MECH2420: Residual Stress Measurement using Neutron Diffraction

Report Handout

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February 27, 2015

Contents

1 Scope and Task

This assessment task requires students to provide an engineering report detailing the analysis and discussion of experimental data. This data originates from a set of residual stress measurements taken from a plastically deformed beam using neutron diffraction techniques. This report should cover the following;

- a review of diffraction based strain measurement techniques,
- an analysis of all experimental data provided, and,
- a discussion surrounding the experimental results in the context of elastoplastic beam bending theory as discussed in the lectures.

The report should be of a standard benefiting a professional engineer.

2 Introduction

2.1 Diffraction Basics

Diffraction refers to a range of phenomena that occur when waves interact with geometric structures. In its simplest form, diffraction refers to the alternating patterns of constructive and destructive interference between waves created at two different point sources (see Figure 1). A good general overview of diffraction phenomena can be found at https://www.youtube.com/watch?v=Iuv6hY6zsd0.

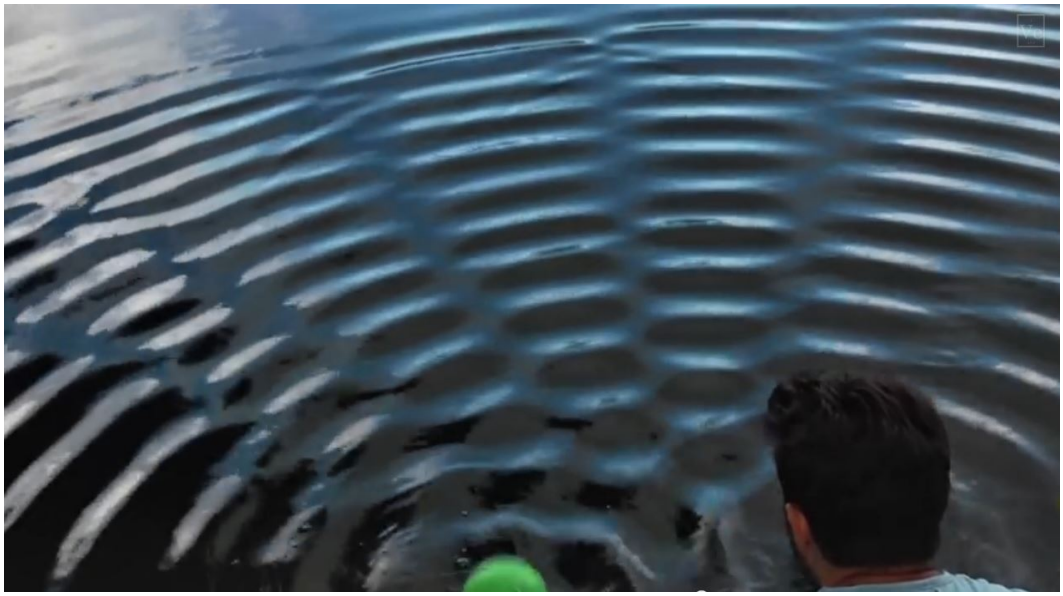

Figure 1: Constructive and destructive interference in water waves leading to diffraction peaks. (See `https://www.youtube.com/watch?v=Iuv6hY6zsd0`)

A central concept in the theory of quantum mechanics is that all sub-atomic particles (photons, electrons, neutrons, protons, etc.) have both particle and wave-like properties. The de Broglie wavelength of a given particle, λ, is related to its momentum, p, through Planck's constant, h;

$$\lambda = \frac{h}{p} \tag{1}$$

The wave-like behaviour of these particles means that diffraction phenomena can occur when radiation interacts with solid crystalline materials. When particles interact with atoms in a crystal lattice, each atom becomes a source for further radiation via Huygen's principle. If the wavelength is fixed, this scattered radiation forms patterns of constructive and destructive interference in exactly the same way as the water waves above (except in three dimensions). With reference to Figure 2, diffraction peaks (i.e. constructive interference) occur at angles where any given scattered ray travels an integer number of wavelengths further than its neighbour. Through some simple geometry we can express this as Bragg's law;

$$n\lambda = 2d\sin\theta, \tag{2}$$

where, in the case of a crystal structure, d represents the interatomic spacing between crystal planes. As is (or will be) discussed in MECH2250 (Material Science and Engineering 1), many different planes exist within a crystal and diffraction peaks corresponding to each plane are usually observed.

