MEASUREMENT OF RESIDUAL STRESSES IN ALUMINIUM ALLOY AEROSPACE COMPONENTS

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Abstract

The deep hole drilling technique for residual stress measurement is introduced as a practical and versatile technique for measuring through thickness residual stress distributions in aluminium alloy aerospace components. Details and recent developments of the technique are presented and then deep hole drilling is used to determine the through thickness residual stresses in a stepped aluminium alloy, Al7XXX, plate originating from the wing skin of a modern civilian aircraft. In addition to deep hole drilling (DHD), conventional incremental centre hole drilling (ICHD) is also applied at the same surface location in order to provide the detailed near-surface residual stresses, and neutron diffraction is used to validate measurements. The results presented demonstrate that DHD and ICHD work well together to provide both near-surface and through thickness residual stress distributions. The results are in reasonable agreement with the neutron diffraction results which assumed a constant stress-free lattice parameter value. The methodologies and techniques described in this paper will be used in the forthcoming EU-FP 6 project 'COMPACT – A concurrent approach to manufacturing induced part distortion in aerospace components' as part of a suite of complementary residual stress measurement techniques.

1 Introduction

Many techniques can be used to measure residual stresses, but most only work close to the surface of a component. The deep hole drilling (DHD) method [1] provides complete, through-thickness, measurements of residual stress which can be used to validate numerical models. A small, high-precision, accurately aligned hole is drilled through the component and its diameter is measured to a high degree of accuracy at many angular orientations and depths. A cylinder of material co-axial to this hole is then cut free by electro-discharge machining. This releases the residual stresses contained in the core of material and causes the diameter of the initial hole to change. By measuring the new diameter at the same angular positions and depths, the residual stress field may be determined. In this paper, DHD is used to determine the through-thickness residual stress distributions in a modern aerospace component. In addition, conventional incremental centre hole drilling (ICHD) is used as part of an integrated measurement procedure [2] to determine the near-surface residual stresses at the same location in the same component. Furthermore, neutron diffraction measurements of residual stress are made on the component in order to validate the results.

2 Component and measurement details

Measurements were made on a 280mm long and 150mm wide stepped plate, with the thickness varying from 30mm to 6mm, Fig. 1. The plate was fabricated from a larger plate of rolled Al7XXX series alloy, used in the wing skin of a modern civilian aircraft. The challenge imposed to the application of the deep hole drilling technique arose from the relatively low level and rapid variation of residual stresses generated near to the surface and consisted of evaluating the ability of the technique to accurately resolve the residual stress distribution near to the surface.

Both ICHD and DHD measurements were made at the locations shown in Fig. 2 using the integrated approach described in [2] and illustrated in Fig. 3. The measurement equipment for both techniques was co-located on the specimen. First, a strain gauge rosette was attached to the surface to enable the ICHD measurement, undertaken using a conventional Measurement Group RS200 drilling rig. On completion of the ICHD measurement, the air turbine assembly of the RS200 drilling rig was replaced by a guide cylinder assembly in order to permit DHD measurements to be made. The diameter of the reference hole used in the DHD measurements was slightly larger than that used in the ICHD measurement. A schematic diagram of the experimental arrangement is shown in Fig. 3.

Neutron diffraction measurements were also made at locations shown in Fig. 2 on the ENGIN-X instrument at the ISIS facility, UK. For the measurements, a small gauge volume of 2x2x2mm^3 was used, to allow a large number of measurements to be made within the plate. The interval between measurement points was increased deep inside the plate as the variation of the stress field (shown by the DHD measurement) was less severe, and due to the limited beamtime available to conduct the measurements. The ‘stress-free’ lattice spacing, d_0, was obtained by making measurements on a cube of material extracted from one corner of the specimen, also shown in Fig. 2.

