

NEUTRON DIFFRACTION MEASUREMENTS OF RESIDUAL STRESSES IN NPP CONSTRUCTION MATERIALS

Robert Hince¹ and Gizo Bokuchava²

¹ Department of Nuclear Physics and Technology, STU Bratislava, Slovakia, hince@elf.stuba.sk

² Frank Laboratory of Neutron Physics, JINR Dubna, Russia, gizo@nf.jinr.ru

ABSTRACT

Neutron diffraction is one of the most powerful methods for condensed matter studies. This method is used for non-destructive determination of residual stresses in material. The fundamental aspects of neutron diffraction are discussed, together with a brief description of the experimental facility. The principal advantage of using neutrons rather than the more conventional X-rays is the fact that neutron can penetrate deeply (2-4 cm for steel and more than 10 cm for aluminium) into metals to determine internal parameters within the bulk of materials. We present results of measurements residual stresses in NPP construction material – austenitic stainless steel (Cr-18%, Ni-10%, Ti-1%) coated with high-nickel alloy.

INTRODUCTION

Stress investigations using neutron diffraction occupy a special position in non-destructive testing. The principle is similar to that of the well-known X-ray technique in which the internal lattice stress present in a material is obtained from the measured elastic lattice strain it produces in the crystallites of which it is composed. Lattice strains for all available crystal planes (hkl) were obtained from relative shift of diffraction peaks.

The main difference between this techniques is that X-rays can be used only in the surface region ($\approx 100 \text{ \AA}$) due to the strong absorption in the matter, whereas neutrons can penetrate a few centimetres (2-4 cm for steel and more than 10 cm for aluminium) into metals to determine internal parameters within the bulk of materials. On the other hand, X-rays can be made available in any laboratory and operation of X-ray diffractometers is much cheaper as operation of intense neutron sources.

THEORETICAL BASIS OF STRESS MEASUREMENT

Material structure information is obtained from measured neutron intensity spectra. A regular crystal lattice gives rise to sharp Bragg reflections (FIGURE 1). Disorder, like interstitials or vacancies, reflects itself in diffuse scattering between Bragg peaks.

Large objects, like clusters in alloa, polymer conglomerates, or biological macromolecules, are imaged at small neutron scattering angle.

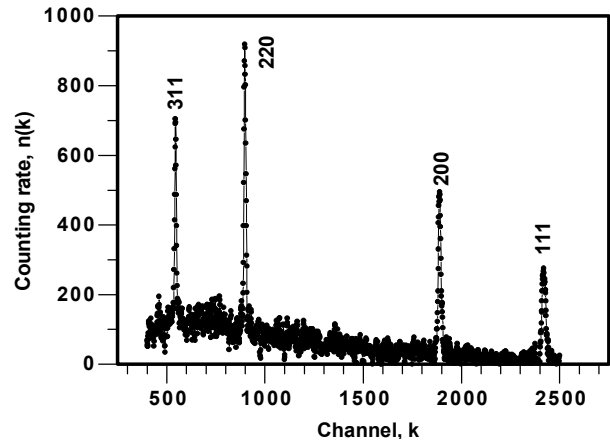


FIGURE 1. Diffraction spectrum of an austenitic stainless steel

The interplanar distance d_{hkl} can be evaluated by using the Bragg law:

$$\lambda = 2d_{hkl} \cdot \sin \theta \quad (1)$$

Lattice strain is defined as:

$$\epsilon_{hkl} = \frac{d_{hkl} - d_0}{d_0} \quad (2)$$

where d_0 is the hkl-interplanar distance in a stress-free material.

Precise determining d_0 is very important because each error implies systematic errors in all stress values. We have measured d_0 in a specimen from investigated material special thermal treated in order to relieve the residual stress.

For evaluation of stresses we have used an elastically isotropic model with Young's modulus $E = 214 \text{ MPa}$ and Poisson's ratio $\nu = 0,3$.

The strains in this model are calculated by equations [1]:

$$\sigma_{xx} = \frac{E}{(1+\nu)} \cdot \left[\epsilon_{xx} + \frac{\nu}{1-2\nu} (\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) \right]$$

$$\sigma_{yy} = \frac{E}{(1+\nu)} \cdot \left[\epsilon_{yy} + \frac{\nu}{1-2\nu} (\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) \right]$$

$$\sigma_{zz} = \frac{E}{(1+\nu)} \cdot \left[\epsilon_{zz} + \frac{\nu}{1-2\nu} (\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) \right] \quad (3)$$

EXPERIMENTAL FACILITY

The diffraction experiments presented in this paper were carried out at the spectrometer HRFD. It is located on beam-line 5 at the pulsed reactor IBR-2 of Frank Laboratory of Neutron Physics (FLNP) at the JINR Dubna (**FIGURE 2**).

