Using DIC and HEXRD to measure residual stress relaxation and elastic follow-up

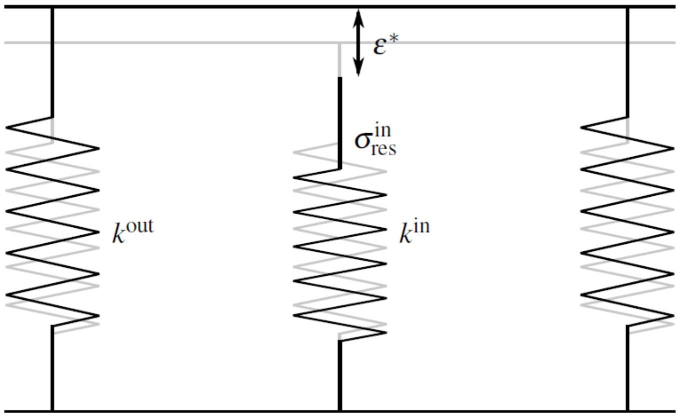
David Smith, Graeme Horne and Matthew Peel

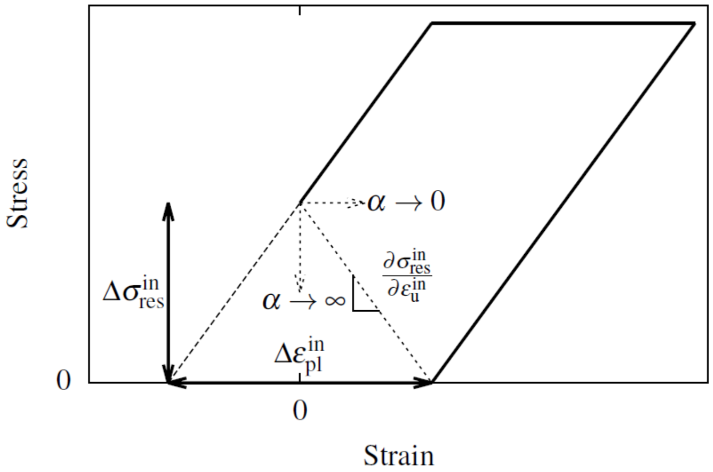
Solid Mechanics Group, University of Bristol

Residual stress relaxation and elastic follow-up

$$\sigma_{\mathrm{res}}^{\mathrm{in}} = E\frac{\alpha}{\alpha+1}\varepsilon^{*}.$$

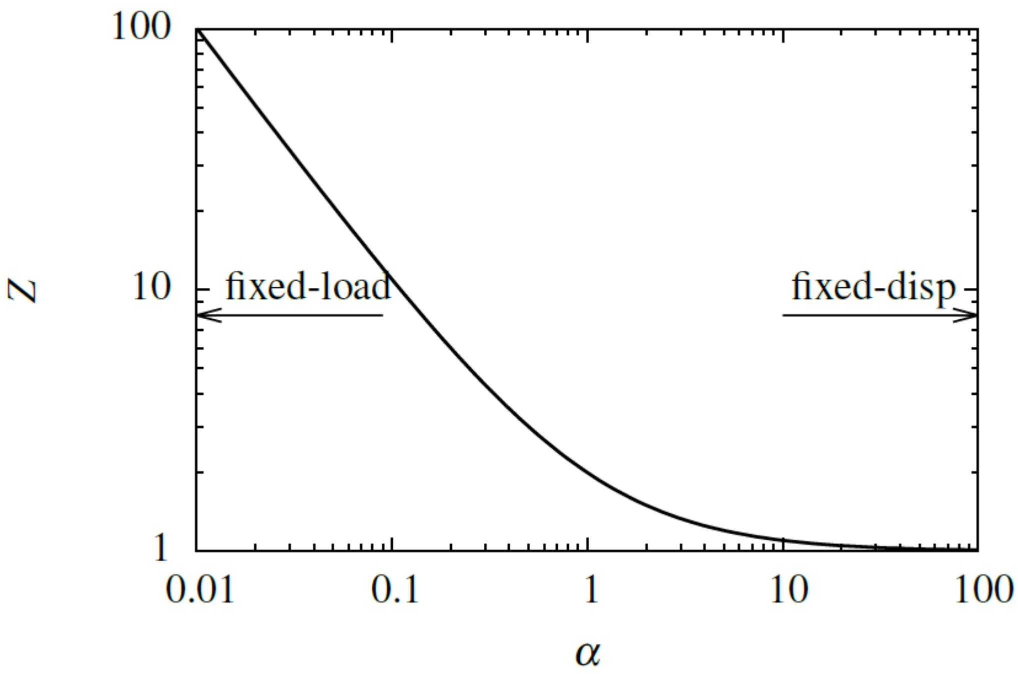
$$\alpha = \frac{k^{\mathrm{out}}}{k^{\mathrm{in}}}.$$





