Highly non-uniform residual stress measurement with reduced plastic error

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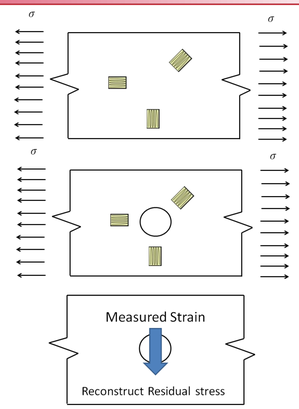
Introduction & Motivation

- Mechanical strain relaxation(MSR) methods consist of 4 steps:
  1. Choose geometry and analytical model
  2. Cutting
  3. Relaxation measurement
  4. Solution of inverse problem
- Two key assumptions
  1. Uniform stress assumption
  2. Purely elastic relaxation assumption



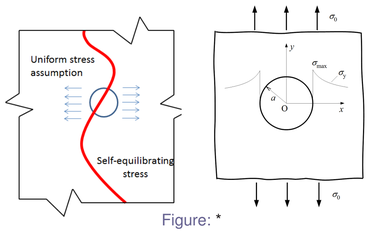


Figure: *

Hole drilling case of high gradient & 3σ at tip

Assumptions are invalid when

- the gradient of stress field is high within the guage
- the magnitude of the stress is close to the yield

In many practical applications these assumptions are known not to be true & cause experimental error !!

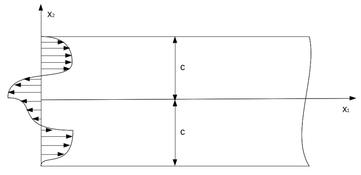
Proposed analytical model

Timoshenko's "Theory of Elasticity", 3rd ed, 1970, p. 61 :

- Semi-infinite 2D strip of width 2c
- Analytical stress functions

$$f = Ce^{-\gamma x_1/c}(\xi\cos\frac{\gamma x_2}{c} + \frac{\gamma x_2}{c}\sin\frac{\gamma x_2}{c})$$

$$g = Ce^{-\phi x_1/c}(\psi\sin\frac{\phi x_2}{c} + \frac{\phi x_2}{c}\cos\frac{\phi x_2}{c})$$



- BC

$$x_1 = 0 : \int_{-c}^{c}\sigma_{11}dx_2 = \int_{-c}^{c}\sigma_{12}dx_2 = 0$$

$$x_2 = \pm c : \sigma_{22} = \sigma_{12} = 0$$

- From BC :

$$\sin 2\gamma + 2\gamma = 0 \quad ; \quad \xi = -\gamma\tan\gamma$$

$$\sin 2\phi - 2\phi = 0 \quad ; \quad \psi = -\phi/\tan\phi$$

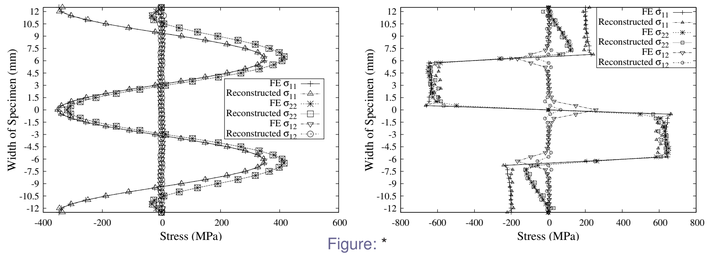
- General solution stress function

$$\theta = \sum_{i=1}^{\infty} a_i \mathrm{Re}f_i + b_i \mathrm{Im}f_i + c_i \mathrm{Re}g_i + d_i \mathrm{Im}g_i$$

- Finally get LLS problem:

$$\Omega = (a_1, b_1, c_1, d_1, \ldots a_N, b_N, c_N, d_N)$$

$$\min_{\Omega} ||\mathbf{A}\Omega - u||_2$$



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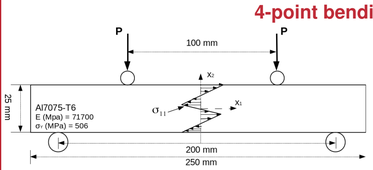
FE validation of analytical model

Experiments: 4-point bending + DIC

4-point bending & relaxation



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Schematic diagram of 4pb

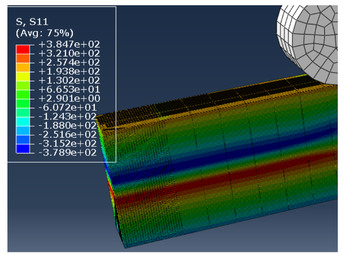


Figure: *

σ_{11} *distribution from 4pb modelling*

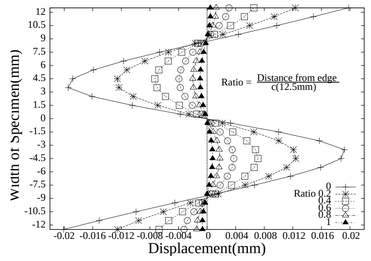


Figure: *

Relaxation analysis

- 25 × 25 mm² bar 9 mm disp. P = 53.05KN.
- $u_{max} \approx 21$ μm
- **Decays very quickly!** Collect the data as close to the cut as possible.