3 Residual stress measurement methods

3.1 The Deep Hole Drilling (DHD)Technique

The deep hole drilling technique determines the residual stresses in a component by measuring the distortions of a reference hole in the component after a column of material containing the reference hole as its axis is removed. Step 1 consists of drilling a small reference hole through the component of interest. Step 2 consists of accurately measuring the diameter of this reference hole using an air probe. Diameter measurements are made at many angular positions and at many depth intervals. In step 3, a column of material containing the reference hole as its axis is coaxially trepanned free of the component using an electro-discharge machining (EDM) technique. Finally, step 4 consists of re-measuring the reference hole diameter at the same angular positions and depths using the same air probe. The distortion of the reference hole diameter in the plane normal to the reference hole axis is used to determine the in-plane residual stress field. It is assumed that the stresses relieved by the introduction of the reference hole are negligible and that the trepanned core completely relaxes in a linear elastic manner after trepanning. The analysis also assumes that the trepanned core may be considered as many independent block-lengths. Each independent block-length may be viewed as an infinite plate containing a hole subjected to a uniform, uni-axial stress. Further details of the DHD method may be found in [3, 4].

Accurate measurements of the reference hole diameter, steps 2 and 4 above, are made using an air probe at 18 angular positions. The initial reference hole diameter is denoted by (θ) and the reference hole diameter after trepanning is denoted by $d'(\theta)$. Measurements of $d(\theta)$ and $d'(\theta)$ are taken at depth intervals of 0.2mm in order to determine the through-thickness distribution of residual stress in the component. The difference in the reference hole diameters before and after trepanning is thus given by

$$\Delta d(\theta) = d'(\theta) - d(\theta). \tag{1}$$

The reference hole distortions are related to the relaxation of residual stress in the component in the plane normal to the reference hole axis. The reference hole distortions may be used to determine the normalised radial displacement around the hole, $\overline{u_{rr}(\theta)}$, which in turn may be prescribed in terms of the in-plane residual stress components, σ_{xx}, σ_{yy} and σ_{xy} through the elasticity solution for a hole in an infinite plate [5],

$$\begin{aligned}\overline{u_{rr}(\theta)} &= \frac{\Delta d(\theta)}{d(\theta)} = -\frac{1}{E}[\sigma_{xx}(1+2\cos 2\theta) + \\ &\sigma_{yy}(1-2\cos 2\theta) + \sigma_{xy}(4\sin 2\theta)] \quad (2)\end{aligned}$$

The normalised radial displacement $\overline{u_{rr}(\theta)}$ is linear with respect to the unknown stresses σ_{xx}, σ_{yy} and σ_{xy}, and can be expressed as

$$\overline{u_{rr}(\theta)} = \frac{\Delta d(\theta)}{d(\theta)} = -\frac{f(\theta)\sigma_{xx} + g(\theta)\sigma_{yy} + h(\theta)\sigma_{xy}}{E}, \quad (3)$$

where $f(\theta), g(\theta), h(\theta)$ are known from Eqn. 2.

During application of the DHD method, radial distortions are measured at 18 angular positions, denoted $(\theta_1, \ldots, \theta_{18})$. Eqn. 3 may therefore be re-written in matrix notation as

$$\begin{bmatrix} \overline{u_{rr}(\theta_1)} \\ \overline{u_{rr}(\theta_2)} \\ \vdots \\ \overline{u_{rr}(\theta_{18})} \end{bmatrix} = -\frac{1}{E} \begin{bmatrix} f(\theta_1) & g(\theta_1) & h(\theta_1) \\ f(\theta_2) & g(\theta_2) & h(\theta_2) \\ \vdots & \vdots & \vdots \\ f(\theta_{18}) & g(\theta_{18}) & h(\theta_{18}) \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix} \quad (4)$$

or

$$\overline{\mathbf{u_{rr}}} = -\frac{1}{E}\mathbf{M_{2D}} \bullet \sigma, \quad (5)$$