Elastic follow-up factor

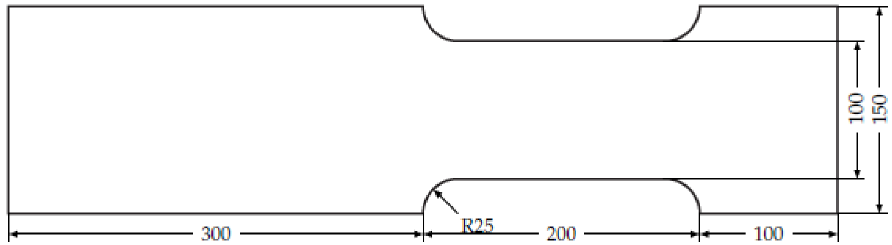
$$Z = \frac{\alpha+1}{\alpha}.$$



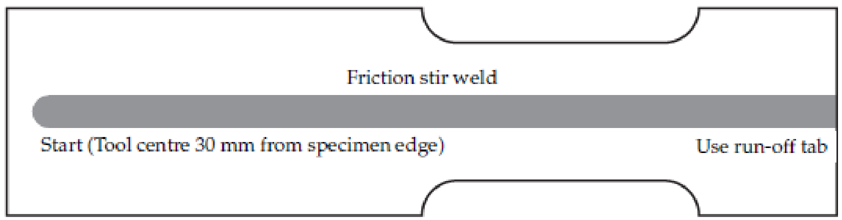
$$Z = \frac{\alpha + 1}{\alpha}.$$

Conventionally residual stresses are treated as “displacement controlled” stresses

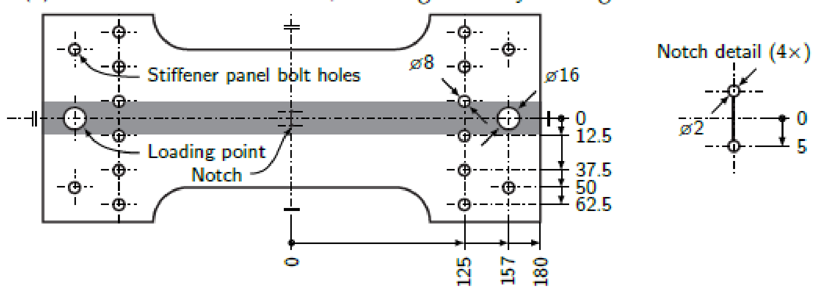
BUT our simple model shows that the rate of relaxation depends on the relative stiffness within a structure



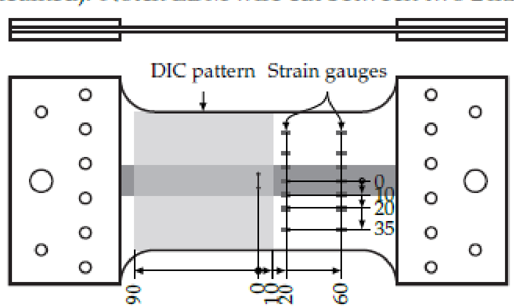
(a) Specimen geometry pre-welding. Water jet cut from aluminium alloy 5083 3 mm sheet in O temper (annealed condition), specimen longitudinal direction aligned to rolling direction.



(b) Friction stir weld location, running centrally in longitudinal direction.



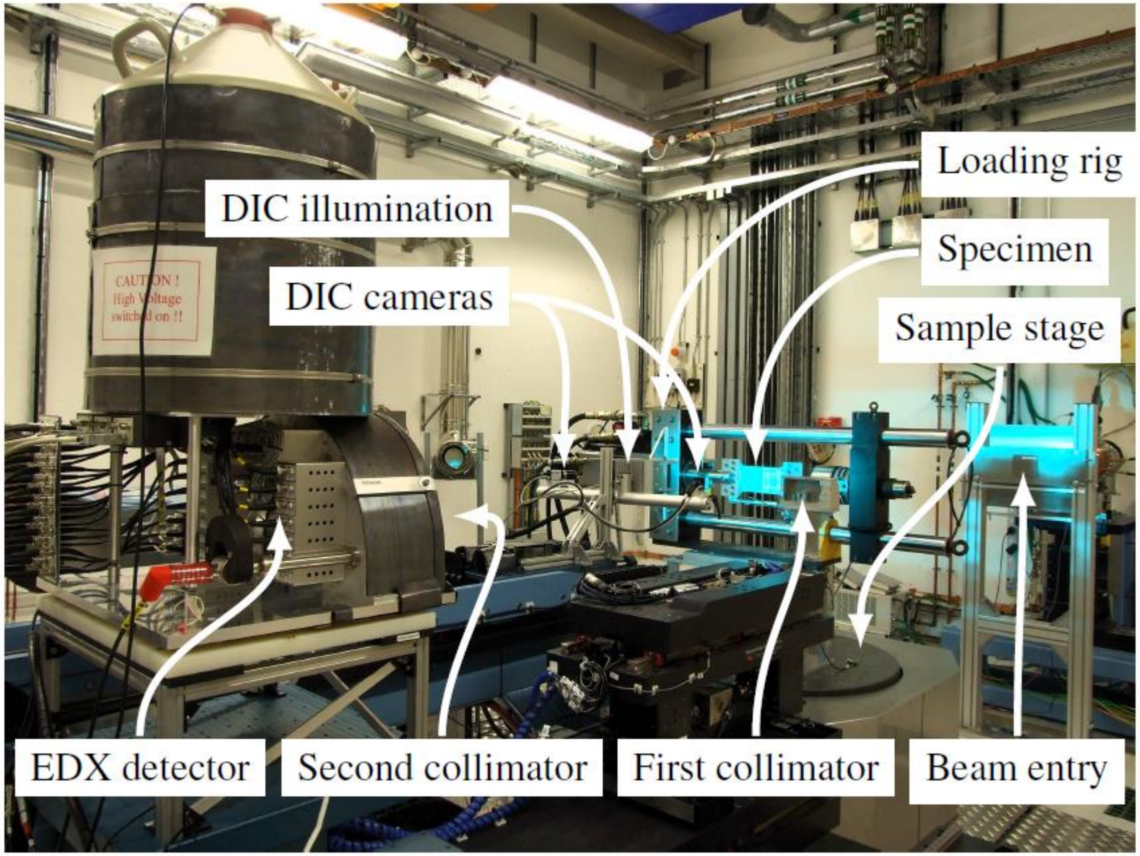
(c) Machined specimen with loading pins and stiffener panel bolts locations (drilled and reamed). Notch EDM wire cut between two 2 mm holes.



