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Title: Forensic Determination of Residual Stresses from Fracture Surfaces

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Forensic Determination of Residual Stresses from Fracture Surfaces

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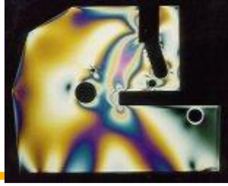
Defining “forensic”

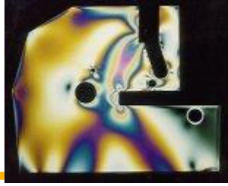


- **Since “forensic” is a less common English word, I should define it for you**

forensic [fəˈrɛnsɪk]
adj

– relating to or used in a court of law
  [from Latin *forēnsis* public, from FORUM]

- **Not really what I meant**
  - I do not want to be associated with lawyers
  - I should have looked the word up in the dictionary before I used it

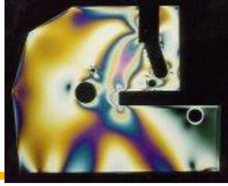


Try again

Forensic engineering

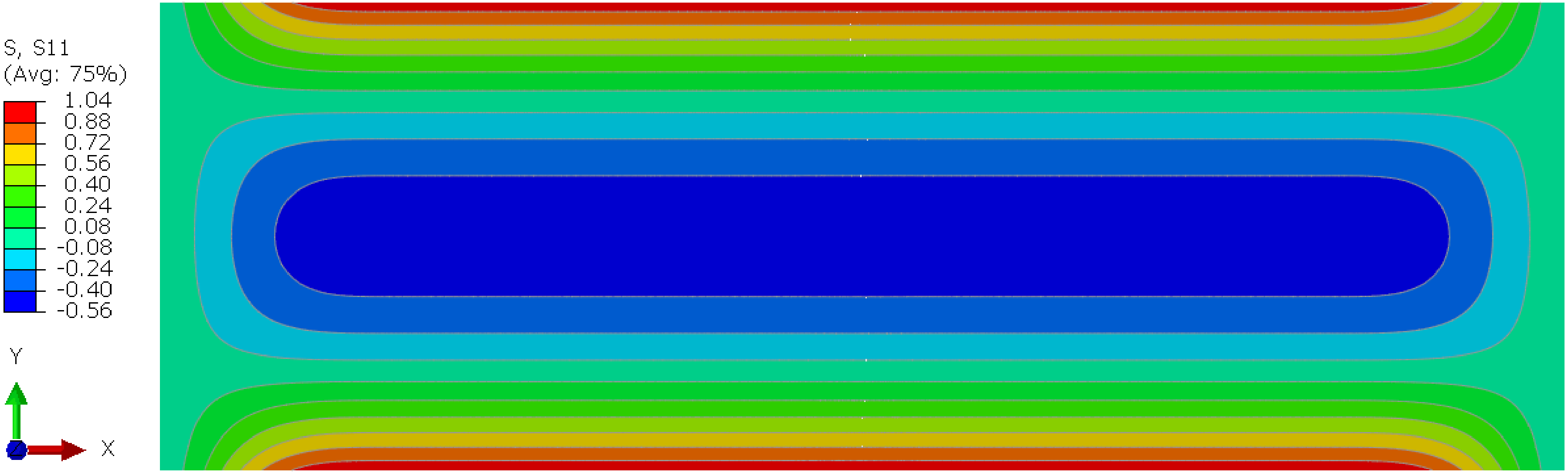
– the scientific examination and analysis of *failed* structures and parts relating to their failure or cause of damage

