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Journal of Materials Processing Technology 117 (2001) 395–399

Journal of Materials Processing Technology

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Non-destructive measurement of residual stress by neutron diffraction

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Abstract

Residual stresses can be introduced into components during manufacture and use. They can have a significant influence on the load-carrying capacity and resistance to fracture of these components. It is important that their magnitude and distribution are known accurately for performance to be estimated. In this paper, the neutron diffraction method of measuring these stresses is presented. Procedures are described for achieving accurate and reliable results. It is demonstrated that strains can be determined to a resolution of 10^{-4}, corresponding to a stress of ±7–20 MPa in most engineering materials. Some examples of the application of the technique are considered. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Residual stress measurement; Non-destructive methods; Neutron diffraction

1. Introduction

Residual stresses can be introduced into engineering components during manufacture as a result of, e.g., forging, bending and welding processes. They can also be caused by the forces and thermal gradients imposed during operation. These stresses can affect the load-carrying capacity and resistance to fracture of components. In order to quantify their effect it is necessary to know their magnitude and distribution [1].

Several techniques are available for measuring residual stresses [2–8]. They include X-ray diffraction, neutron diffraction, hole drilling, slicing and magnetic methods. However, only neutron diffraction is capable of determining these stresses non-destructively within the interior of components. In this paper, the principles of this technique are described. The measurement procedure is outlined and progress [9,10] in the preparation of a draft standard, under the auspices of VAMAS TWA 20 (Versailles Project on Advanced Materials and Standards, Technical Working Area 20), for making the measurements is reported. Advice on achieving reliable results is presented and some applications to a range of practical examples considered.

2. Principles of the technique

When a beam of neutrons of wavelength λ is incident on a crystalline material, a diffraction pattern with sharp maxima is produced. The angular positions of the maxima for a family of crystallographic planes of separation d are given by the Bragg equation

$$2d \sin\theta = n\lambda \quad (1)$$

where n is an integer and 2θ is the diffraction angle. Measurements can be made with a continuous monochromatic or a pulsed polychromatic beam of neutrons. For a monochromatic beam of constant wavelength any change in lattice spacing Δd will cause a corresponding shift $\Delta\theta$ in the angular position of the Bragg reflection so that the lattice strain in the direction of the scattering vector Q (Fig. 1) is given by

$$\varepsilon = \frac{\Delta d}{d} = -\Delta\theta \cot\theta \quad (2)$$

With this method, a single peak profile is examined and a Gaussian/Lorentzian fitting routine used to determine its angular position as illustrated in Fig. 2. When an intermittent beam composed of a range of wavelengths (velocities v) is employed, measurements are made at a constant scattering angle (usually $2\theta = 90°$). In this case, the change in the time-of-flight of the neutrons between the moderator and the detector is recorded and a full diffraction spectrum is generated, as indicated in Fig. 3. Consequently, strain can then be determined from an analysis of individual peaks or from a Rietveld refinement of the entire spectrum [9,10].

To calculate absolute values of strain, the unstressed lattice spacing d_0 must be known. Also, in general, to define the strain tensor at a point completely, measurements in six orientations are required. However, when the principal

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PII: S0924-0136(01)00802-0

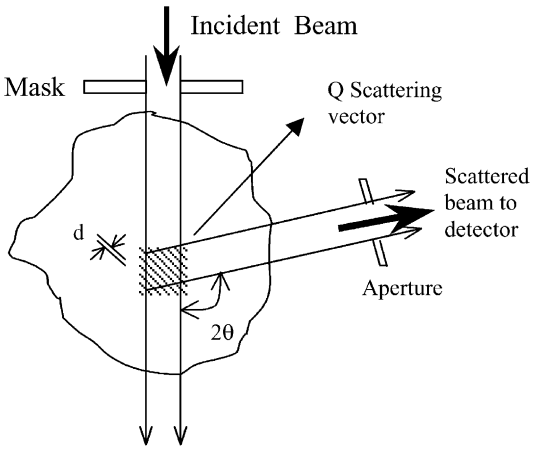

Fig. 1. Principles of neutron diffraction.