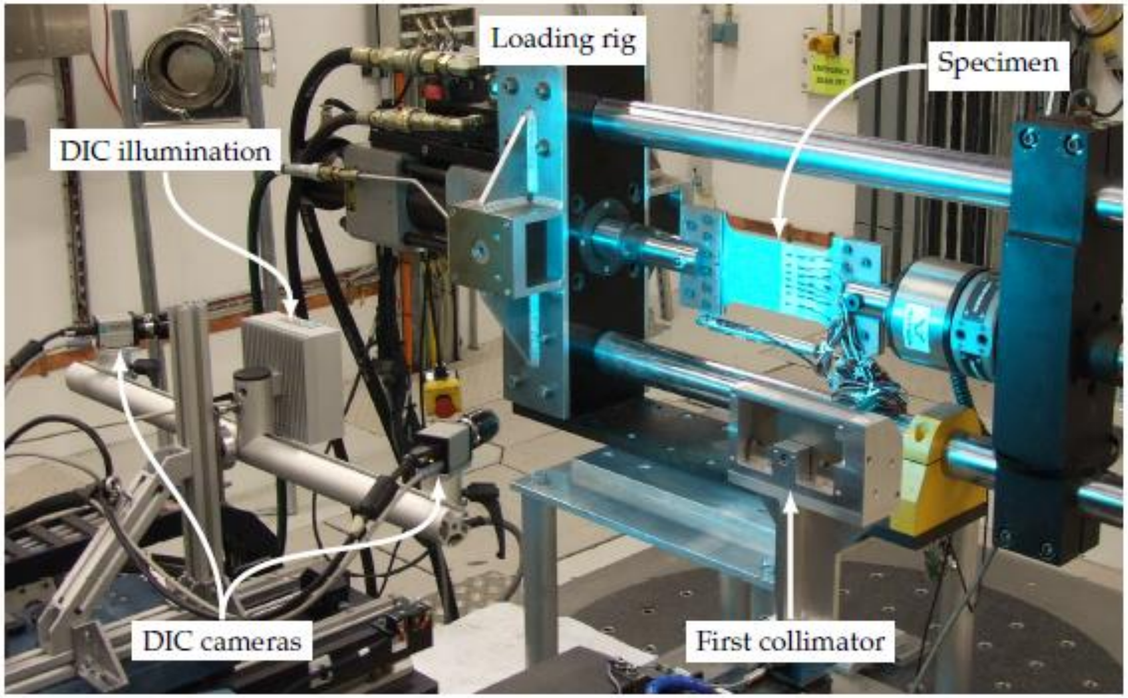
(d) Assembly of specimen and stiffener plates, also showing digital image correlation (DIC) speckle pattern and strain gauge location.