The challenge

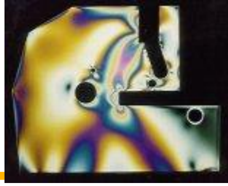


This part originally contained residual stresses

Parabolic, +1 at top and bottom, -½ at mid-thickness



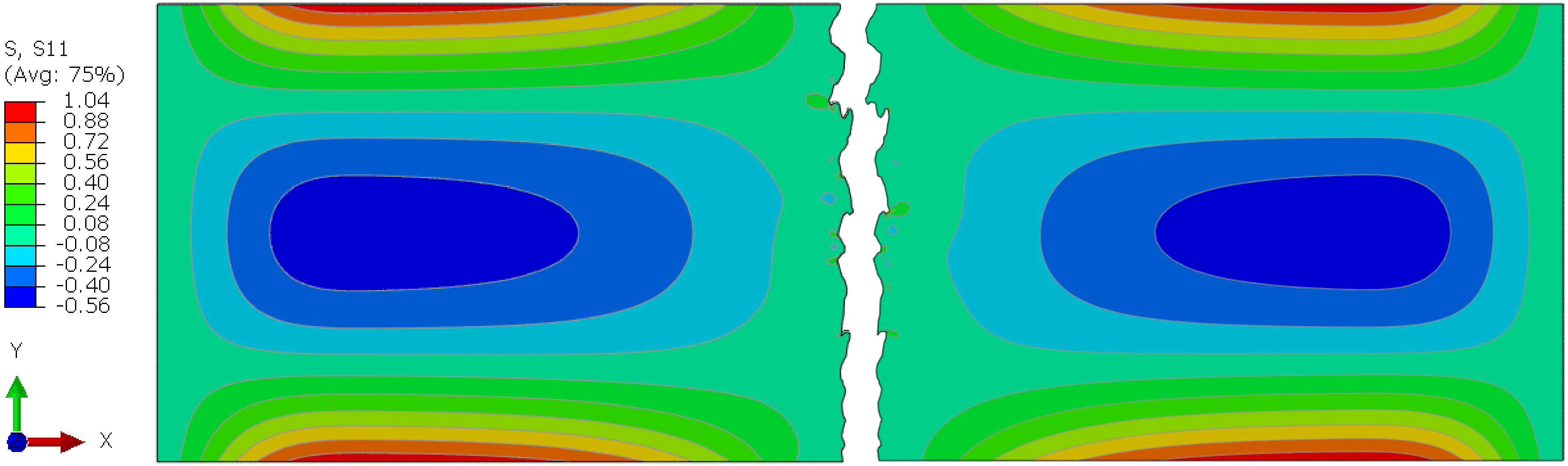
σ_X plotted ⟷



The evidence & the question

- **It fractured in two**

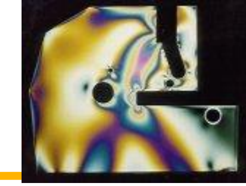
σ_x plotted

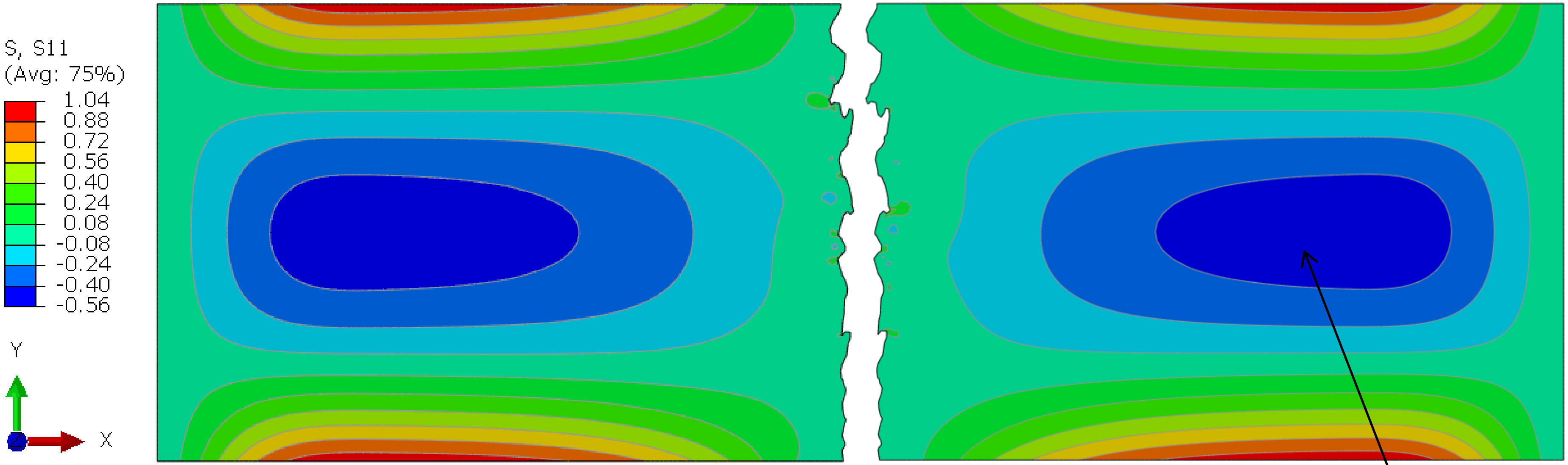


- **The x-stresses are now zero on the fracture surface**

What were the original residual stresses where the fracture surface is now?

The constraints

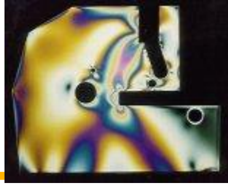




- **What you can assume**
  - Brittle fracture into two pieces
  - You can measure anything you want on either or both of the pieces

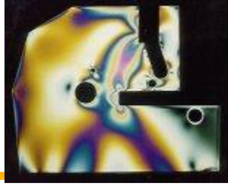
- **Not the answer:**
