*ICANS-XI International Collaboration on Advanced Neutron Sources*
*KEK, Tsukuba, October 22-26, 1990*

# ENGINEERING STRAIN MEASUREMENTS using the NPD at LANSCE

M. A. M. Bourke, J. A. Goldstone, K. J. Lovell.
LANSCE
Los Alamos National Laboratory
New Mexico, 87545
USA

## Abstract

The presence of residual stress in engineering components can affect their mechanical properties and structural integrity. Neutron diffraction is the only measuring technique which can provide spatially resolved non-destructive strain measurements in the interior of a component. By recording the change in the interplanar spacings elastic strains can be measured for individual lattice reflections. Also on a pulsed source, where all lattice reflections are recorded, profile refinement is an option which allows the strain to be obtained from changes in the lattice parameter. Measurements made at LANSCE demonstrate the potential for stress measurements on a pulsed source and indicate the advantages and disadvantages over measurements made on a reactor.

## Introduction

Measurements of macroscopic residual stress in engineering components were first made in the early eighties on reactor sources (refs. 1,2). However it is only recently that pulsed sources like ISIS and LANSCE have produced sufficient neutron intensities to make measurements in components which may involve neutron path lengths in a specimen of several centimeters. Engineering strain measurements necessitate positioning of samples to accuracies of 0.1mm relative to precisely defined neutron beams. Different positions are examined by translating the specimen through a defined volume. The strain in different directions is measured by reorienting the specimen with respect to the detectors. Thus the main requirements are a multi-axis manipulation system and precise, repeatable collimation of both the incident and exit beams. On the NPD at LANSCE or POLARIS at ISIS the collimation and manipulators must be placed in a sample can of diameter less than 1m which limits the range of travel available and complicates the positioning of specimens. The approach taken on the NPD at LANSCE is to independently mount both the apertures and translators on a frame which can be placed precisely in the sample can using cone locators. This has proved effective since the specimens can accurately be aligned optically prior to insertion of the apparatus into the vacuum can.

### Definition of a sampling volume

On most neutron powder diffractometers or spectrometers the incident beam cross section is several $cm^2$. However stress fields near crack tips or due to severe processing may vary over distances comparable to a millimeter. Thus the sampling volumes required for strain examination by neutron

diffraction are typically between 10 and 60mm$^3$. Definition of a sampling volume is achieved by masking the incident and diffracted neutron beams to produce a single intersection from which neutrons can reach the detectors. The optimal scattering angle is 90° since this gives the best spatial resolution in the specimens.

The manipulation system which has been developed for use on the NPD (neutron powder diffractometer) at LANSCE provides 360° rotation about a vertical axis, XY horizontal travel of 35cm and a vertical range of 45cm. It can carry components up to 50kg. The NPD has four detector banks at ±90° and ±148° which potentially offer four simultaneous strain measurements during each measurement. However at this time exit collimation has only been installed on the 90° banks. The collimating apertures are supported from optical benches and may be moved on radii from the centre of the sample can. Positional adjustment is achieved using microcontrol manual adjusters. The masks were machined from commercially obtained boron nitride (cost ~$1000US/1000cm$^2$ at 1.3cm thick). Boron is used as the active component for collimation on pulsed sources since (unlike cadmium) it remains opaque to neutrons with wavelengths less than 0.5 Å. Boron nitride proved to be easy to machine and a variety of precise aperture shapes were fabricated.

The NPD lies 32m from a tungsten target and the divergence of the incident beam at the sample position is small. Consequently the distance between the incident aperture and the specimen is not critical to the definition of a sampling volume. The defocussing at the sample position due to the inherent beam divergence for a 2mm square placed 50mm from the specimen is only ~0.2mm in each dimension. Collimation of the diffracted beams is more sensitive to the position of the exit aperture (more so than on a reactor source) because there is no inherent collimation between the sample position and the detectors. Consequently the spatial resolution along the incident beam decreases with increasing distance of the exit aperture from the incident beam. The time of flight operation of a pulsed source means that to make measurements in acceptable times care must be taken not to achieve exit collimation at the expense of obscuring too large a solid angle of the detectors.