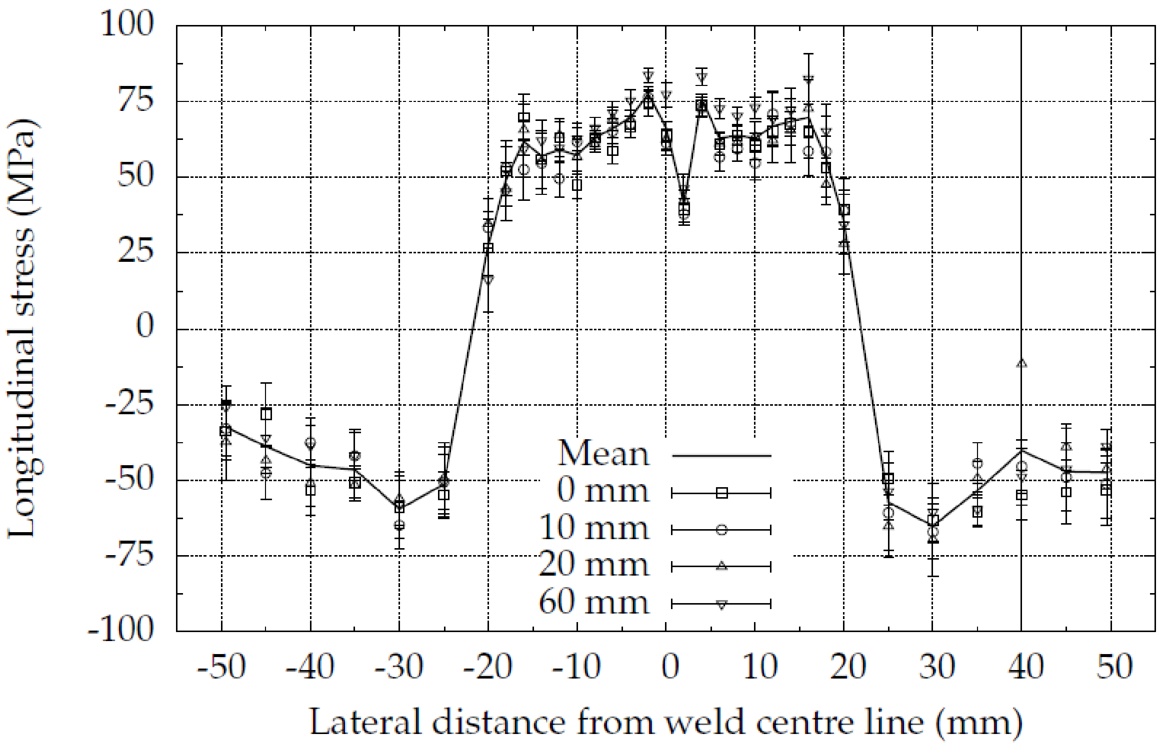
Experiment devised to explore interaction between initial residual stresses and applied stresses

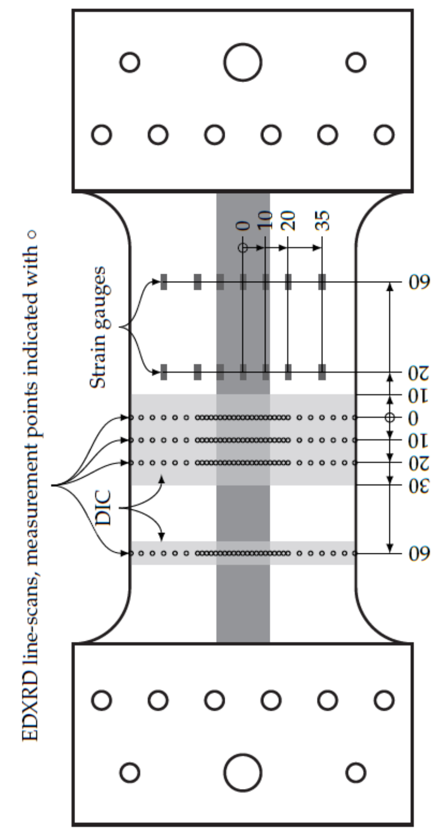
- Introduce weld residual stresses using friction stir welding
- Subject specimen to applied loads
- Measure the internal stresses and surface distortions to determine the stress-strain paths in loaded and unloaded states



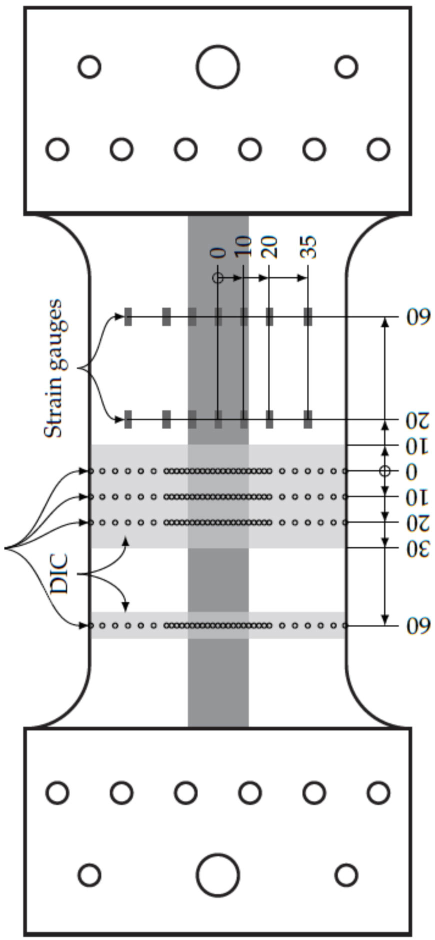
- 3D DIC using Dantec Dynamics Q400 with 5 megapixel, 8 bit cameras.
- EDX using 23 element detector on I12 beamline at Diamond Light Source.
- Loading with 50 kN Instron servo-hydraulic test machine.
- Sample stage translated between diffraction & digital image correlation positions for respective measurements.