  - No just measuring stresses away from the fracture and assuming they are the same
  - You cannot go back and measure something prior to fracture

Outline



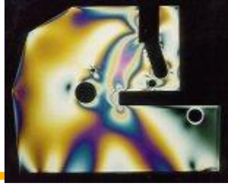
- THE CHALLENGE ✓
- ➤ **What are residual stresses and why do we care?**
  - Other measurement methods & forensic work
- **The failed specimen**
- **THE SOLUTION**
- **Application to our failed specimen**
- **Independent validation**
- **Final thoughts**

What are residual stresses – definition

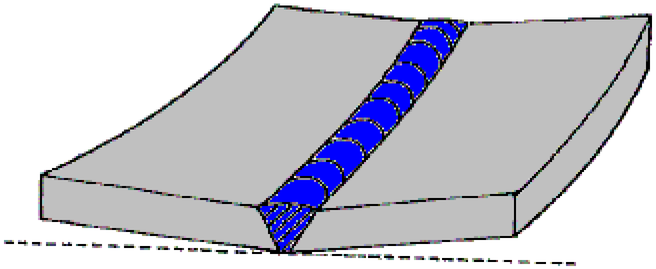


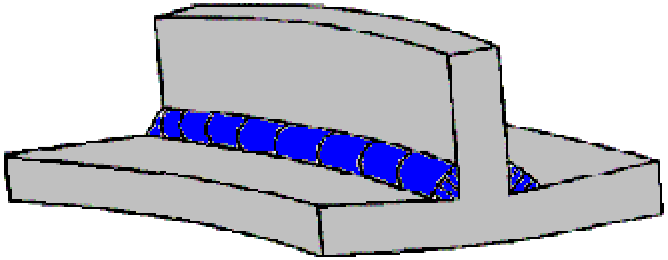
- **The stresses in a body that is free of external loads**
  - No applied forces, pressures, or displacements
  - No body forces (gravity)
  - No thermal gradients
- **They are stresses left behind from some thermal or mechanical process**