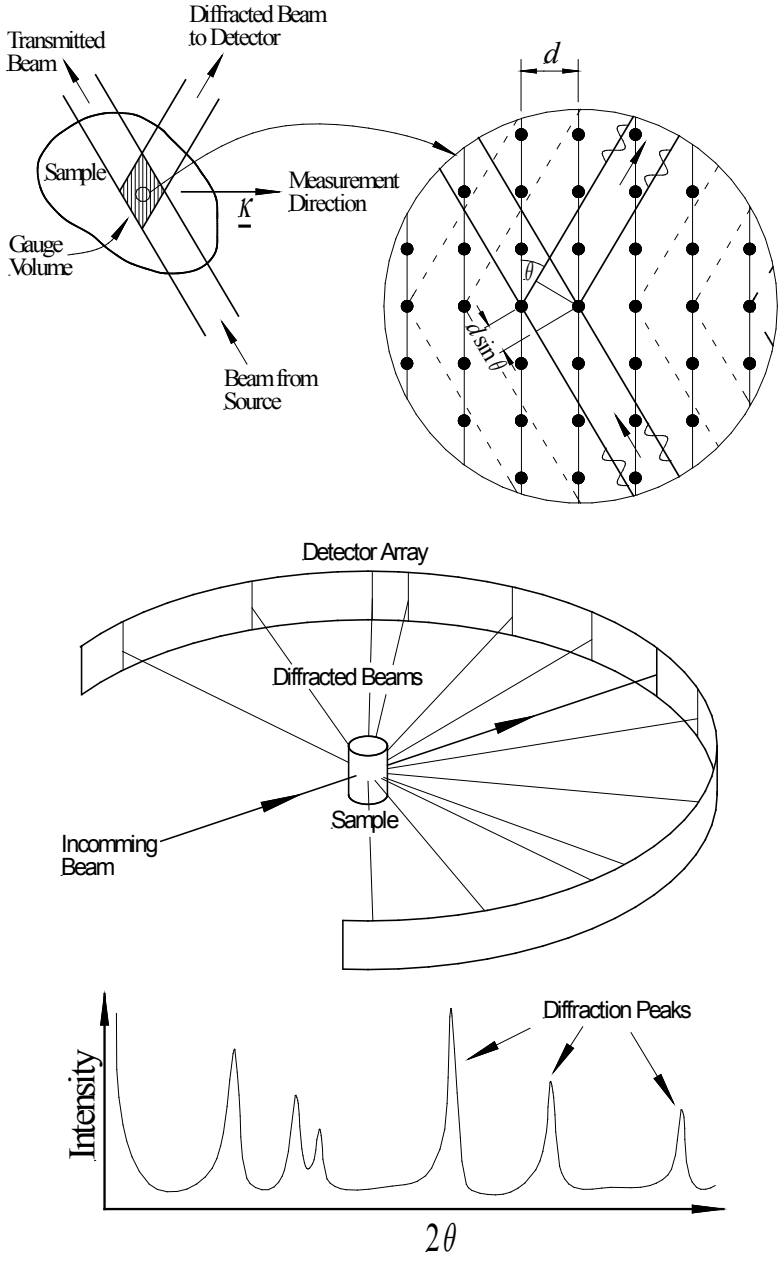

Figure 2: Neutrons (as waves) are scattered by a crystal lattice, forming diffraction peaks at angles satisfying Bragg's law. The full diffraction pattern provides detailed information on the crystal structures within a material; each diffraction peak corresponds to a single lattice spacing.

This phenomenon provides an excellent window into the nature of solid materials; by measuring the location of diffraction peaks a great deal of information can be gained in terms of the crystal structures within. For this reason, diffraction has become one of the most important experimental techniques in crystalography, material science, and solid state physics.

Neutrons are particularly useful for this type of work as they are only scattered by the nuclei of atoms and have no interaction with electron shells. This tends to mean that they only weakly interact with most materials; the size of the nucleus is a tiny proportion of the volume of an atom. The

consequence of this is that neutrons can penetrate relatively large distances within most materials and are able to uncover detailed information deep within a sample.

2.2 Strain Measurement Using Neutrons

An important engineering application of neutron diffraction is the direct measurement of strain. When stress is applied to a solid material elastic strains are produced according to Hooke's law. At the atomic level this appears as minute changes in the interatomic spacing. Modern strain diffratometers (See Figure 3) are able to detect and measure these changes and hence measure strain within a sample in an entirely non-contact way.