where $\bullet$ denotes matrix multiplication. As the matrix $\mathbf{M_{2D}}$ is non-square, and only three residual stress components $\sigma_{xx}(z), \sigma_{yy}(z)$ and $\sigma_{xy}(z)$ need to be determined, a pseudo-inverse matrix is used and an optimum stress vector is determined using a least squares fit to the normalised radial displacement data [4]. The optimum stress vector that best fits the measured normalised radial displacements, $\overline{\mathbf{u_{rr}}}$, is

$$\hat{\sigma} = -E\,\mathbf{M_{2D}^{\star}} \bullet \overline{\mathbf{u_{rr}}} \quad (6)$$

where

$$\mathbf{M_{2D}^{\star}} = \left(\mathbf{M_{2D}^{T}} \bullet \mathbf{M_{2D}^{-1}}\right) \bullet \mathbf{M_{2D}^{T}} \quad (7)$$

is the pseudo-inverse of matrix $\mathbf{M_{2D}}$, and $\mathbf{M_{2D}^{T}}$ is the transpose of matrix $\mathbf{M_{2D}}$.

The locations of the DHD measurements are shown in Fig. 2. Prior to drilling, bushes were adhered to the outer and inner surfaces of the header for both of the DHD measurements. Reference holes with diameters of 3.18mm (DHD location 1) and 1.5mm (all other locations) were then gundrilled through the bushes and the component, proceeding from the outside surface and penetrating fully through the thickness. The bushes were used to provide a stress free calibration measurement and to provide reference points to aid in the depth alignment of the measured $d(\theta)$ and $d'(\theta)$ values [6]. The diameter of the gundrilled reference hole was then measured at 18 angular positions (in equal intervals of 10°) for each depth increment of 0.2mm using a compressed air probe. The airprobe provided a direct reading of the reference hole diameter by measuring air pressure, which was in turn calibrated using prefabricated high precision discs containing holes of well-defined radius. A cylindrical core of material containing the reference hole as its axis was then trepanned using a hollow copper EDM electrode with a diameter of 10mm for the 3.18mm reference hole and 5mm for the 1.5mm reference holes. After trepanning, the reference hole diameter was re-measured through the thickness of the header using the air probe. The measured reference hole distortions were due to the relaxation of residual stress field contained within the core of material. The analysis technique described above was used to interpret the distortion measurements and derive the in-plane residual stress components. The residual stress measurement results obtained using the DHD technique are described in the next section.

3.2 The incremental centre hole drilling technique (ICHD)

In the integral method (IM) the contributions of the residual stresses at all depths to the surface strain relaxation are considered simultaneously. When strain relaxations are determined experimentally from a sufficiently large number of strain gauge measurements with gradually increasing hole depth, and calibration is available, the inverse problem of stress reconstruction can be solved numerically. In practice, the maximum hole depth is divided in intervals and the residual stresses in each interval are approximated by simple distributions using either piecewise functions [7, 8, 9, 10], spline functions [11], or wavelets [12, 13]. For generality, Schajer [10] suggested that the hole depth is treated as a nondimensional variable, by normalising it with the distance r_m from the centre of the hole to the location of strain relaxation measurement. This is shown in Fig. 1.

The classic procedure, using piecewise functions, provides acceptable results in many practical problems. Let σ_{xxi} and σ_{yyi} be the equivalent uniform residual stresses within the i^{th} layer (see Fig. 1) and a_{ni} and b_{ni} the influence coefficients providing strain relaxations due to unit uniform residual stress within the i^{th} layer of a hole containing n increments and having a depth h_n. The strain relaxation along the x-direction is then given by [14]

$$\begin{aligned}\varepsilon_{xxn} &= \frac{1}{2E}\sum_{i=1}^{n}\left[(1+\nu)\,a_{ni}\left(\sigma_{xxi}+\sigma_{yyi}\right)\right.\\ &\quad \left.+b_{ni}\left(\sigma_{xxi}-\sigma_{yyi}\right)\right], \qquad (8)\end{aligned}$$

where E is Young's modulus, ν is Poisson's ratio and $n = 1 \ldots N$ is the depth increment. The influence coefficients can be obtained from cumulative influence functions $\hat{A}$ and $\hat{B}$ determined by FE analysis [10]. By measuring strain relaxations in three directions, three equations of the same form as Eqn,(8) are formed which may be solved simultaneously and permit the three in-plane residual stress components, σ_{xx}, σ_{yy} and τ_{xy}, to be determined. It may also be noted that the through-thickness stress component, σ_{zz}, is neglected.