HRFD is a neutron reverse time-of-flight Fourier diffractometer intended for precise structural studies of polycrystals and residual stress investigations in bulk samples and advanced materials at a resolution level of about 0.001 or better.

HRFD, the first neutron Fourier diffractometer at a pulsed neutron source, combines a high neutron flux at sample position, $\sim 8 \cdot 10^6 \text{ cm}^{-2}\text{s}^{-1}$, provided by the IBR-2 high flux pulsed reactor, and a high resolution over a wide range of d-spacings. The detailed description of the HRFD design, performance and parameters is given in [4].

HRFD includes the following equipment for residual stress studies: four neutron detectors at the scattering angles of $\pm 90^\circ$ (solid angles of 28 and 7 msr) and $\pm 152^\circ$ (the solid angle of 80 msr each), 4-axis (x, y, z, w) linear scanner for simple experiments, 5-axis (x, y, z, w, W) "HUBER" goniometer for total strain tensor measurements, load testing machine "TIRA" for in situ studies of samples under load and nitride boron slit systems for forming the incident and scattered neutron beams. Both $\pm 90^\circ$ -detectors are equipped by multi-slit radial collimators with gauge volume resolution of 2 mm.

High neutron flux at the sample position and high resolution gives a possibility for precise strain measurements at HRFD within a reasonable measuring time.

MATERIAL OF INTEREST

Austenitic stainless steel with the GOST mark 08X18H10T is used as a construction material for reactor internals, primary circuit loop pipelines, collectors of parogenerators etc.

High nickel weld filler is used for maintenance and repair of primary circuit components at Slovak nuclear power plant type VVER. The repair technology was developed at Welding Research Institute Bratislava. Composition of sample material is in **TABLE 1**.

Surfacing high-nickel filler on an austenitic base metal is one of the most progressive techniques in maintenance and repair of primary collector in the primary circuit of nuclear power plant type VVER. Surfacing can leave strong residual stresses locked in within component. Heat treatment after surfacing is by primary circuit

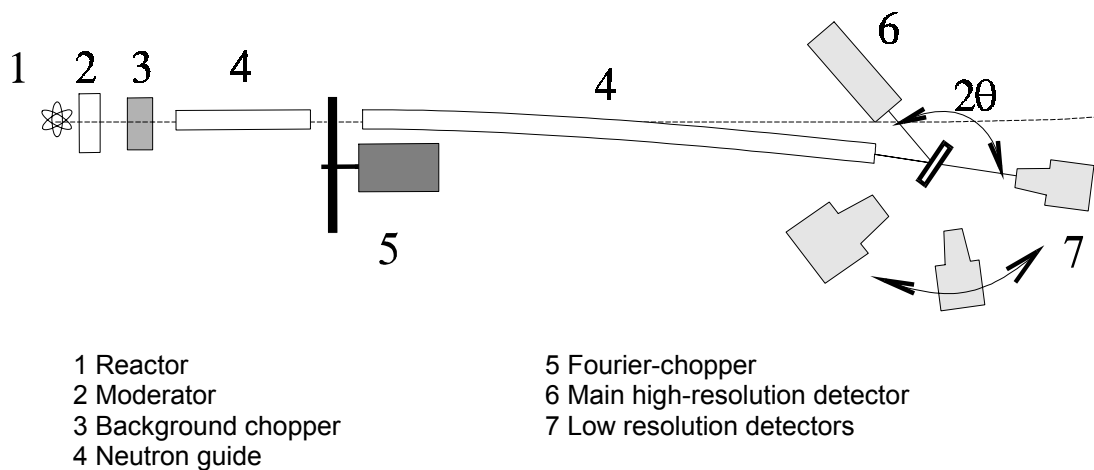


FIGURE 2. Layout of HRFD diffractometer

TABLE 1. This table shows composition of sample material (%)

Basic Material	C	Si	Mn	Cr	Ni	Ti	S	P	Fe	Weld filler	Ni	Cr	Nb
08X18H10T	0.08	0.8	2.0	18	10	0.7	0.02	0.035	rest		70	20	10

components very tricky or impossibly. In application of surfacing technology on complex structural nodes it is very important, from the viewpoint of residual life, to know the level of residual stresses.