By assuming sharp cut-offs at the edges of the exit slits the angle of the 90° detector visible at different positions along the incident beam can be evaluated. The parameters which can be altered for the exit apertures are their width (d), thickness (t) and distance (l) from the specimen (fig 1). Many specimens possess plate geometries which are placed at 45° to the incident beam for simultaneous in-plane and normal strain measurements using the 90° detectors. Some apertures have been fabricated with slits at 45° to the surface. This permits the aperture to be placed adjacent to the specimen surface (i.e. closer to the incident beam than a flat aperture) which improves the resolution along the incident beam. This is illustrated in figure 2.

Calibration measurements were made by translating a vertical 4mm diameter steel pin through the sampling volume defined for different aperture sizes and positions. The diffracted intensity was noted as the pin was moved parallel and normal to the incident beam. The dimensions of the sampling volume normal to the incident beam direction showed sharp cut-offs indicating that it could be treated as parallel sided. Scans parallel to the incident beam demonstrated the sensitivity of the resolution along the incident beam path to the position of the exit aperture. It was shown that the resolution could be calculated for different exit mask arrangements from geometric considerations.

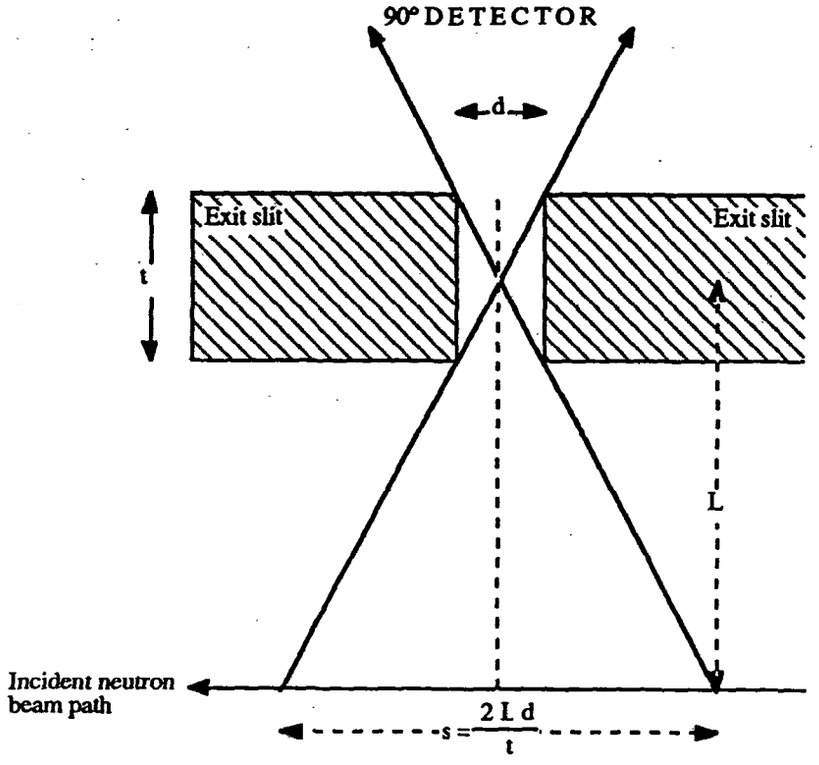


Figure 1: Shows the spatial resolution (s) along the beam path (not including the finite angle subtended by the detectors).