It is mathematically convenient to decouple the equation set using transformations of the strain and stress variables. For instance, for a three-element strain gauge rosette (1, 2, 3), with elements orientated at 0°, 45° and 90°, the recommended transformed strains, p_n, q_n, t_n, and stresses, P_n, Q_n, T_n, are given by

$$p_n = \frac{\varepsilon_{xxn}+\varepsilon_{yyn}}{2} \qquad (9)$$

$$q_n = \frac{\varepsilon_{xxn}-\varepsilon_{yyn}}{2} \qquad (10)$$

$$t_n = \frac{\varepsilon_{xxn}-2\varepsilon_{xyn}+\varepsilon_{yyn}}{2} \qquad (11)$$

and

$$P_n = \frac{\sigma_{xxn}+\sigma_{yyn}}{2} \qquad (12)$$

$$Q_n = \frac{\sigma_{xxn}-\sigma_{yyn}}{2} \qquad (13)$$

$$T_n = \frac{\sigma_{xxn}-2\tau_{xyn}+\sigma_{yyn}}{2}. \qquad (14)$$

P and p represent the mean 'pressure' of the residual stresses and their corresponding 'volumetric' strains, respectively, whereas the other four variables represent the shear stress and strain components.

The set of three equations, of form similar to Eqn. (8), linking measured strains with residual stresses may conveniently be written in matrix form and solved to give the stress components P_n, Q_n and T_n, and the principal stresses, σ_{nmax} and σ_{nmin}. In matrix form, it follows that

$$\mathbf{P} = \frac{E}{1+\nu}\mathbf{A}^{-1}\mathbf{p}, \quad \mathbf{Q} = E\mathbf{B}^{-1}\mathbf{q}, \quad \mathbf{T} = E\mathbf{B}^{-1}\mathbf{t}, \qquad (15)$$

where $\mathbf{p}$, $\mathbf{q}$ and $\mathbf{t}$ are the vectors of the transformed strains, $\mathbf{P}$, $\mathbf{Q}$ and $\mathbf{T}$ are the vectors of the transformed stress components, and $\mathbf{A}$ and $\mathbf{B}$ are lower triangular matrices containing the influence coefficients a_{ni} and b_{ni}, respectively. The vectors of the principal stresses, $\sigma_{\max}$ and $\sigma_{\min}$, and their orientation, β, can be recovered from the calculated stress components P, Q and T,

$$\sigma_{\max}, \sigma_{\min} = P \pm \sqrt{Q^2+T^2} \quad \beta = \frac{1}{2}\arctan\left(\frac{T}{Q}\right). \qquad (16)$$

4 Results

4.1 Thick plate section

Figure 4 shows the results of all measurements performed through the thickness of the 'thick' section of the plate, namely at locations DHD1, DHD2, ND1 and ICHD1 shown in Fig. 2. All methods display the same residual stress distribution with a small variation of amplitude. It can be seen that the general stress distribution of the measurement DHD2 is higher than the DHD1, which can be explained by the core size difference, i.e. 10mm for DHD1 and 5mm for DHD2. The neutron diffraction measurement and ICHD measurements were in relatively good agreement with the DHD measurements.

4.2 Medium plate section

Figure 5 shows the results of all measurements performed through the thickness of the 'medium' section of the plate, namely at locations DHD3, DHD3, ND2 and ICHD2 shown in Fig. 2. It can be seen than both DHD measurements are identical. The ND measurement has the same shape than the DHD measurement with lower amplitude. The ICHD measurement is in good agreement with others measurement.