For experimental measurement of residual stresses were prepared 5 types of specimens with $25 \times 70 \times 80 \text{ mm}^3$ and 2 specimens with $15 \times 100 \times 100 \text{ mm}^3$ dimensions (FIGURE 3).

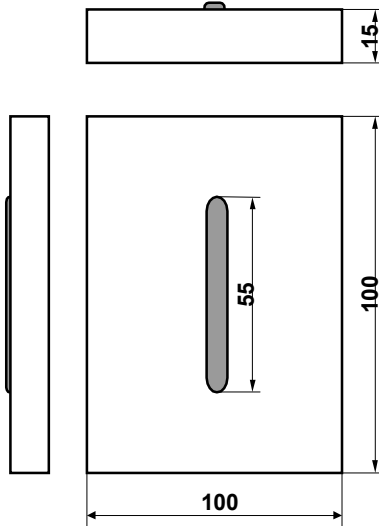


FIGURE 3. Sample with welded bead

All specimens were before surfacing stress relief heat treated to attain the stress free state. For determination of lattice parameter has been used a stress free reference specimen.

RESULTS

During the 4th cycle of IBR-2 reactor in April 1999 and 1st cycle in January 2000 the samples with 1 bead of high-nickel weld filler has been investigated (FIGURE 4).

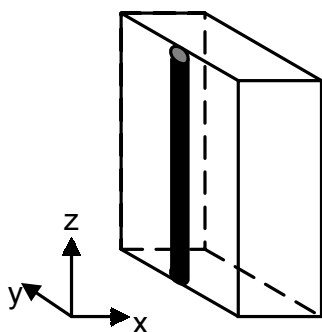


FIGURE 4. Sample with 1 bead and decided directions

Lattice strain has been measured in three directions (normal, transverse and longitudinal to the welding direction). The measuring points were chosen under bead (in the direction of X axis) at the distance of 1, 3, 5,

7 and 10 mm for sample with 25 mm thickness and 1.5, 3.2, 5, 6.8 and 8.6 mm for sample with 15 mm thickness.

The slit width for first measurement has been decided at 1.5 mm. Following it has been enlarged at 2.2 mm because of low counting rate. Since the stress state centre of the sample was uniform along the Z-axis, a slit height of 40 mm for normal and transverse direction measurement was appropriate (FIGURE 5). Hence, the gauge volume became $2.2 \times 2.2 \times 40 \text{ mm}^3$ (for 2nd sample the gauge volume became $2 \times 2 \times 35 \text{ mm}^3$). For measurement of longitudinal strain component e_z the gauge volume $3 \times 6 \times 3 \text{ mm}^3$ was appropriate.

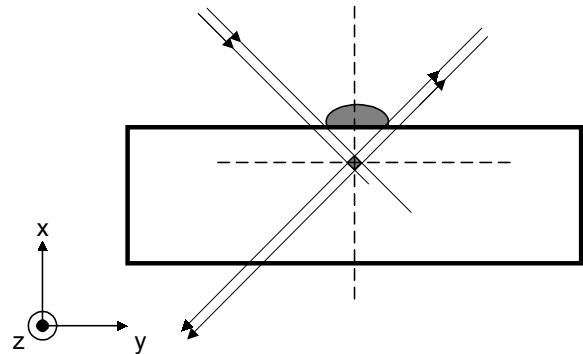


FIGURE 5. Measurement of normal and transverse strain component (e_x, e_y)

Measured data of normal and transverse strain component of 25 mm thick sample are plotted in FIGURE 6. Longitudinal strain component e_z was not acquired because of low counting rate for transmitted neutron beam from small gauge volume in sample material. These measurements would require too long time.