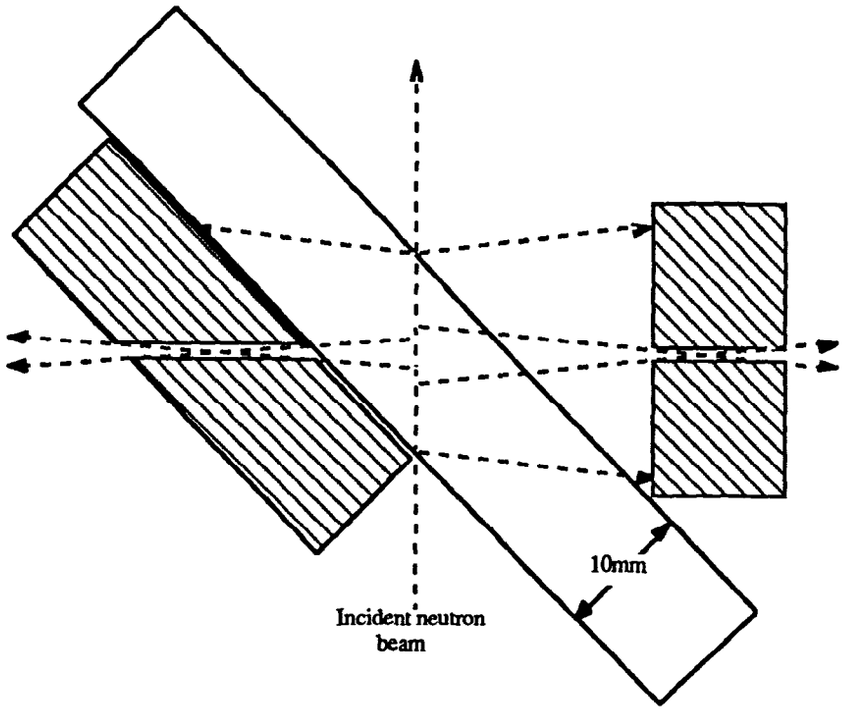


Figure 2 : Comparison of the spatial resolution for the normal and 45° exit apertures.

## Data analysis

Measurement of grain interaction stresses has already been performed on pulsed sources (ref 3) however the measurements made at LANSCE represent the first attempt to define small gauge volumes within components to investigate the variation of macroscopic residual stress variations through a component. Consequently there is uncertainty concerning minimum count times to obtain specified strain accuracies for different materials, specimen geometries and aperture geometries. Measurements performed at ISIS on a thin autofrettaged ring (with no exit collimation) demonstrated that profile refinement of spectra obtained from different regions in a component permits the strain to be obtained from changes in the lattice parameter (ref 4). This is important since count times for each measurement may be reduced if the strain is obtained from the lattice parameter instead of from individual lattice reflections. This approach is attractive from an engineering standpoint since it averages any anisotropic variations due to differences in elastic compliance offering a strain value which might, in the absence of preferred orientation, be assumed to represent a bulk average. If detailed information concerning the strains for grains in specific orientations is required then count times must be increased in order to obtain adequate statistical accuracy for individual peak fits.

The two 90° detectors on NPD at LANSCE each consist of sixteen $^3$He tubes which subtend an angle of 11° at the sample position. Each individual tube collects a spectrum corresponding to a unique strain direction in the specimen. However single tubes can take many hours to provide adequate spectra which is unacceptably long. Consequently all the detectors in each 90° bank are added together giving a combined spectrum corresponding to a spread in the scattering vector (and thus of the strain measuring directions ) of 5.5° (fig 3). In addition the backscattering detectors also give an indication concerning the texture of the material and strain measurements but with poorly defined sampling volumes.

