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# Neutron Strain Tomography using the Radon Transform

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## Abstract

Determining bulk residual elastic strains is a topic of critical importance for predictive modelling and materials testing. Although there are numerous approaches to obtaining this information the process is often time-consuming and frequently involves destructive sectioning of the sample. This paper presents the latest developments in Bragg-edge neutron strain tomography which offers a rapid, non-destructive means of determining residual elastic strains in polycrystalline materials with high spatial resolution. Neutron strain tomography utilises the fact that the energy-resolved transmission spectrum of thermal neutrons from a polycrystalline sample displays well-defined, sudden jumps in intensity known as 'Bragg-edges', which reveal information about the average residual elastic strain throughout the sample volume. By measuring the spatially resolved transmission spectrum for a number of different sample orientations it is possible to recover the underlying three-dimensional residual elastic strain profile. This process is analogous to conventional absorption tomography where a three-dimensional map of the sample density is recovered from a lower order two-dimensional set of integral absorption measurements. Using the newly developed microchannel plate *TimePix* neutron detector in time-of-flight experiments, elastic strains can in principle be recovered with 10 um spatial resolution. The current work demonstrates a model-free method for direct inversion of the average strain profiles obtained from Bragg-edge measurements using results from linear elasticity theory and the Radon transform, which is the basis for absorption tomography reconstructions. We demonstrate this method in simulation on an axisymmetric sample with analytic strain profile before applying it to a 'real-world' sample where the results are validated against conventional neutron diffraction and hole drilling measurements.

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## 1. Introduction

Non-destructive neutron and x-ray diffraction techniques have become the principal means for studying residual elastic strains within polycrystalline materials and engineering components [1, 2]. Knowledge of residual elastic strain provides a method for predicting fatigue lifetimes or component failure and for the validation of finite element models. Strain measurement by diffraction relies on Bragg's law, $\boldsymbol{\lambda = 2d \sin \theta}$, which relates the interplanar lattice spacing, $\boldsymbol{d}$, and the wavelength of the incident radiation, $\boldsymbol{\lambda}$, to the scattering angle, $\boldsymbol{\theta}$. The average lattice spacing is measured in a single direction within the scattering gauge volume, which is defined by collimating or focusing the incident beam. Typical spatial resolutions for diffraction based techniques are of the order ~1 mm for neutron or ~1 um for x-ray synchrotron experiments [3]. The elastic strain, $\boldsymbol{\varepsilon}$, is defined as the relative shift in lattice spacing from the 'strain-free' value $\boldsymbol{d_0}$. Since diffraction is primarily sensitive to lattice spacing, the elastic strain component in one direction can be found by measuring the relative change in diffraction peak position. By raster scanning the scattering gauge volume through the sample, the elastic strain fields can be mapped in two or three dimensions (depending on the collimators used). Diffraction methods generally measure only one strain component in a single voxel at a time, hence to fully characterise the strain state of a sample many measurements at multiple sample orientations are required. Therefore, obtaining a full strain map is often an arduous process.

An alternative approach exists in the case of neutron sources however; Bragg-edge neutron transmission measurements [4, 5] provide information about the average strain through the sample in the direction parallel to the incident beam. The transmission spectrum of thermal neutrons through a polycrystalline material displays sudden well-defined increases in intensity as a function of neutron wavelength when recorded on a pixelated energy resolving detector. This is due to the fact that for a given lattice spacing with a particular lattice constant, $d_{hkl}$, the Bragg angle increases as a function of wavelength until $2\theta$ is equal to $\pi/2$. At wavelengths greater than this critical value no scattering occurs, giving rise to a sudden increase in the transmitted intensity, known as a 'Bragg-edge'. The wavelength at which this Bragg-edge occurs, gives a direct measure of the average lattice spacing in the direction parallel to the incident beam.

By recording the wavelength resolved transmission spectrum (e.g. via neutron time-of-flight (TOF)) on an area detector, a two-dimensional map of the average elastic strain component in the transmission direction is obtained. The basic aim of Neutron strain tomography [6, 7, 8, 9] is to recover the three-dimensional spatially resolved strain distribution from a set of two-dimensional measurements of the average through-sample strain. This is analogous to absorption tomography in the sense that higher order, three-dimensional, information is recovered from a set of lower order projection measurements. The primary difference in the present case is that neutron strain tomography aims to recover the components of the second rank strain tensor instead of the scalar absorption coefficient. This difference increases the number of degrees of freedom per sample voxel from one to (at least) two and, until now, has prevented neutron strain tomography [10] from being applied without significant regularisation of the recovered strain profile. For example, Bragg-edge measurements have previously been used to recover the spatially resolved strain components by representing the underlying strain distribution using a set of strain compatible basis functions with the additional constraint that the solution must be 'smooth' [6, 7, 8, 9].

This paper describes and demonstrates a new model-free approach for directly inverting average transmission strain data for axisymmetric strain distributions requiring no *a priori* knowledge of either the sample or strain distribution. A formulation derived from linear elasticity theory and the Radon transform is used to invert the average strain data in order to recover three-dimensional strain maps. The mathematical basis for neutron strain tomography is briefly reviewed before the Radon transform approach to strain inversion is demonstrated through use of an example. The method is then demonstrated using simulated strain tomography data before being applied to experimental neutron strain transmission measurements. The results from the neutron strain tomography are validated via neutron diffraction and hole-drilling measurements.