What are residual stresses – example



- **Welds usually have tensile residual stresses from cooling of the weld bead**

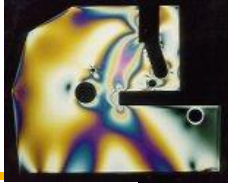




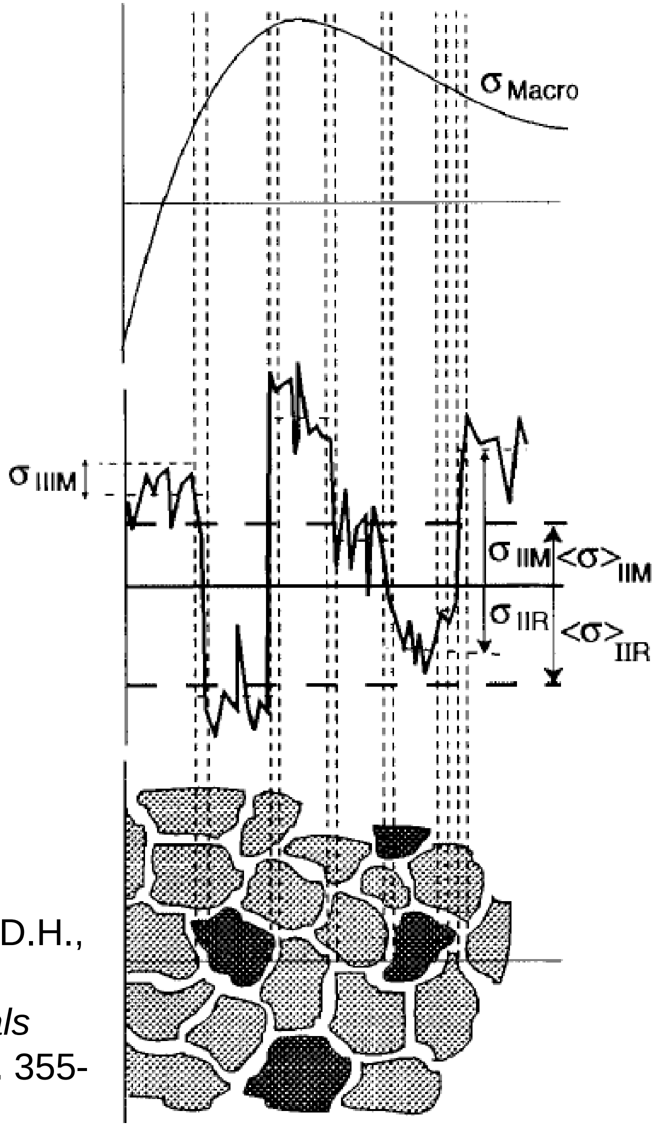
http://www.weldingengineer.com/Distortion.htm

- **Virtually all processes results in residual stress**
  - Sometimes good (compressive), often not

Residual Stresses – Definition of Macro-Micro

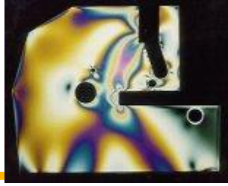


- **Residual Stresses are often characterized by their length scale**
- **Macro – Type I**
  - Long length scales
  - Has most effect at engineering scale
- **Micro – Type II – intergranular**
  - Grain to grain variations
  - Average to zero
- **Micro – Type III – intragranular**
  - Vary within grains
  - Average to zero



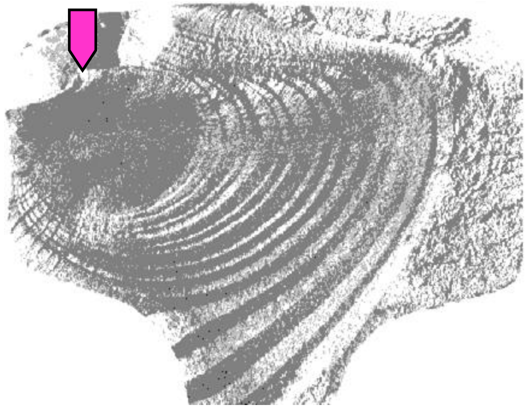
Withers, P. J., and Bhadeshia, H.K.D.H., 2001, "Residual Stress–Part 1–Measurement Techniques," *Materials Science and Technology*, 17(4), pp. 355-365.

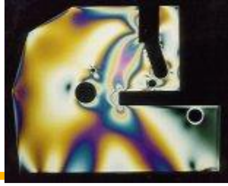
Why do we care about residual stress?