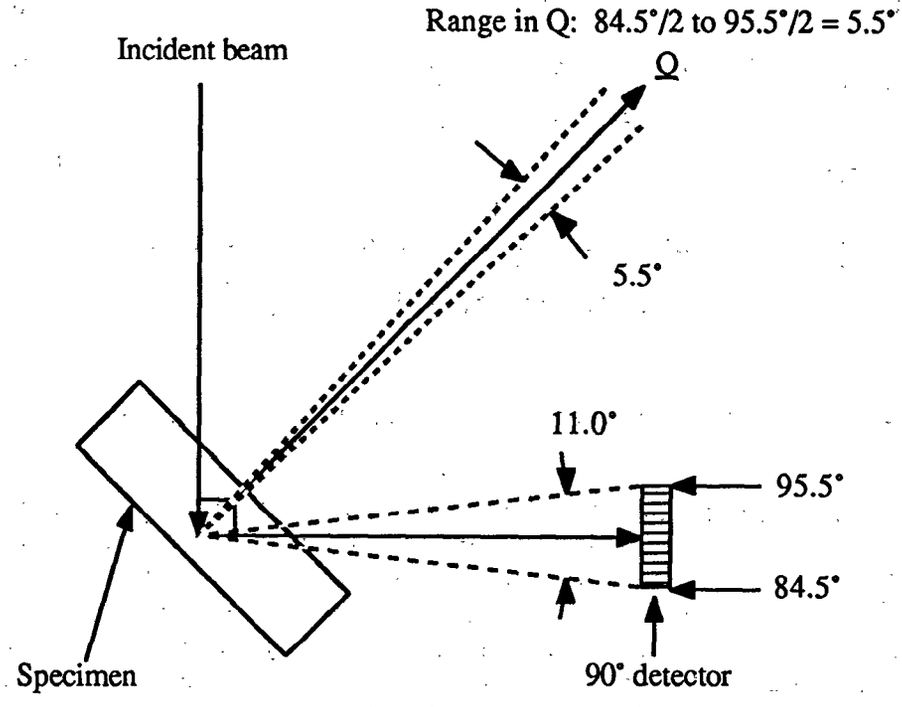


Figure 3: Range in scattering vector resulting from addition of all spectra obtained from 90° detector.

## Preliminary Results

To evaluate the capability of making residual strain measurements with restricted sampling volumes, in collaboration with Tom Holden of AECL, we examined a deformed stainless steel ring which has been modelled by detailed finite element calculations and has been previously studied at Chalk River National Laboratory, Canada (ref 5). The ring is approximately 76mm ID, 127mm OD, and 13mm thick and was compressed along a diameter. Our measurements were along a radius in a section of the ring at 90 degrees from the applied stress point. Using a sampling volume of 40 $mm^3$ with a beam current of ~75μA two strain directions were measured at each position every 4 hours. The accuracy for strong reflections was <±80μstrain. Three strain components, tangential, radial and axial were measured on the 90° detectors by using two orientations of the ring. Figure 4 shows the tangential strain data available from many of the reflections observed. The trend in the strain is evident in all reflections and these data agree with the (111) and (200) reflections measured at Chalk River and the calculations.