Loading rig
Specimen
DIC illumination
DIC cameras
First collimator



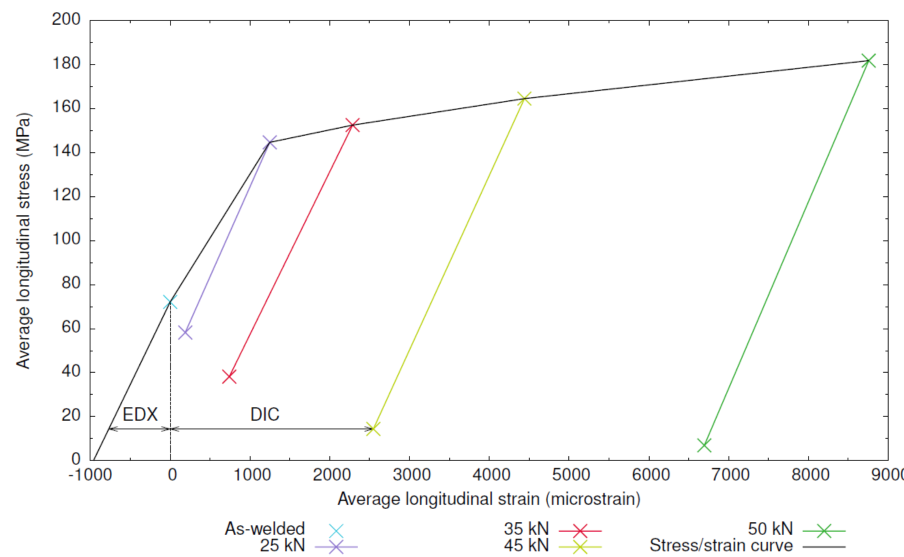


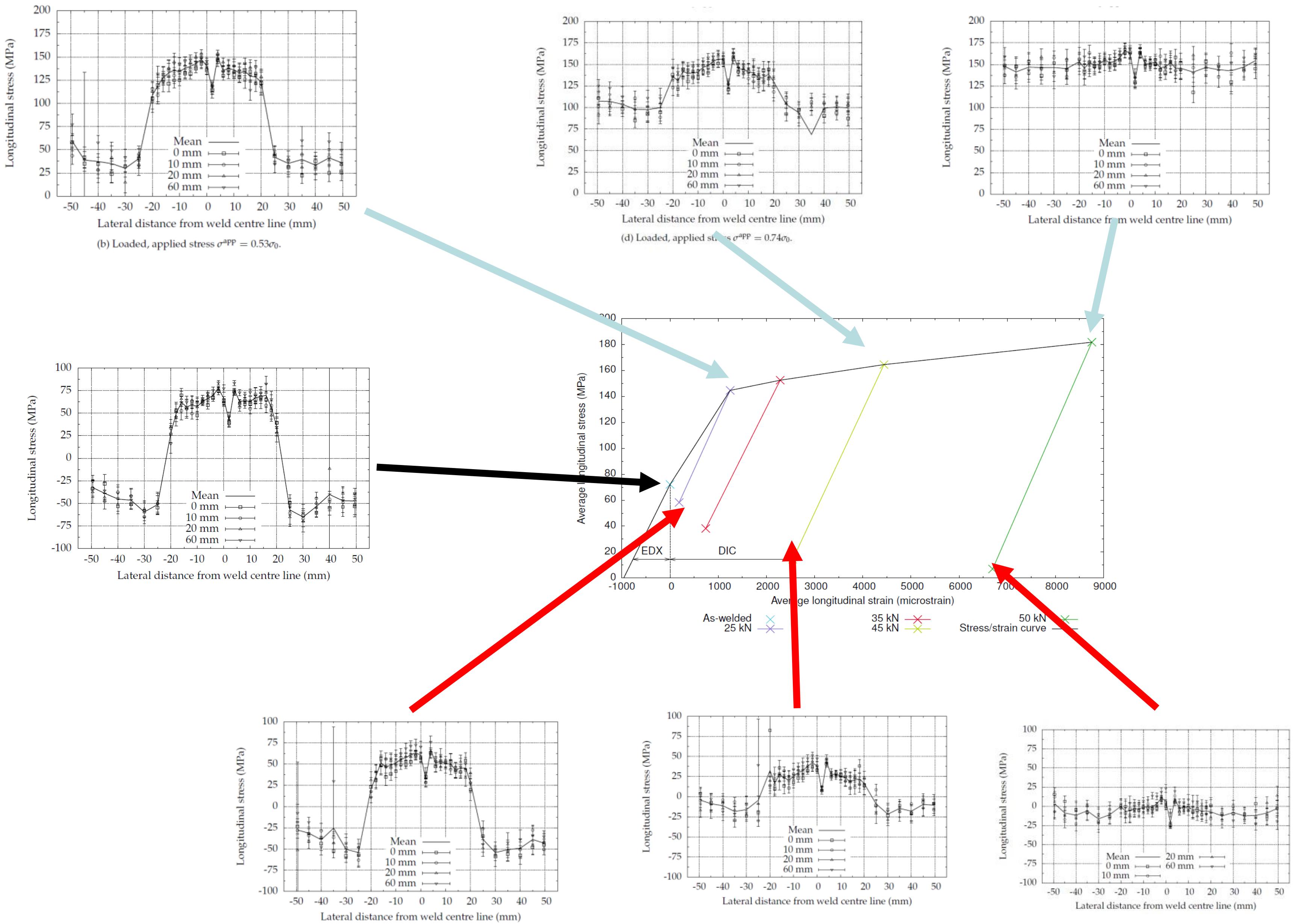
(a) Measurement locations on welded specimen with no notch.



