Optimising Neutron Strain Scanning by the Use of Electron Backscatter Diffraction

V. Stelmukh and L. Edwards, The Open University, Milton Keynes, UK

INTRODUCTION
The presence of residual stresses in welded joints can have a significant effect on their load carrying capacity and on the damage tolerance of resultant structures. Strain scanning using neutron diffraction is a non-destructive technique that uniquely provides insights into stress and strain fields deep within engineering components and structures. Furthermore, it is the only non-destructive means of measuring the stress state under conditions (temperature, stress, atmosphere, etc.) representative of those which might be experienced in service [1].

Stresses are determined from strains measured from atomic planes that satisfy Bragg’s law, $2d_{hkl} \sin \theta = \lambda$, where $d_{hkl}$ is the lattice spacing for the planes described by Miller indices (hkI) and $\theta$ is the Bragg scattering angle. When strain scanning is performed at a reactor neutron source, a monochromator is used to produce a collimated beam of neutrons with a single wavelength $\lambda$. Although this wavelength can be varied, e.g., by adjusting the monochromator take-off angle, for a polycrystalline material with cubic symmetry, only a few reflections give an acceptable neutron count when using the preferred scattering angle close to 45°. This geometry is desirable as it produces a similar spatial resolution for all diffracted beams (see Fig 1).

If a material exhibits preferred orientation of its crystallites (crystallographic texture) then preliminary assessment of the most advantageous reflections and sample orientations is usually necessary, since engineering samples are rarely suited for use in a Eulerian cradle. Although electron backscatter diffraction (EBSD) is mainly used for the determination of point-to-point misorientation relationships and local textures [2], it can also be used to examine macrotexture, provided some information is available about how the material was processed. In addition, EBSD orientation mapping can be used to determine grain size distributions, and hence estimates can be made of the number of suitably oriented grains that would contribute to the intensity of a neutron diffraction peak. These combined advantages of the EBSD technique open up new opportunities for optimising strain measurements in engineering components exhibiting texture variation. This article describes a strategy that was successfully deployed for residual strain mapping in friction stir (FS) welded aluminium alloy plates.

MATERIALS AND METHODS
Two 12.6 mm thick AA7050 plates were FS welded in the T7451 condition. The welding (or longitudinal) direction (LD) was parallel to the rolling direction (RD) of the parent plates. The weld was subjected to a post-welding ageing at 120°C.

Prior to the neutron diffraction experiment, EBSD measurements were made on the cross-sectional area perpendicular to LD. The EBSD specimen was prepared by cutting using an electro discharge machining (EDM), gentle grinding, diamond polishing and subsequent etching. Kikuchi patterns resulting from backscattered electrons were obtained using hardware from Jelen Technology, Norway, mounted on a JEOL 820 SEM operating at 25kV. The specimen was inclined in the SEM at 70° to the incident electron beam. The software used to acquire and analyze the Kikuchi bands (Channel 4) was produced by HKL Technology ApS, Denmark.

Automated scans were carried out in the stage-scanning mode using 10 mm stepsize within a 1 mm square grid pattern. The location of several regions, each containing about 10,000 measurement points, is indicated on the macrophotograph of the weld cross-section shown in Fig 2F. The fraction of EBSD patterns that could not be indexed was never higher than 17% for any region. The resulting texture data is presented here as pole figures generated by post processing software (Mambo, HKL Technology), using the equal-area projection method because of its advantages for examining population densities. For example, a uniform density of points on a pole figure will correspond to a random distribution of orientations in an isotropic material.

Neutron strain scanning was performed on the G5.2 instrument at the Orphée reactor (LLB, Saclay, France). The instrument is equipped with a linear position sensitive detector, which enables a complete diffraction peak to be measured simultaneously. The dimensions of the test-piece studied were 92 mm in LD and 190 mm in the transverse direction (TD). Correction of the measured strains to allow for

Figure 1: Definitions of the gauge volume and the LD-<k> measurement direction coincident with the scattering vector (k).
variation in the stress-free lattice spacing (d0) across the weld was made by measurements on rectangular pieces, removed from an identical part of the weld by EDM, at orientations corresponding to equivalent measurements in the bulk material. The dimensions of each 12.6 mm long piece were 2.7 x 2.7 mm² in the LD-TD plane. A 2 x 2 x 10 mm³ gauge volume was used for the TD strain measurements. Contour maps presented in this paper were obtained using Gsharp 3.1 software [3] using bilinear interpolation of several hundred individual strain and intensity values.

RESULTS AND DISCUSSION

The parent material (PM) and all other zones of the joint affected by the welding process with the exception of the very centre of the weld are characterised by a strong texture. Pole figures obtained for PM (Figs 2A and D) confirm that the Brass, <211> (110), texture is one of the strongest components [4]. As can be seen by comparing multiples of uniform density (MUD), the preferred orientation is sharper in the inner portion of the plate than in its outer portion. Virtually no change in the texture was observed in the heat-affected zones (HAZ), presumably due to the relatively small heat input used in FS welding, which is a solid-state process [5]. The major transformations occur in the thermo-mechanically affected zone (TMAZ). The central part of the zone, or so-called ‘nugget’, differs from the rest of the TMAZ, as here the material is believed to undergo dynamic recrystallization [6].

The typical pole figure presented in Fig 2B contains a distinctive maximum, which moves over the pole figure’s area when changing the position of the acquisition region within the nugget. In the vicinity of the nugget, the parent material is also subject to significant mechanical deformation that causes rotation of elongated grains. The manner in which this rotation takes place is dependent on the proximity of the area of interest to the top surface of the weld. For the mid-point, it is essentially uplifting of the grains (Fig 2E), whilst additional rotation in the LD-TD plane is observed in the upper region (Fig 2C). The latter is due to the deformation action of the tool shoulder, which is in direct contact with the top surface of the plates during welding.

Aluminium is a poor neutron scatterer and therefore selection of the most advantageous reflection for the strain mapping is important. Analysis of the pole figures for (111) and other (hkl) planes shows that (111) is the only fcc aluminium reflection that could be used, if the range of neutron wavelength readily available (from 2.6 to 5.0 Å) is also taken into account. At the wavelength of 3.335 Å used in the experiment, the (111) peak was seen at 2θ = 91° and could be measured in the TD and LD-α directions, where α (approx 19.5°) is the rotation angle about the plate’s normal (see Fig 1). The LD strains were obtained later from the strain data for LD-α and TD using a formula derived from plane trigonometry, equivalent to the construction of Mohr’s circles [7]. This simplified approach is based on the fact that aluminium possesses little elastic anisotropy [8].

As can be seen from Fig 3A, the gauge volume used, 2 x 2 x 2 mm³, makes the neutron diffraction measurements insensitive to the texture variation observed within the nugget by EBSD, as its linear dimension in LD was much larger than both the depth of the inter-

REFERENCES

3. G. Sharp, Advanced Visual Systems, Waltham, Massachusetts USA; (www.avs.com)