5 Conclusions

The incremental centre hole drilling and deep hole drilling techniques applied for residual stress measurement in the aluminium alloy aerospace component worked well as complementary techniques. Results demonstrated that the residual stress distribution in components can be optimally resolved by using the incremental centre hole drilling technique for depths up to approximately 1mm from the surface and the deep hole drilling technique for depths greater than 1mm. Sub-surface deep hole drilling measurements performed at different locations confirmed very good repeatability of the deep hole drilling technique. More generally, all of the measurements revealed a very low state of residual stress in the component.

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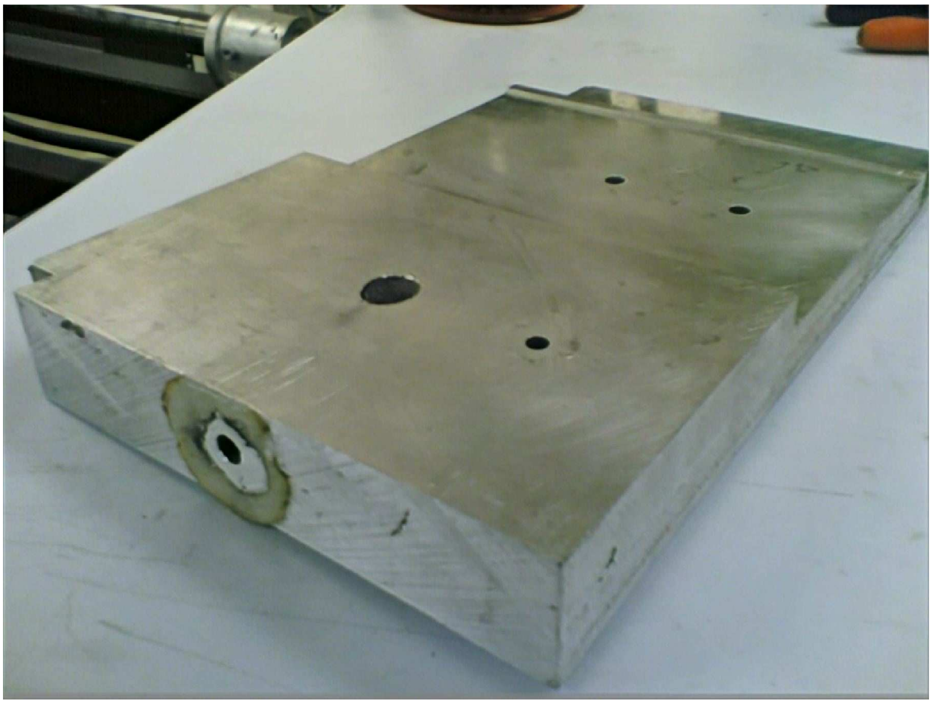