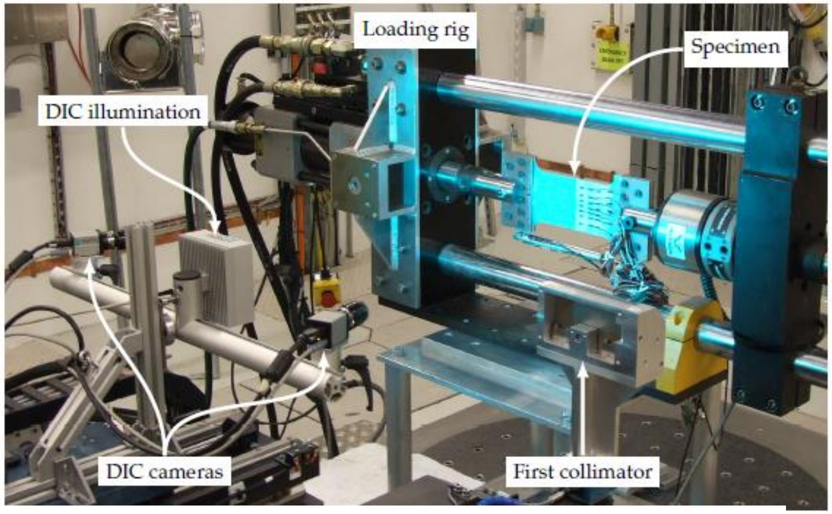
Loading cycle	Applied load (kN)	Applied stress (MPa)	Normalised applied stress as fraction of σ_0
1	25	83	0.53
2	35	117	0.74
3	45	150	0.95
4	50	167	1.05

Specimen response





Longitudinal stress (MPa)
Lateral distance from weld centre line (mm)
Mean
0 mm
10 mm
20 mm
60 mm
(b) Loaded, applied stress $\sigma^{app} = 0.53\sigma_0$.
(d) Loaded, applied st ss $\sigma^{app} = 0.74\sigma_0$.
Average longitudinal stress (MPa)
Average longitudinal strain (microstrain)
EDX
DIC
As-welded
25 kN
35 kN
45 kN
50 kN
Stress/strain curve



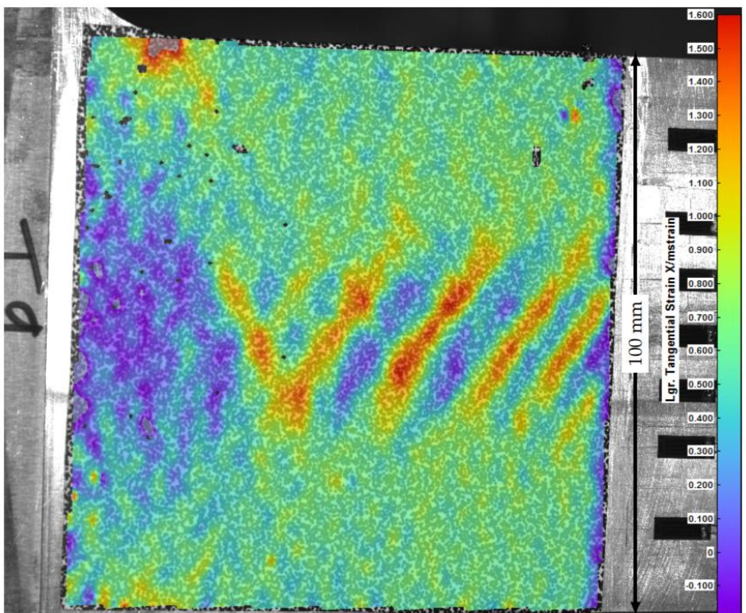
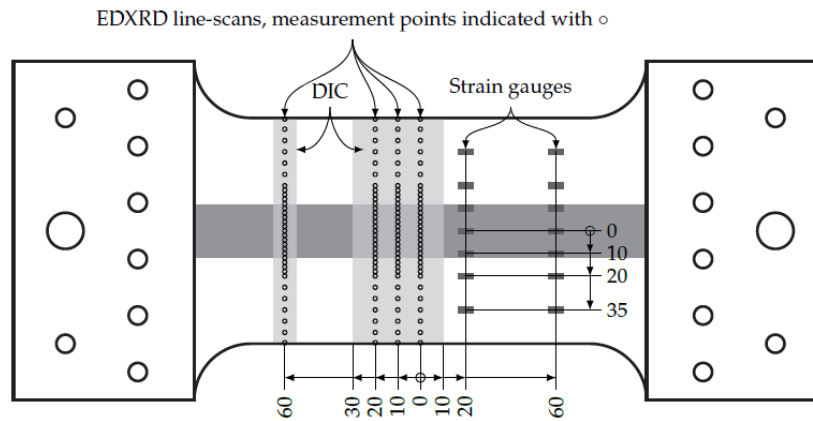
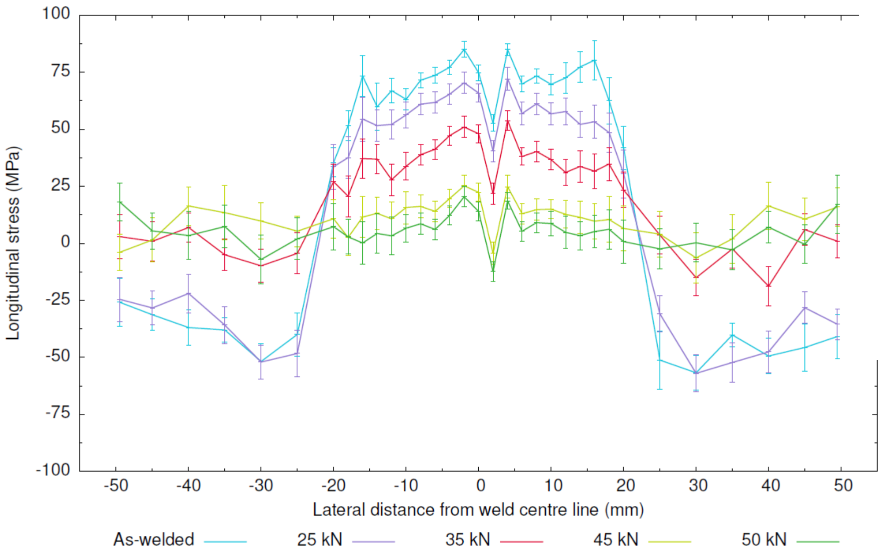