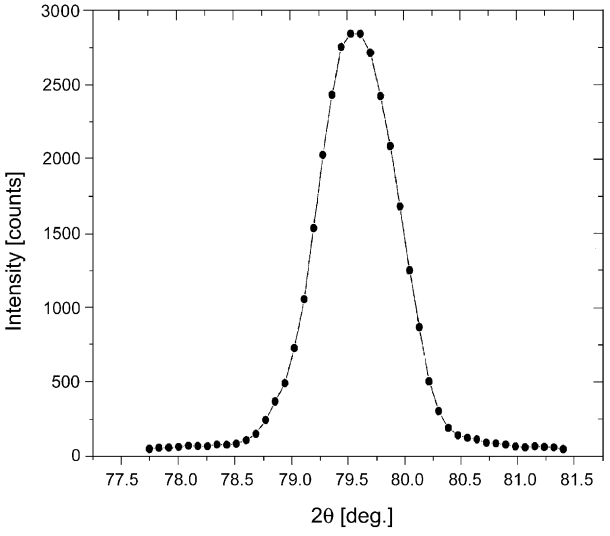

Fig. 2. Neutron peak profile.

directions are known, three will suffice. When these coincide with the coordinate directions x, y and z (or r, θ and z for polar coordinates), the principal stresses are given by

$$\sigma_x = \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_x + v(\varepsilon_y + \varepsilon_z)] \quad (3)$$

with corresponding expressions for σ_y and σ_z. In this equation, E is the elastic modulus and v Poisson's ratio. For a single peak analysis, the values appropriate to the specific ($h\,k\,l$) crystallographic plane on which the strain is being measured are used; for a multi-peak Rietveld refinement analysis usually bulk values are employed.

3. Measurement procedure

Several factors need to be considered when making residual stress measurements by neutron diffraction. These include the size, shape and material of the component being examined, the depth to which residual stresses are required and the stress gradients anticipated.

In order to obtain the stress distribution along a line (or across an area) in a component, it is necessary to identify a suitably small sampling volume (as shown in Fig. 1) and traverse this through the component in suitably small steps to obtain adequate resolution. It is desirable to use an approximately square-section volume so that the same volume of material is examined when making measurements in different coordinate directions. The volume must be sufficiently large that acceptable neutron count rates are obtained and a statistically representative number of grains is sampled. A typical acceptable minimum volume size is about 8 mm^3. This can be in the form of a $2 \times 2 \times 2$ or $1 \times 10 \times 1\,mm^3$ 'match-stick' shape if there is little stress variation along the axis of the match-stick.

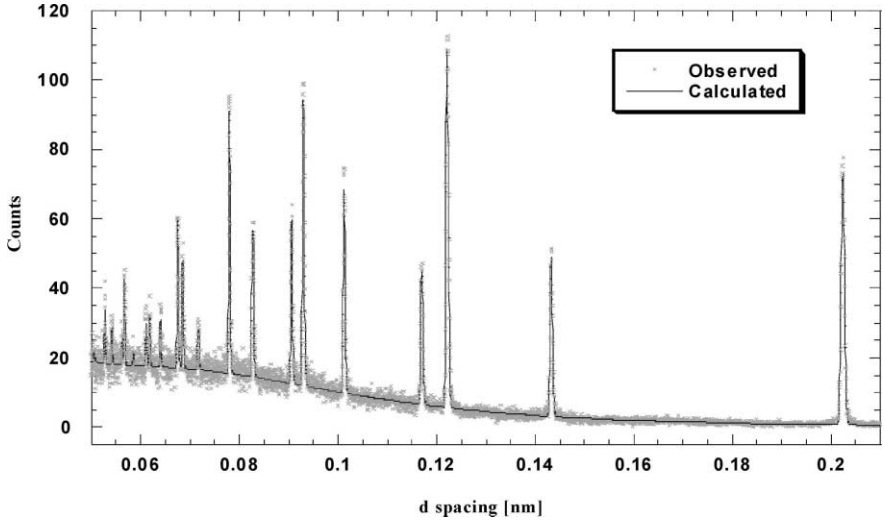

Fig. 3. Time-of-flight pattern.

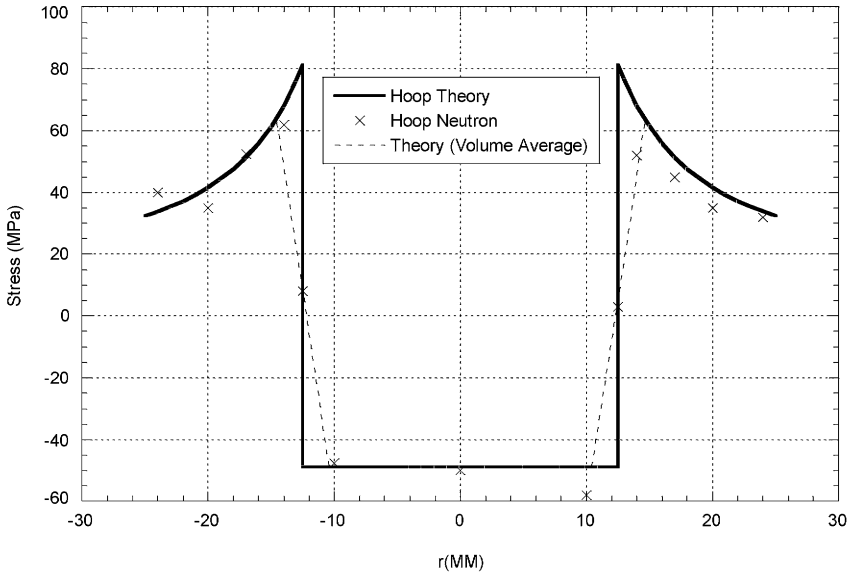

Fig. 4. Hoop residual stress distribution in ring and plug.