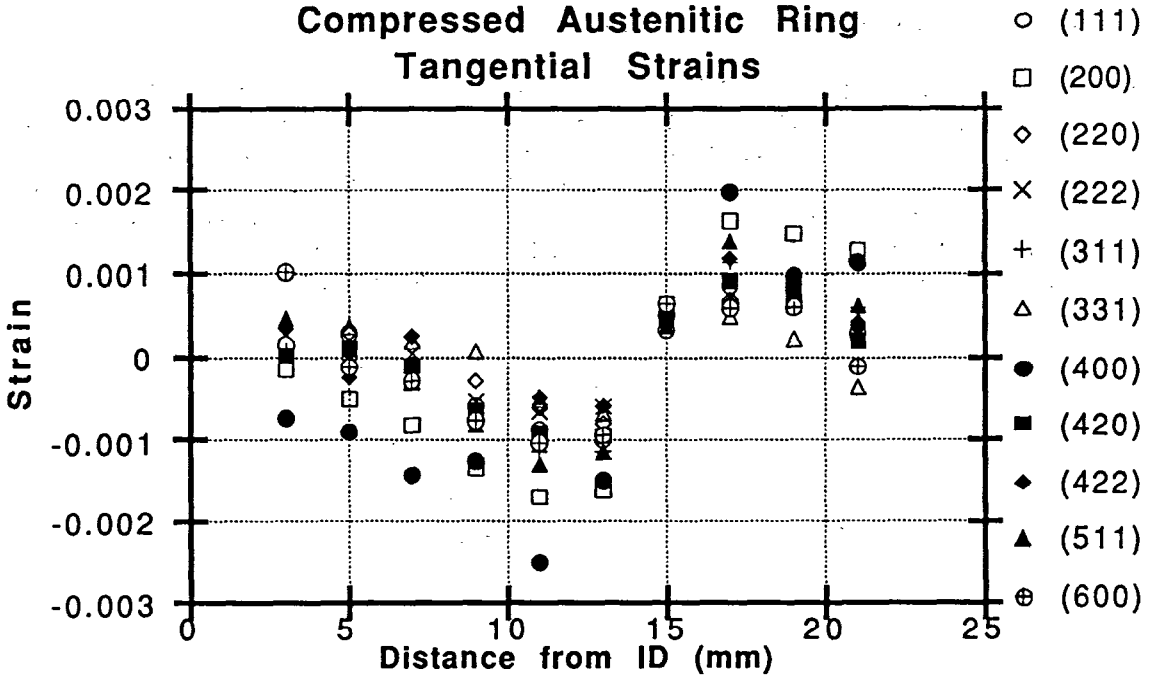


Figure 4: Tangential strain measurements for selected (hkl) reflections.

An advantage of a pulsed source is that strain information can be obtained for all lattice reflections in each measurement. The anisotropic strain response is illustrated in figure 5. The strains at a single measuring position are plotted for each reflection against the anisotropy factor $A_{hkl}$ (= $[h^2k^2 + k^2l^2 + l^2h^2]/[h^2 + k^2 + l^2]$ ). In principle the relationship between the strain and $A_{hkl}$ is given by $\varepsilon_{hkl} = \sigma[S_{11}-2SA_{hkl}]$, where $S = S_{11}-S_{12}-S_{44}/2$ (ref 2). Using the single crystal compliance values, the slope and intercept give an estimate of the elastic stress in the material. Deviations from the elastic model or the inappropriateness of using the single crystal compliances will appear as inconsistencies in stress computed from the different strain components

Other samples examined include whisker and particulate reinforced Al-SiC composites, multipass welds, and a compacted powder. The Al-SiC metal-matrix composite specimens did not require a small sample volume because the strains of interest were assumed to be uniform throughout the samples.

Uniaxial tension or compression specimens were deformed to differing levels of plastic deformation and then released. The residual strain states of the two components in the composites were then examined. Neutron diffraction is a valuable tool for studies of this nature because the matrix and reinforcement can be examined simultaneously and non-destructively. This basic study of the composite response to stress was complimented by the examination of a composite automobile component.