Figure 6.7: Digital image correlation contour plot showing longitudinal strain in the unloaded state following the $0.74\sigma_0$ loading cycle. Localised bands of plastic strain can be seen in the central welded region. Colour bar: minimum, purple, -200×10^{-6} strain; maximum, red, 1600×10^{-6} strain.

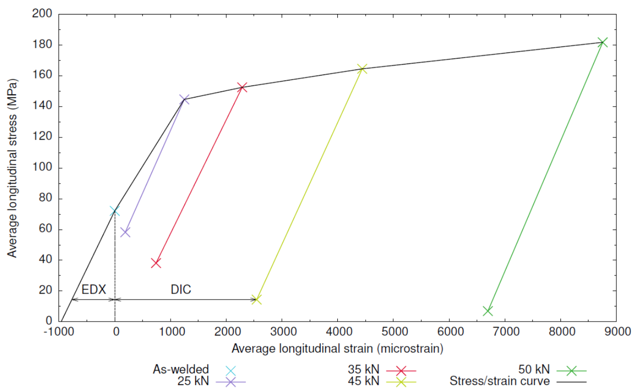


(a) Measurement locations on welded specimen with no notch.

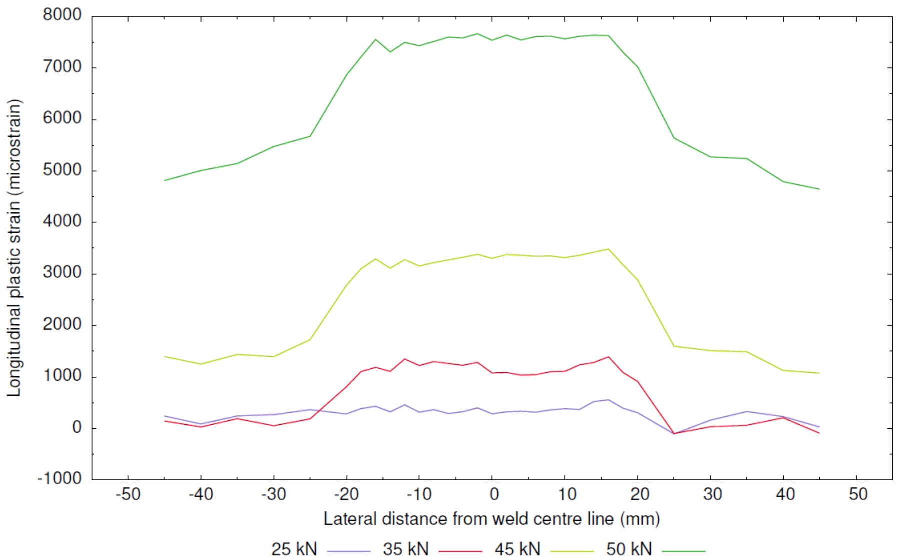
Diffraction results



Specimen response

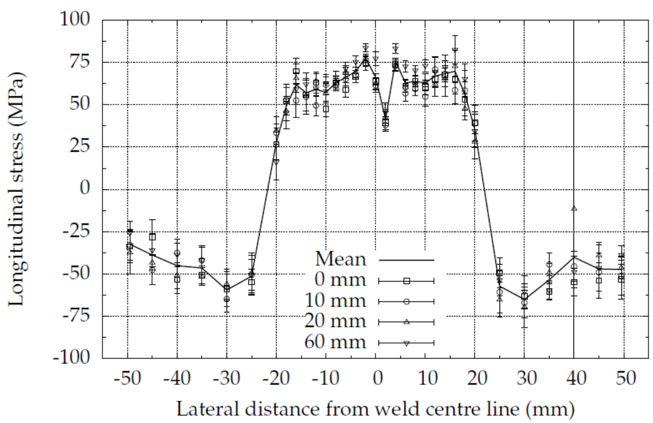


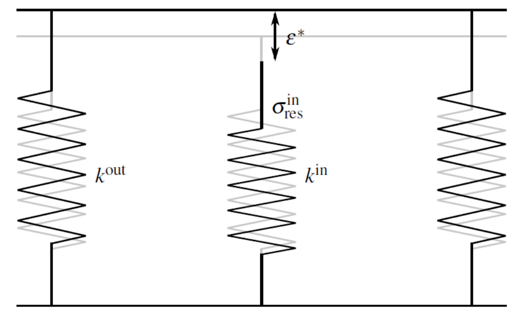
Plastic strain



Determination of elastic follow-up factor

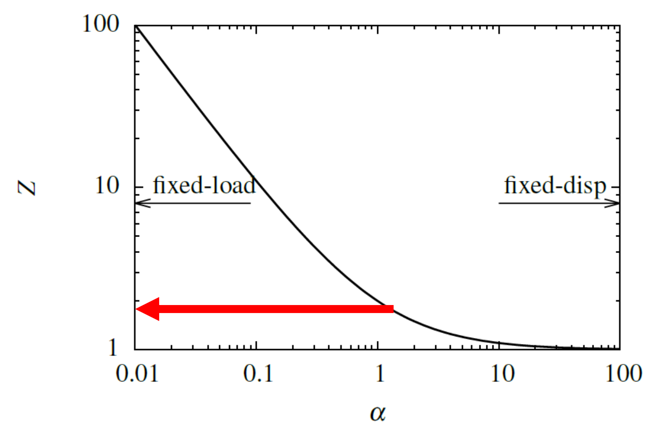
1. Based of relative stiffness of tensile and compressive regions of residual stress