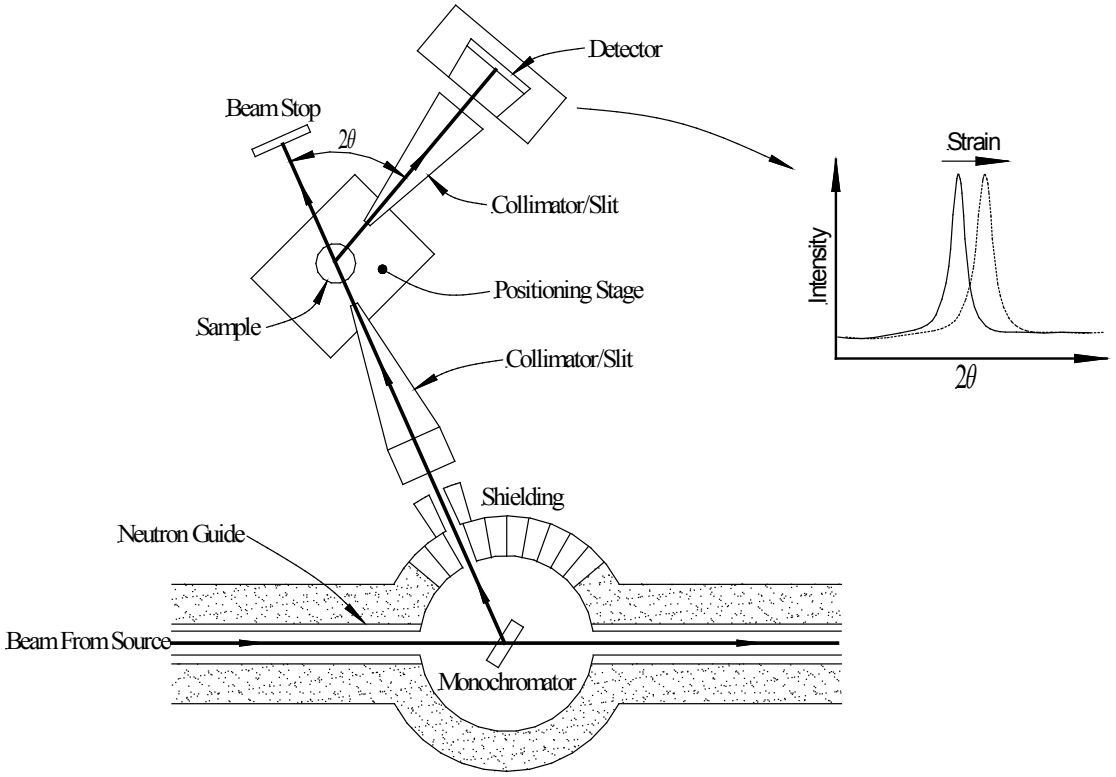

Figure 3: A strain diffractometer precisely measures the position of a single diffraction peak. Movements of this peak correspond to changes in the lattice spacing due to elastic strain.

The measurement of strain using this approach relies upon measuring two lattice spacings (via Bragg's law); an undeformed (reference) spacing, d_0, and a deformed version, d. Strain is then calculated as;

$$\epsilon = \frac{d - d_0}{d_0} \tag{3}$$

Several things are worth mentioning about this type of strain measurement;

- the strain measurement refers to a normal component of strain in the direction bisecting the incoming and diffracted beams; as indicated by the 'Measurement Direction' in Figure 2,
- the measurement refers to an average in a small well-defined region formed by the intersection of the incoming and diffracted beams known as the gauge volume (again see Figure 2), and,
- only the elastic component of strain is measured. Plastic strains are related to slip mechanisms within the lattice; they do not affect the lattice spacing. In other words, the measured strain is related to the applied stress directly by Hooke's law - regardless of the amount of plasticity in the sample.

By moving the gauge volume around and measuring in various directions it is possible to map-out the distribution of the full stress tensor within a sample using this approach. This technique can be used to map-out and measure applied stresses within *in situ* loaded samples as well as residual stresses caused by plastic deformations or thermal processes (e.g. welding).

3 Experiment Description

A neutron diffraction experiment focused on measuring residual stress in plastically deformed aluminium bars was carried out carried out on the KOWARI diffractometer in the OPAL nuclear reactor Beam Hall at Lucas Heights in Sydney Australia. This instrument is operated by the Bragg Institute within the Australian Nuclear Science and Technology Organisation (ANSTO).