Care is needed with the initial set-up of the diffractometer and with positioning of the component to be measured. Stress gradients can be as high as 2000 MPa/mm making precise location of the point of strain measurement critical. The axis of rotation of the diffractometer ω-table is usually taken as the reference. This can be identified by positioning a fine pin on the ω-table and rotating it until there is no translation of the pin when observed through carefully positioned theodolites. It is then required to locate the centroid of the sampling volume precisely on this axis by traversing the pin across the neutron beam. With this procedure it should be possible to achieve a positioning accuracy of $\pm$0.1 mm. Aberrations can occur when traversing the sampling volume through a surface or an interface particularly when a position sensitive detector is used. These can be minimised by placing the beam masks (Fig. 1) as close to a component surface as possible.

When a monochromatic beam of neutrons is used, the neutron intensity profile of a single ($h\,k\,l$) reflection is measured (Fig. 2) and the shift in its peak recorded to determine the strain. Although polycrystalline engineering materials are usually isotropic, single crystals are often anisotropic. This means that different ($h\,k\,l$) reflections may exhibit different strains when subjected to the same stress [11]. It is, therefore, important for engineering purposes that measurements are only made on those planes which represent bulk behaviour and are not affected by plastic strain. Suitable planes for ferritic steels are (2 1 1) and (1 1 0) and for aluminium and nickel alloys (3 1 1) and (1 1 1).

In all the cases, it is necessary to have an accurate knowledge of the stress-free lattice spacing d_0 (or lattice parameter a_0). This is best obtained by taking measurements in a region of known zero stress or on small cubes (or powder) of identical composition. Finally, checks should be made for force and moment equilibrium where possible. Allowance must be made for any change in d_0 due to material composition gradients (e.g. through a weld) where appropriate.

A series of 'Round-Robin' experiments has been carried out using the procedures outlined under the auspices of VAMAS TWA 20 on a shrink fit aluminium alloy ring and plug [9,10]. The hoop residual stresses that were measured across the diameter of the ring and plug are shown in Fig. 4. It is evident that excellent agreement is attained with theory when allowance is made for averaging of the stress over the whole sampling volume. From this study it has been found that, provided the experimental procedure described is followed, strains can be determined to an accuracy of 10^{-4}, which corresponds to a resolution of stress of $\pm$7–20 MPa in most engineering materials.

4. Practical applications

In order to illustrate the application of neutron diffraction for measuring residual stress, a number of practical cases will be considered. Examples involving shallow and steep stress gradients through homogeneous and inhomogeneous materials will be examined. These are presented in Figs. 5–8.

Fig. 5 shows the residual hoop stress distributions that can be generated across a circumferential electron beam weld between two nickel alloy rings. It indicates that residual stress in excess of yield can be developed in the weld and heat affected zone regions and that post-weld-heat-treatment (PWHT) significantly reduces, but does not eliminate, the residual stresses. Fig. 6 demonstrates the depth of compression that can be generated close to surfaces by shot-peening processes [12] to inhibit crack initiation and growth there.