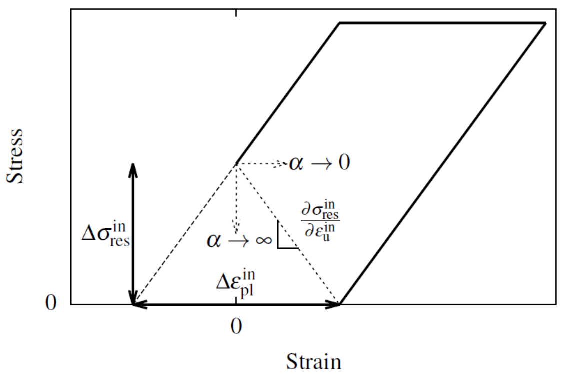


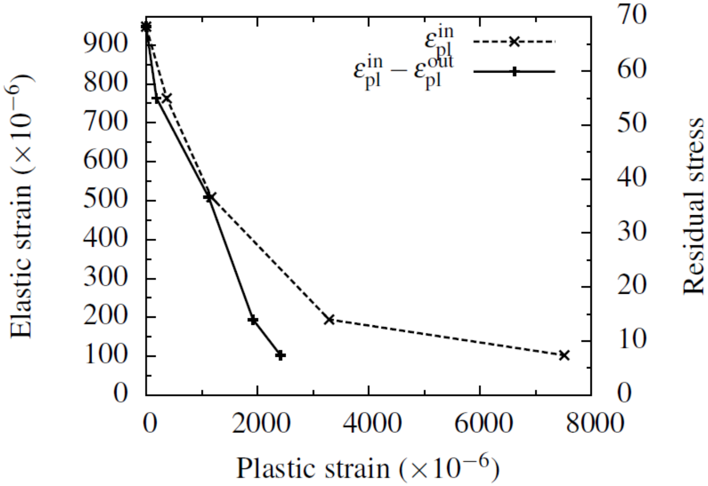
$$\alpha = \frac{k^{out}}{k^{in}} = \frac{100 - 44}{44} = 1.27$$

$$Z = 1.79$$



2. Based on the experimental rate of residual stress relaxation





$$Z = \frac{\Delta\varepsilon^*}{\Delta\sigma_{res}^{in}/E} = \frac{\Delta(\varepsilon_{pl}^{in} - \varepsilon_{pl}^{out})}{\Delta\sigma_{res}^{in}/E}.$$

$$Z = 2.93$$

Elastic Follow-up and Its Consequences

- Elastic follow-up describes boundary conditions that lie between load and displacement control
- Elastic follow-up has a consequence on residual stresses relaxation due to plasticity
- Elastic follow-up CREATES additional accumulation of plastic deformation