The following section provides all of the relevant details of this experiment. Further information can be provided by the Course Coordinator if required.

3.1 Sample Preparation

3.1.1 Sample Descriptions

The experiment centred around two samples of commonly available precipitation hardened aluminium alloys in the form of rectangular bars; one sample of 6061-T6 and one sample of 7075-T6. These samples were cut from larger rolled plates by a supplier in Sydney. These samples were prepared by facing all sides on a milling machine before polishing. The final dimensions of each sample was as shown in Table 1.

Table 1: Dimensions of the two aluminium bars

Sample	Dimensions (mm)
6061-T6	40×44.45×300
7075-T6	40×38.1×300

3.1.2 4-Point Bending

The two samples were deformed in a 4-point bending apparatus in the University's mechanical testing machine. A schematic of this apparatus is shown in Figure 4.

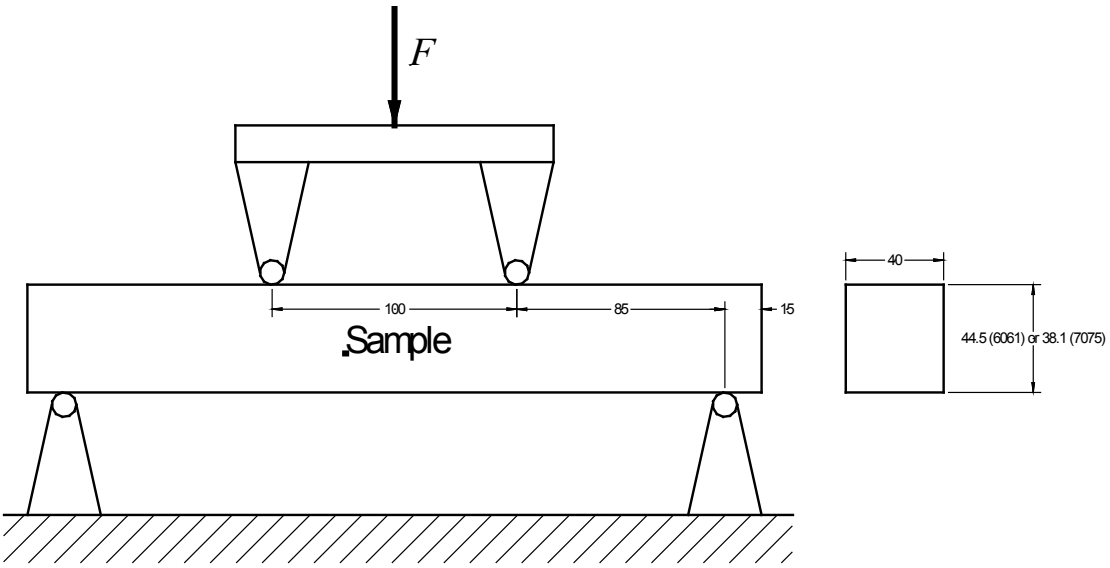

Figure 4: The 4 point bending apparatus used to deform the aluminium samples.

After careful alignment, load was gradually applied to the samples up to a maximum value before being removed. Deflection at the centre of each bar was monitored during this process using a small steel ruler. Table 2 provides details of the applied loads and measured deformations.

Table 2: Maximum loads and deformation data during 4-point bending of the samples

Sample	Maximum Load (kN)	Maximum Deflection (mm)	Residual Deflection (mm)
6061-T6	131	7.2	4.5
7075-T6	179	7.0	2.1

After bending the samples were cut into three 100mm lengths, with the central (deformed) 100mm portion being retained as the final sample for the neutron experiments.

3.2 Mechanical Testing and Material Properties

In order to determine material properties, smaller samples from the same plates were prepared and tested in the University's mechanical testing machine. Dimensions of these smaller samples (known as 'dogbones') are shown in Figure 5.

Standard tensile tests were performed on these samples. Each test consisted of the gradual application of tensile load while continually monitoring load and deformation. Force was measured by a load cell while deformation was indicated by a clip-gauge (see Figure6). At some point after yielding, the clip-gauge was removed and the sample tested to destruction. The final load and strain recorded at this point is given in Table 3.

Table 3: Final load and maximum elongation for the tensile test coupons

Sample	F_F (kN)	ϵ_U
6061-T6	290	0.2
7075-T6	555	0.18

All data measured during these tests is available on BlackBoard (see Section 3.4).