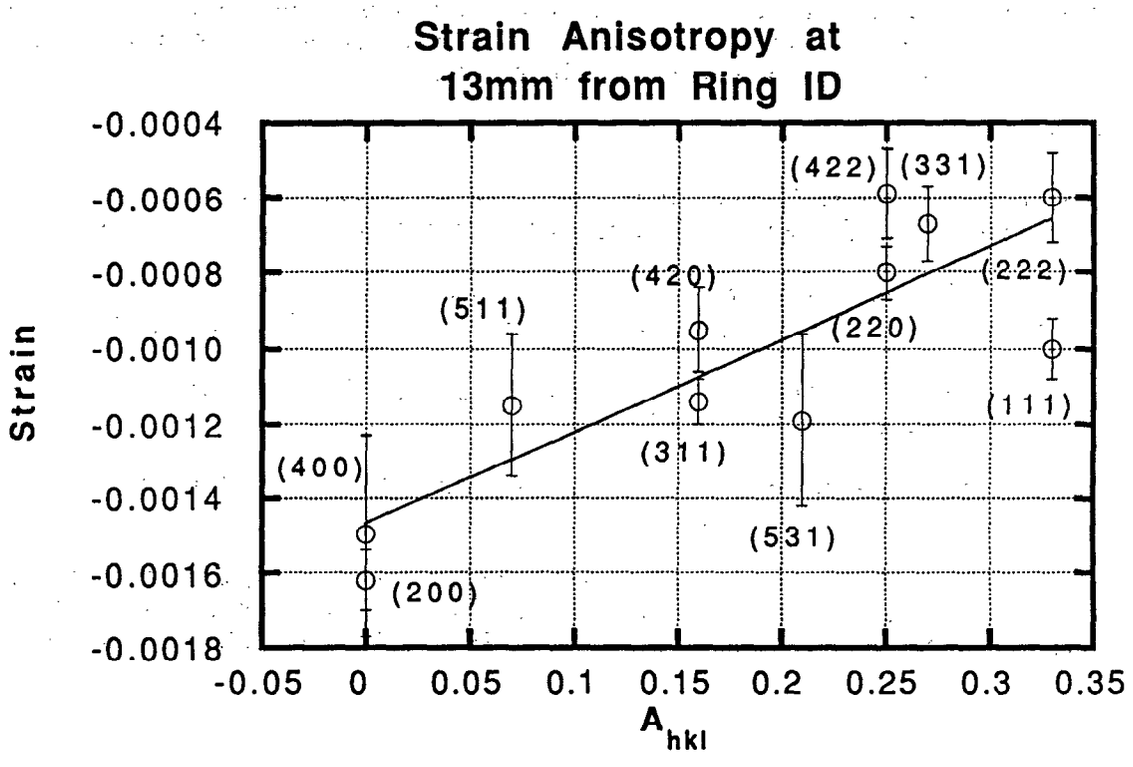


Figure 5: Anisotropic strain for selected (hkl) reflections at 13mm from the ring ID.

The multipass welds were in 2.5 cm thick stainless plates (30cm x 30cm). They represented a severe test concerning the maximum path length ($2.5\sqrt{2}$ cm) in steel over which the neutrons can pass while still giving representative strain measurements in reasonable time scales. The weld was scanned from the top surface to the bottom of the weld vee using an extended sampling volume to take advantage of the symmetry along the weld direction. Data were taken to evaluate the nature of residual strain developed by different weld methods. In compacted metal powders, the integrity of the part is strongly affected by the residual strains from processing. We began a basic study of the strains in a cylindrical ejected compacted powder sample, looking at the strains through a diameter and in the corner of the specimen. Results will help improve models of the strain state.

## Conclusions

A manipulation and collimation system has been installed on the NPD at LANSCE. Components up to 50kg can be moved within the confines of the sample tank. Sampling volumes as small as $10mm^3$ have been achieved for thin flat samples. However for complicated specimen geometries unless the exit collimation can be placed within 30mm of the incident beam it is impossible to define small ($<20mm^3$) sampling volumes and make individual strain measurements in less than a day.

Although collimation has only been installed on the ±90° detectors strains are recorded on all detectors, and "bonus information" is collected in the backscattered directions. Using the two 90° banks two strain measurements (normal to each other) with well defined sampling volumes are obtained in each measurement. Consequently when measuring triaxial stress distributions there may be duplication of measurement in one direction which provides a check and calibration of the experiment.

The presence of all the lattice reflections in each spectrum provides information concerning the overall stress state of the material at a granular level. This is important in understanding grain interaction stresses, slip processes in polycrystals and will help to calibrate measurements on reactor sources where strains are usually inferred from only one or two Bragg reflections.

## References


1. *Measurement of residual stresses by neutron diffraction*, Stacey, A., MacGillivray, H.J., Webster, G.A., Webster, P.J. & Ziebeck,K.R.A. Journal of strain analysis, **1985a**, Vol. 20, No 2, 93-100.

2. *Neutron diffraction methods for the study of residual stress fields*, ,Allen, A.J., Hutchings, M.T., Windsor, C.G. & Andreani, C, Advances in physics, **1985**, Vol. 34, No4, 445-473.

3. *The use of time of flight neutron diffraction to study grain interaction stresses*, MacEwen, S.R., Faber, J. & Turner, P.L., Acta metall, **1983**, Vol 31, No 5, 657-676.

4. *Residual stress measurement in engineering components by neutron diffraction*, Bourke, M.A.M., PhD Thesis, University of London **1990**.

5. *A comparison of finite element analysis with neutron and X-ray measurements of residual strains in stainless steel*, Flower, E.C., MacEwen, S.R., Holden, T.M., Hosbons, R.R., Proceedings of the international conference on residual stresses, **1989b**, Nancy (1988), pbld by Elsevier.