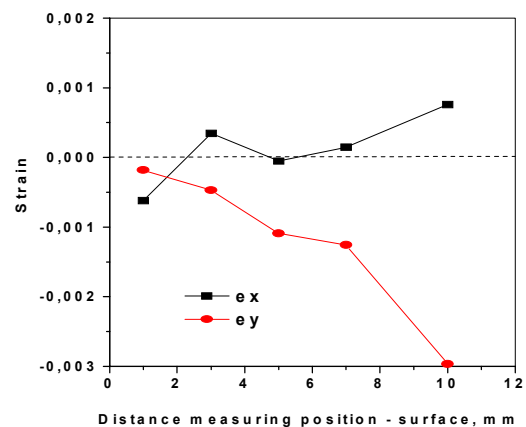


FIGURE 6. Normal and transverse strain component measuring data (e_x, e_y) of sample with 25 mm thickness

For continuation, 2 samples with 15 mm thickness are prepared. The complete three directional lattice strain measurements were performed during the reactor cycle in January 2000. Measured strain data are plotted in FIGURE 7.

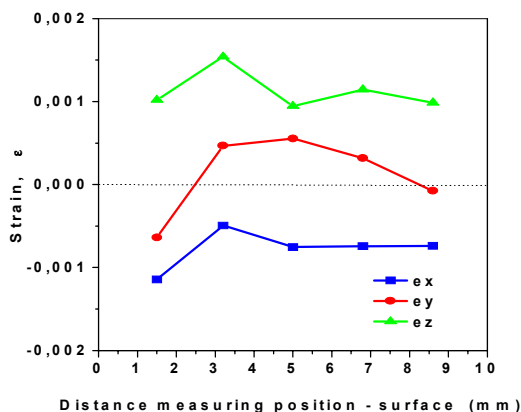


FIGURE 7. Measured strain component data of sample with 15 mm thickness

An elastically isotropic model (3) with Young's modulus $E = 214 \text{ MPa}$ and Poisson's ratio $\nu = 0,3$ has been used for evaluation of stress components. Calculated stress data are plotted in **FIGURE 8**.

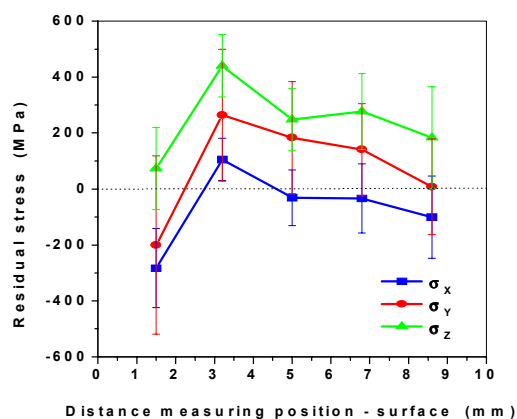


FIGURE 8. Measured stress components data of sample with 15 mm thickness

DISCUSSION

The aim of the investigation is to study the level of residual stresses induced by the surfacing in the weld deposit zone and in the base metal where considerable thermal gradients exist.

Measurements of residual stresses in the weld overlay and in the base metal are desirable to prove the mechanical analysis and to verify residual stresses determination on welded material by numerical computer welding simulation.

For verification of numerical simulations, it is important take the gauge volume averaging effect into account.

Investigations of residual stresses are important to develop the optimal welding techniques.

CONCLUSIONS

A set of samples with simple geometry was prepared for measurements. Geometry was chosen in order to simplify further comparing of obtained data with calculated values by numerical simulation.

Complete measurements in reasonable time were achieved for austenitic stainless steel 08X18H10T 15 mm sample.

For construction materials of facilities with internal pressure, high residual tensile (high positive level of residual stress component) is unsuitable because of its combination with external load which could damage or destroy the facility. From this viewpoint, the longitudinal stress component e_z is of crucial importance at the surfacing technique.

ACKNOWLEDGEMENTS

We are thankful for specimen preparation to V. Magula from Welding Research Institute Bratislava.

REFERENCES

- [1] Noyan I. C., Cohen J. B. – Residual Stress. Measurement by Diffraction and Interpretation, Springer-Verlag New York Inc. (1987)
- [2] Albertini G., Bruno G., Carrado A., Fiori F., Rogante M., Rustichelli F. – Determination of residual stresses in materials and industrial components by neutron diffraction, *Meas. Sci. Technol.* **10**, R56-R73 (1999)
- [3] Fletcher, A. J. – *Thermal stress and strains generation in heat treatment*, Elsevier Science Publishers LTD, (1989)
- [4] Aksenov V.L., et al. Performance of the high resolution Fourier diffractometer at the IBR-2 pulsed reactor, *J. of Neutron Research*, **5**, pp. 181-200 (1997).