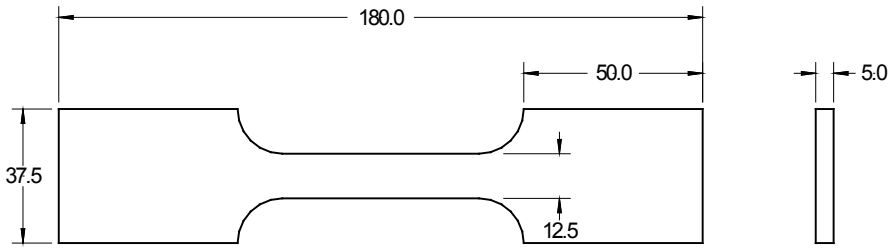

Figure 5: Tensile test coupon ('dogbone') dimensions.

3.3 Strain Measurement

Residual strain measurements were carried out on the two aluminium samples using the KOWARI strain diffractometer located at the Bragg Institute in Sydney. These measurements were made using a neutron wavelength of 1.73Åwhich provides a 90° measurement geometry for the 311 lattice planes (indicated by Miller indices). A gauge volume of 2×2×20×mm was used in all measurements. Both axial and transverse measurements were made, with geometries as shown in Figure 7. The results of these measurements are available on BlackBoard (see Section 3.4).

Measurements were also carried out on an undeformed sample of each material to establish reference d-spacings. The results of this process are provided in Table 4.

Table 4: d_0 measurements for each aluminium sample

Sample	d_0 (Å)
6061-T6	$1.2181161 \pm 8\times10^{-6}$
7075-T6	$1.2188861 \pm 5\times10^{-6}$

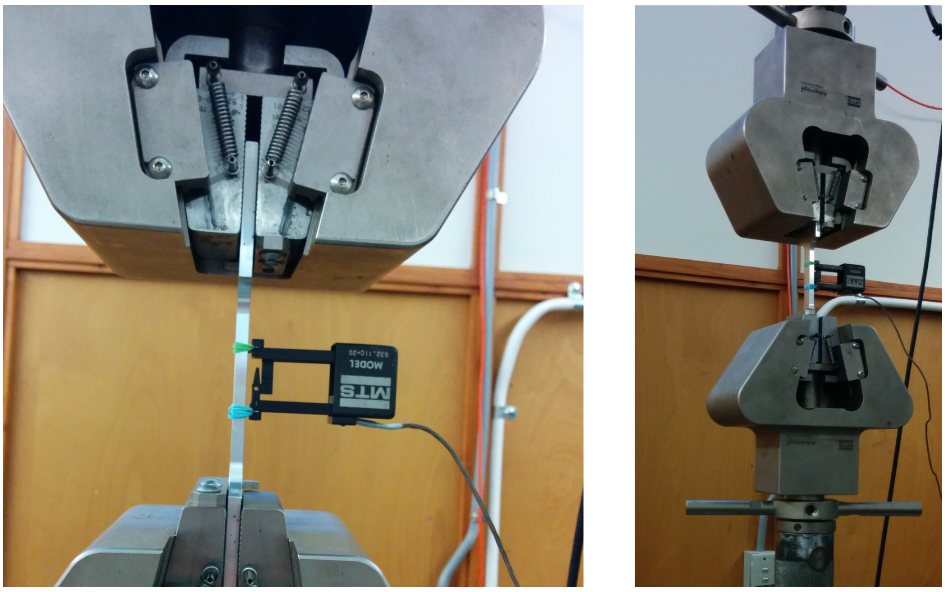

Figure 6: Mechanical testing of 'dog-bone' samples of 6061-T6 and 7075-T6 aluminium.