Fig. 1 Photograph of the stepped aluminium alloy plate

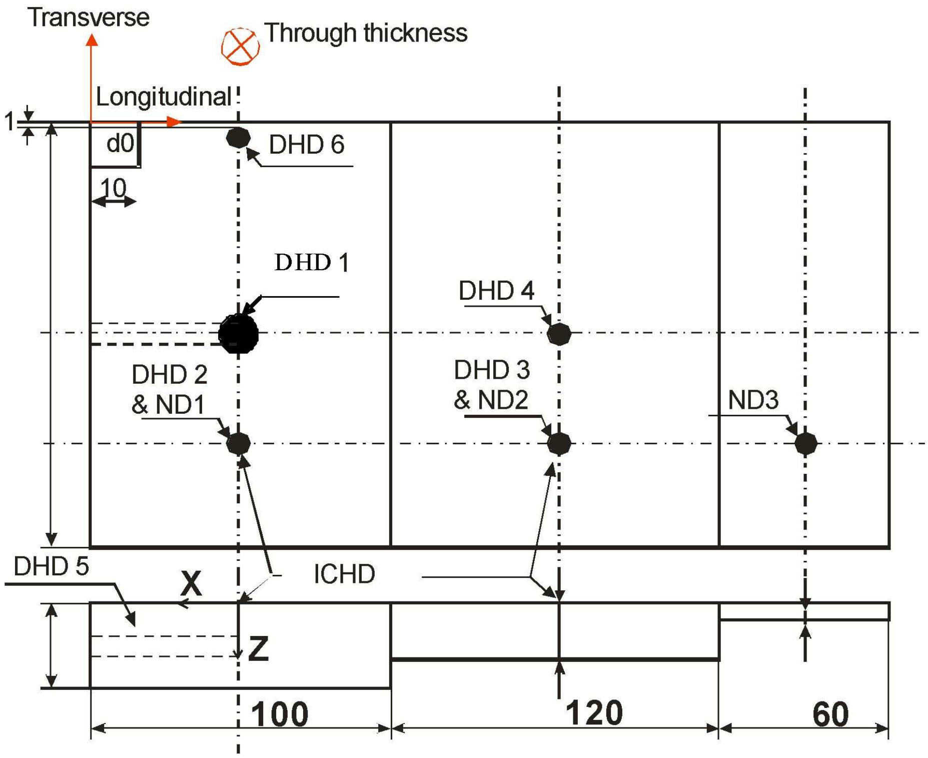

Fig. 2 Schematic diagram of the stepped aluminium alloy plate. All dimensions are in mm