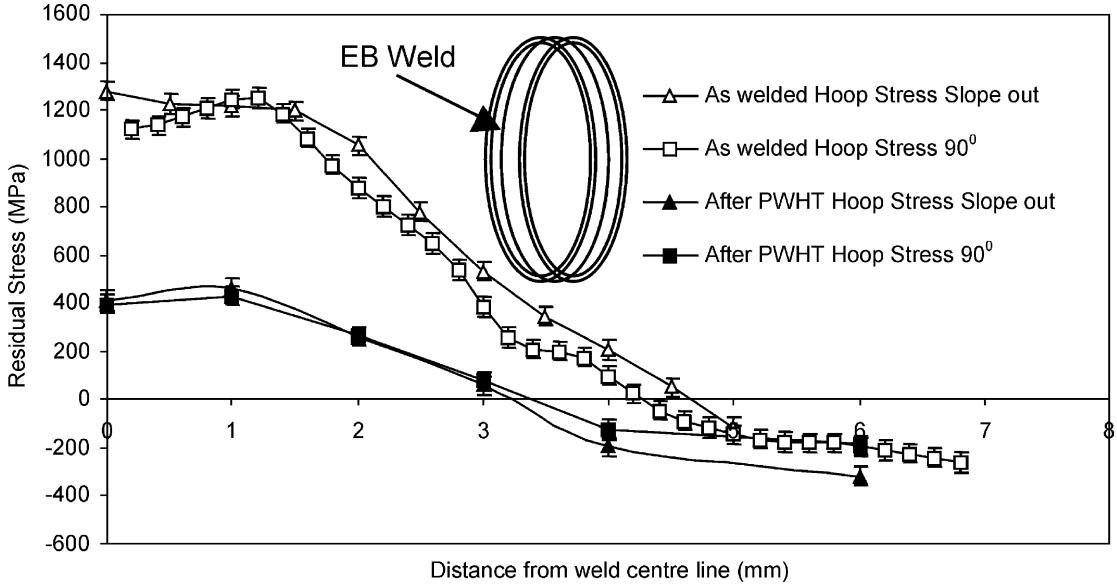

Fig. 5. Hoop residual stress distribution in an electron beam welded nickel alloy ring.

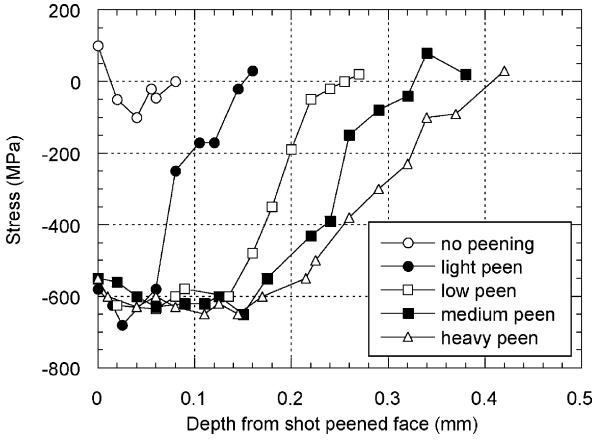

Fig. 6. Depth of compression caused by different peening conditions.

Fig. 7 indicates the stresses introduced by laser surface treatments which are employed to generate a hard surface layer in martensitic steels in order to improve their resistance to corrosion and wear [13]. In this instance, allowance for a change in d_0 from the surface is required to allow for a change a carbon composition through the melted and heat affected zones (HAZ). Fig. 8 shows that residual hoop compression is produced by cold hole expansion adjacent to the hole in a nickel alloy which may be expected to give protection against fatigue failure. However, it is evident that fatigue cycling causes relaxation in the beneficial compression which may cause some erosion in fatigue performance. The neutron diffraction results show that this redistribution in residual stress can be predicted from finite element analysis.

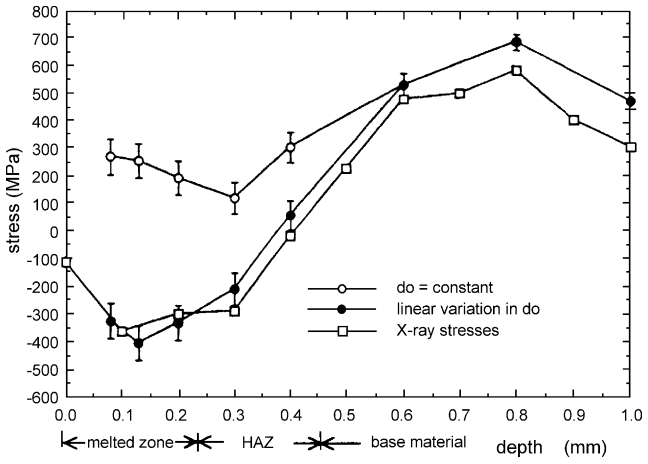

Fig. 7. Residual stress generated by laser surface treatment of a martensitic steel.

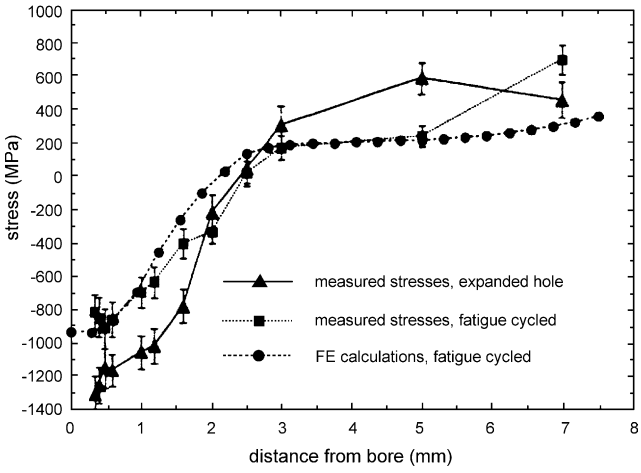

Fig. 8. Hoop residual stress produced adjacent to an expanded hole before and after fatigue cycling.

Acknowledgements

Authors would like to thank the EPSRC, UK, the European Commission and the DERA, UK, for financial support; Rolls-Royce for the provision of test samples and the contributions of his colleagues in VAMAS TWA 20.

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