Optical system and DIC result

- 7.6μm/pixel spar. res.
- 10.6 × 8mm FoV
- 175 mm working distance.
- P180 sandpaper & Ring right
- 10bit CCD with a 1392 × 1040
- 25 by 25 subset size

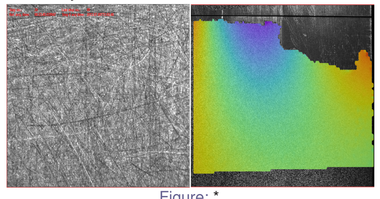
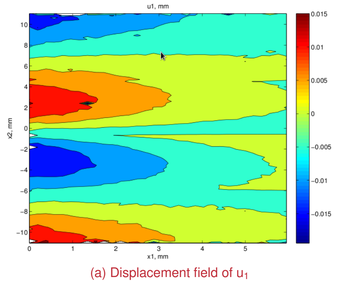


Figure: *

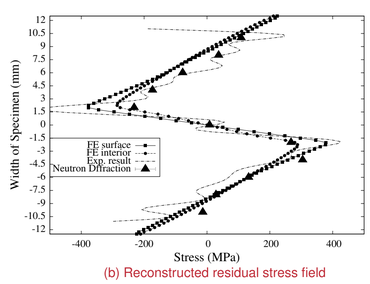
Scratch Pattern & Damaged pattern

Figure: *

Reconstructed residual stress



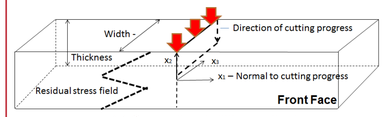
(a) Displacement field of u_1



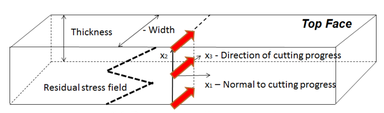
(b) Reconstructed residual stress field

- Pattern preservation is essential.
- High mag = Many images ⟶ stitching & Complex experiment
- Out-of-plane motion is unavoidable
- Surface measurement ⟶ plane stress condition
- Challenge of getting better accuracy of measured disp.

Plastic flow on cutting



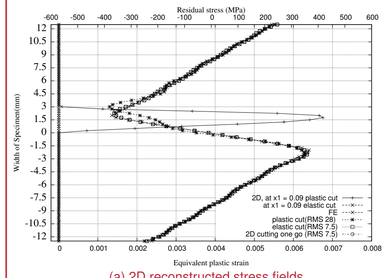
(a) Conventional slitting method



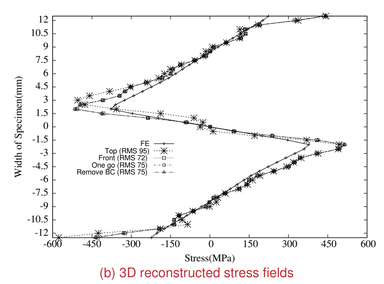
(b) Proposed cutting method

- Cut from top
- The stress along the cutting edge is **constant**.
- **Stress redistribution**

- Cut from front
- The stress along the cutting edge is **non-uniform**, self-equilibrated.
- **No stress redistribution**



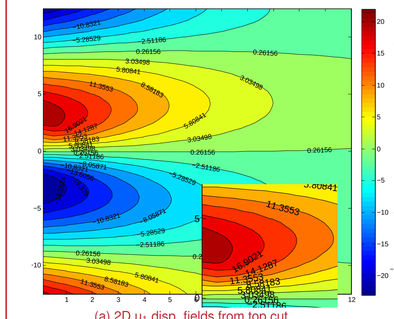
(a) 2D reconstructed stress fields



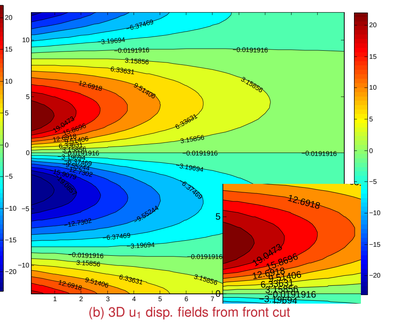
(b) 3D reconstructed stress fields

- Plastic flow is substantial in the region of residual stress peak
- No plastic flow on the front cutting

- Front cut still diagrees with FE
- Top cut - significant discrepancy in the peak



(a) 2D u_1 disp. fields from top cut



(b) 3D u_1 disp. fields from front cut

- Plastic flow distorts disp. field
- Leading to descrepancy in stress field in the peak

- No distortion, but 3D peak higer than 2D
- Mismatch between 2D analytical model and 3D real exp.

Concluding Remarks

- By carefully choosing the orientation and the direction of the propagation of the cut, plastic flow on relaxation can be minimised.
- Stress non-uniformity is still a problem. Using 2D model for a 3D experiment leads to errors. Need a fully 3D model.
- An assessment of the sensitivity of other MSR methods to the direction and the manner of propagation of the cut

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