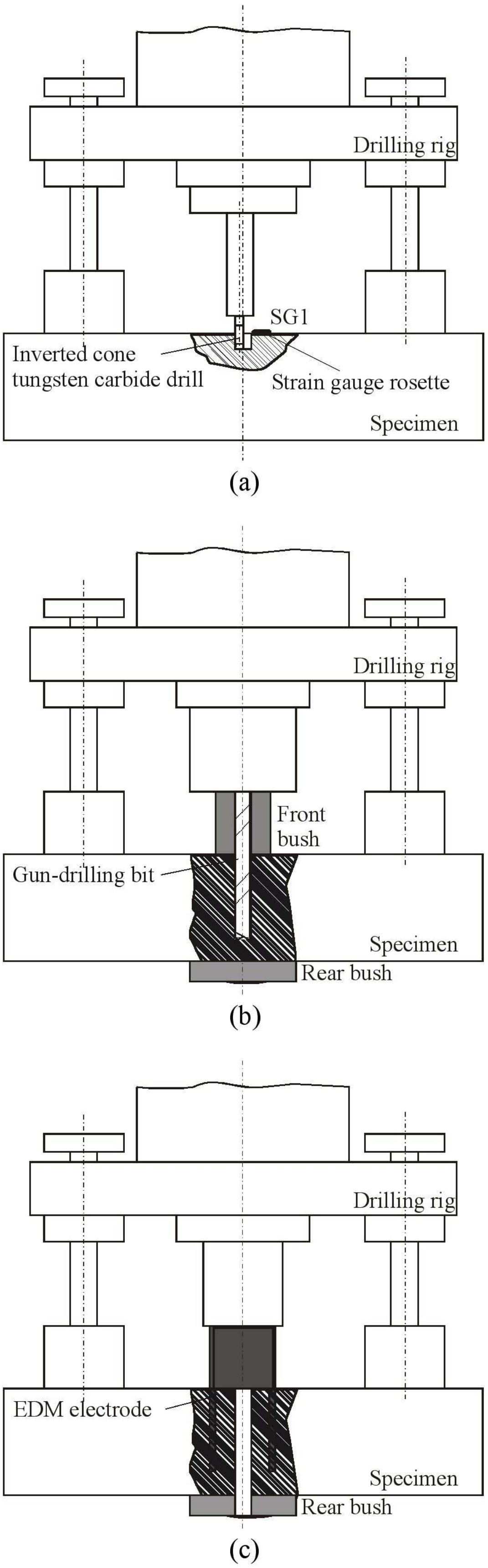

Fig. 3 Schematic of integrated DHD and ICHD

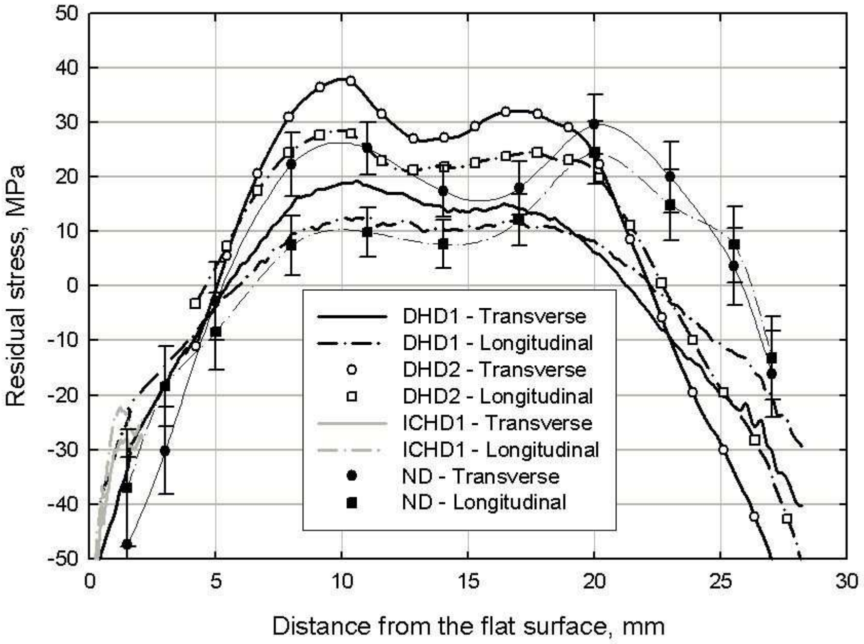

Fig. 4 Near-surface and through-thickness residual stress distribution measured in the thick section of the stepped plate by ICHD, DHD and neutron diffraction

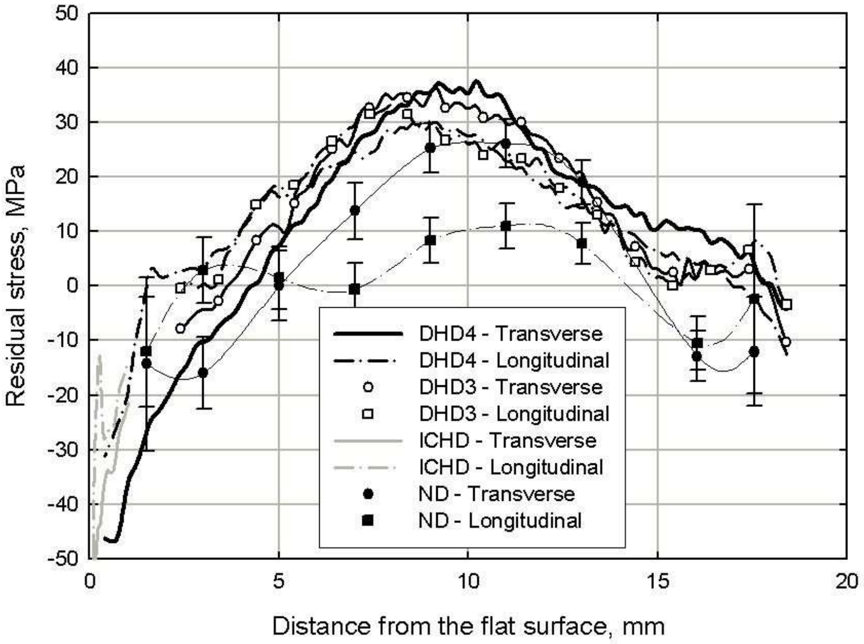

Fig. 5 Near-surface and through-thickness residual stress distribution measured in the medium section of the stepped plate by ICHD, DHD and neutron diffraction