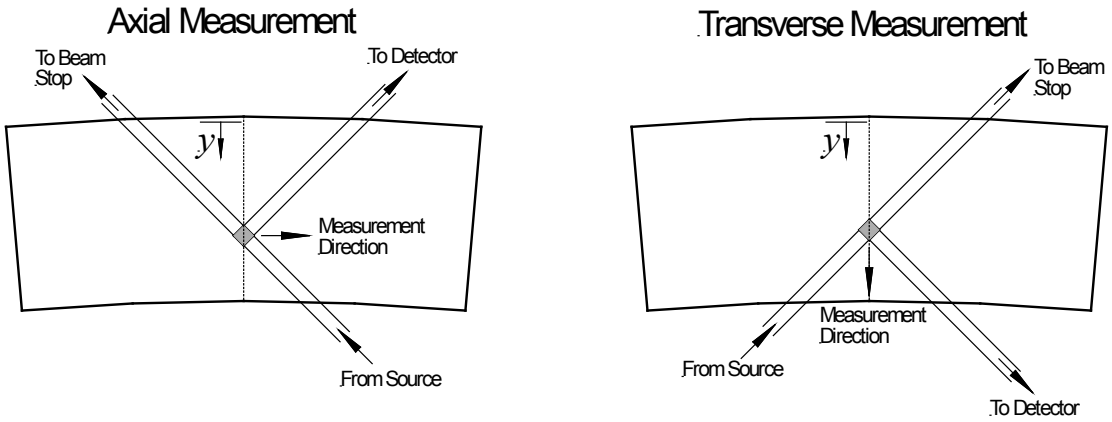

Figure 7: Measurement geometries for the axial and transverse strain measurements on KOWARI.

3.4 Data Format

All experimental data from the mechanical testing of dogbones and neutron diffraction experiment is contained within three text files uploaded on BlackBoard. The content of these files is as follows;

'Stress_Strain_7075.txt' and 'Stress_Strain_6061.txt':
These two files contain the experimental data from the mechanical testing of the dogbone samples. Each file contains a header and two columns of data; the first column is the length measured by the clip-gauge, the second is applied load.

'Diffraction_Data_6061.txt' and 'Diffraction_Data_7075.txt':'
This files contains all of the diffraction data. Each files contains a header and five columns of data; the first column is the y-coordinate of the measurement position, the second and third columns are the d-spacings and associated errors from the axial measurement and the fourth and fifth are equivalent measurements in the transverse direction. The error values represent estimates of measurement uncertainty from the peak fitting process and are quoted as a standard deviation. Units of measure are specified in the header lines.

Tab delimiters are used in all files. This format can be directly read by Microsoft Excel or easily imported into MATLAB using the `importdata` command, e.g.;

```
D = importdata('filename.txt','\t',1); % read tab delimited data with 1 header line
Col1 = D.data(:,1) % extract the first column into the array Col1
Col2 = D.data(:,2) % extract the second column into the array Col2
...  % etc.
```

4 Expectations and Report Structure

You are required to analyse the experimental data provided in order to calculate the distribution of residual stress in each bar. This will require the processing of the tensile test data to establish elastic properties and characterise the plastic behaviour. All relevant material properties can be determined from the tensile test data with the exception of Poisson's ratio. A value of $\nu = 0.34$ is suggested.

Once you have calculated the residual stress distribution in each bar you should compare these results to expected distributions based on elastoplastic beam theory as covered in the course materials.

This task is assessed through the preparation of a professional standard engineering report. Each student is required to prepare an individual report detailing the entire experiment including the background, results, and analysis of data. There is no specified minimum or maximum length for this report; it should be as long as it needs to be to communicate the required information (exercise your own judgment).

Students are free to structure the report however they wish, however a *suggested* structure is as follows;

1. Abstract/Summary
2. Introduction and Background
3. Experiment Details
4. Results and Data Analysis
5. Discussion
6. Conclusions
7. References
8. Appendices (if necessary)

Marks will be awarded based on the following questions/criteria;

- Is the report of a professional standard (i.e. style, language, presentation, quality and labeling of figures, etc.)?
- Is a good summary provided?
- Does the report provide a good overview of the experimental technique and background of the experiment?
- Is the analysis of data correct?
- Have meaningful comparisons to elastoplastic beam theory been made?
- Is there a discussion and analysis of errors?
- Are meaningful conclusions made?

One indicator of a good report is a demonstration that the student has branched out and read more widely on the experimental technique and/or plasticity theory. The outline provided in this handout gives a very brief overview of this area - much more information is available. This handout should <u>not</u> be your only reference!

5 Acknowledgements

The authors would like to thank Dr Valdimir Luzin and the Bragg Institute within ANSTO for providing expertise and access to the KOWARI diffractometer during the production of the experimental data at the centre of this assessment task. We are also grateful for the help provided by Mitchell Gibbs from Mechanical Engineering during the mechanical testing experiments.

6 Suggested Reading

Asside from Google...

EH Kisi and CJ Howard, "Applications of neutron powder diffraction", *Oxford University Press* (2008)

ME Fitzpatrick and A Lodini, "Analysis of residual stress by diffraction using neutron and synchrotron radiation", *Taylor & Francis* (2003)

IC Noyan and JB Cohen, "Residual stress - Measurement by diffraction and interpretation", *Springer-Verlag* (2006)