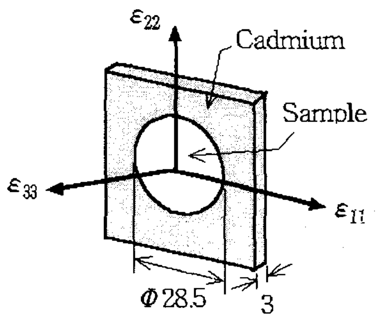
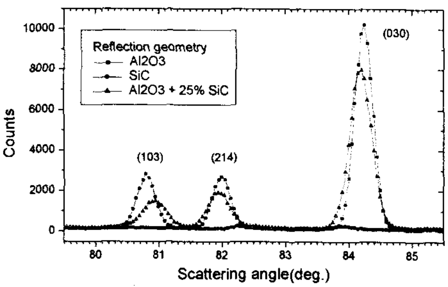


Fig. 6. Schematic of ceramic powder sample

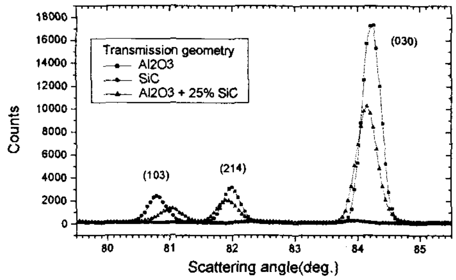
Measurement of strains was carried out using conventional set up of powder diffractometer : 20' soller collimator was installed between monochromator and sample and 32 detector bank was used.

Analyses of neutron diffraction patterns of Al_2O_3, SiC and composite Al_2O_3+25%SiC brought to the decision to choose the reflection (103) at 2θ=80.7° for SiC and reflections (214) at 2θ=82° or (300) at 2θ=84.26° for Al_2O_3.

We assumed that one of the principle directions (z) is normal to the sample plate and two others (x,y) lie in the central plane of the sample plate. Measurement was carried out by alignment of corresponding direction along the scattering vector. Normal component was measured in reflection geometry and plane component in transmission geometry.



(a) reflection geometry



(b) transmission geometry

Fig. 7. Neutron diffraction pattern of ceramic sample

On Fig. 7, which shows the part of neutron diffraction pattern scanned in reflection and transmission geometry, one can see that in the ceramic composite, the peaks (214), (300)/(030) corresponding to Al_2O_3 are shifted to the smaller angle while diffraction peak (103) of SiC is shifted to the higher angle. Thus Al_2O_3 is expanded and SiC is contracted in composite. The values of strain components obtained from measurement were:

for Al_2O_3 :

$\varepsilon_{33} = 3.9\times10^{-4}(\pm0.20)$

$\varepsilon_{11} = \varepsilon_{22} = 7.0\times10^{-4}(\pm0.14)$

for SiC :

$\varepsilon_{33} = -1.3\times10^{-3}(\pm0.24)$

$\varepsilon_{11} = \varepsilon_{22} = -2.2\times10^{-3}(\pm0.8)$

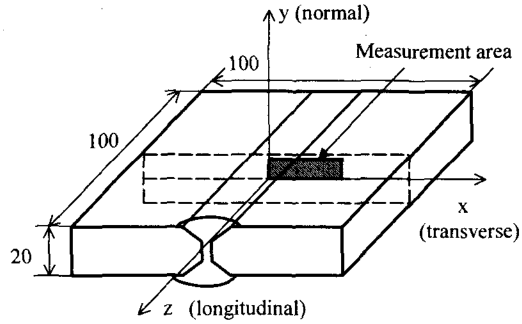
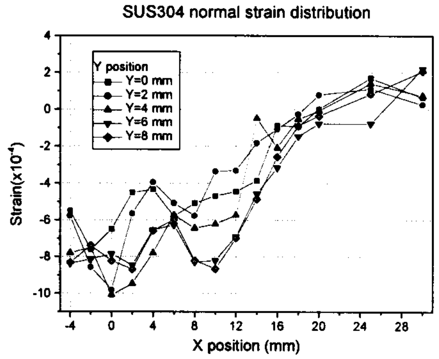
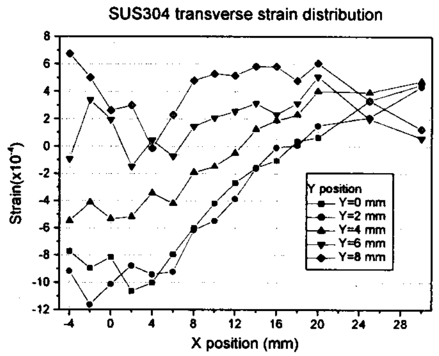


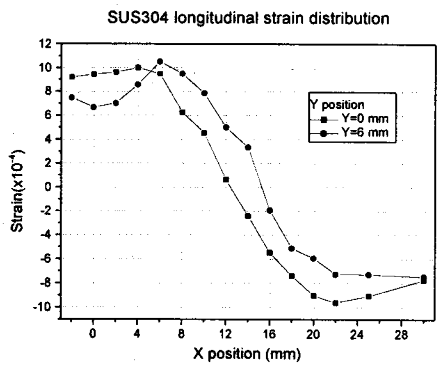
Fig. 8. Schematic view of welded plate



(a). Normal component



(b) Transverse component



(c) Longitudinal component

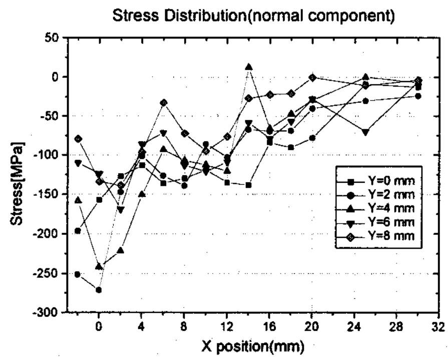
Fig. 9. Strain distribution in SUS304 welded plate

5. Welded Stainless Steel Plated

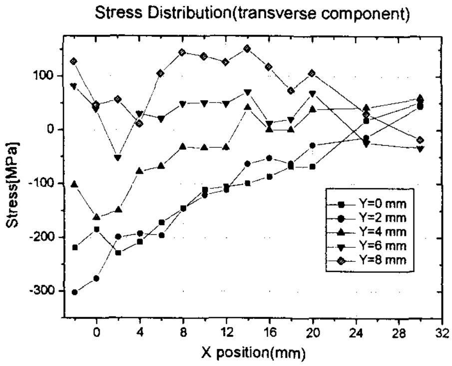
The sample (Dr. Dong-Yong Jang, SNUT) was prepared by welding of two SUS304 stainless steel plates of sizes $20\times50\times100mm^3$. In Fig.8 the Cartesian co-ordinate system adopted for the strain components and measurement positions is shown. It was assumed that the principal strain directions were along and perpendicular to the weld in the plane of the plate, and normal to it, and measurements were made in these three directions. Sample symmetry relative to the axes X, Y was assumed, and strain distribution in the one fourth of section perpendicular to the weld in the middle of the weld (Z=0) was measured. Diffraction peak (220) ($2\theta \approx 95^0$) was scanned. The plate 20×50×100mm3 from the same material was studied to determine diffraction angle $2\theta_0$ corresponding to the stress-free material. The strain was measured with a typical error of $\pm30\times10^{-6}$. The variation of normal strain component along the transverse line is shown in Fig. 9. The variations of stress components are shown in Fig. 10.

6. Conclusion

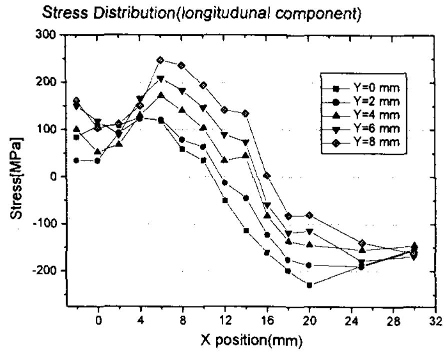
The instrument for residual stress measurements with special position sensitive detector is installed at HANARO reactor in KAERI. Early measurements of model samples showed that instrument allows to measure in-depth stress distribution in industrial components with high accuracy.



(a) Normal component



(b) Transverse component



(c) Longitudinal component

Fig. 10. Stress distribution in SUS304 welded plate

Acknowledgement

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(3) V.T. Em et al., KAERI/TR-1343/99

(4) Chang-Hee Lee et al., KAERI/RR-2040/99