Residual stresses add to applied loads and cause or contribute to:

- **Distortion**
- **Buckling**
- **Stress Corrosion Cracking**
- **Fatigue**
- **and …**



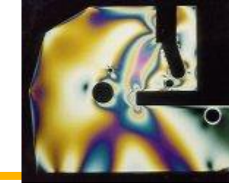


Residual stress effects – fracture

- **Fractures caused completely by residual stress:**

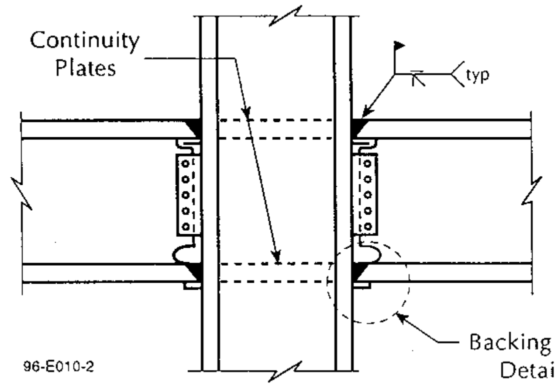
Photo: Ryszard Szymani, Wood Machining Institute

Photo: Mark Newborn, Alcoa

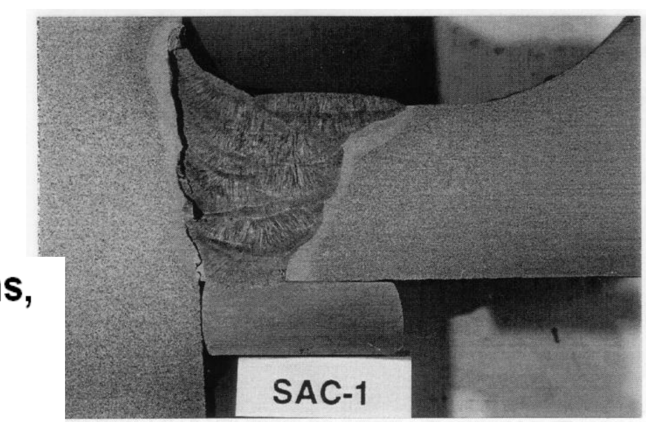


Residual stress effects – fracture example

- **Special-Moment Resisting Frames (SMRF's) used to join columns and beams**
  - Designed to survive large loads
- **Brittle failure in Northridge Earthquake 1994**
- **Un-accounted for welding residual stress a main factor in surprise failures**



Weld Connection



From:

Industrial Welding Residual Stress Problems, Measurements, and Predictions

Pingsha Dong
Center for Welded Structures Research
BATTELLE
Columbus, OH

Residual Stress Summit 2005

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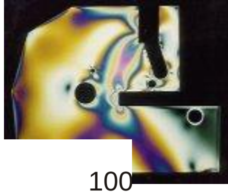
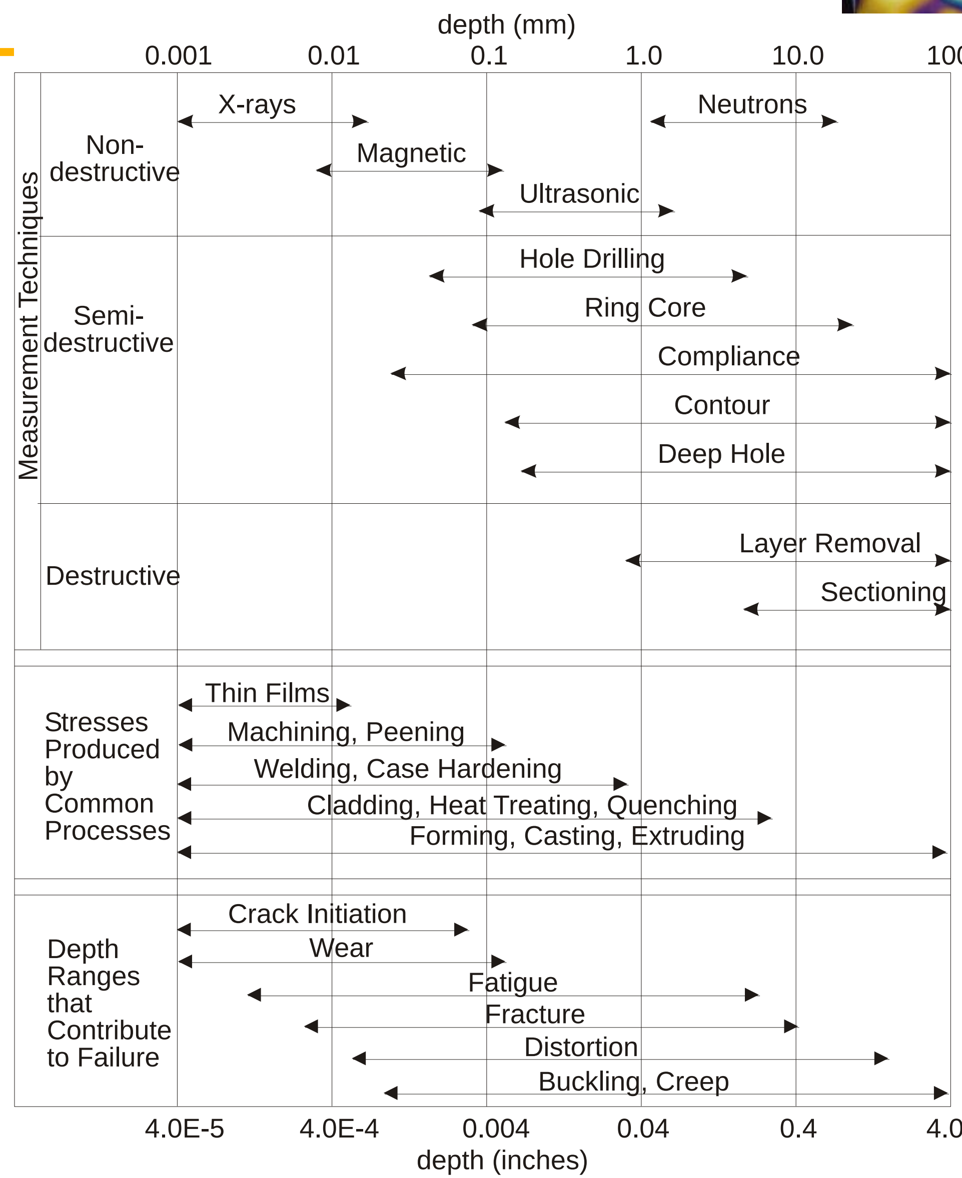
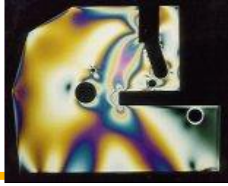
Measurement methods

- **Many measurement methods**
- **Very different physics to determine residual stress**
- **Different length scales**
- **Different capabilities**
- **No one “best” way to measure residual stress**
  - Depends on application
- **Subject of ongoing research**
- **20% accuracy for residual stress measurement is good**

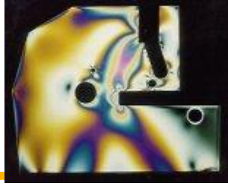




Residual stress forensics

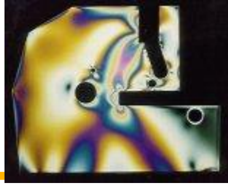


- **Because stresses are relieved by the crack, "testing of undamaged *similar*, or *exemplar* parts, is frequently used as the only alternative in order to understand the residual stress system in the failed part prior to fracture"**
  - Shipley RJ, Becker WT. *Volume 11: Failure analysis and prevention*. ASM Handbook. Materials Park, OH: ASM International; 2002
- **Testing similar parts useful, but limited**
  - Are similar parts even available?
  - Maybe the failed part missed a processing step – so similar part not informative
  - Did failed part stresses change in service?
    - Thermal excursion
    - Overload
    - Fatigue loading
    - …



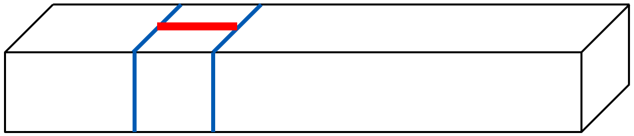
Outline

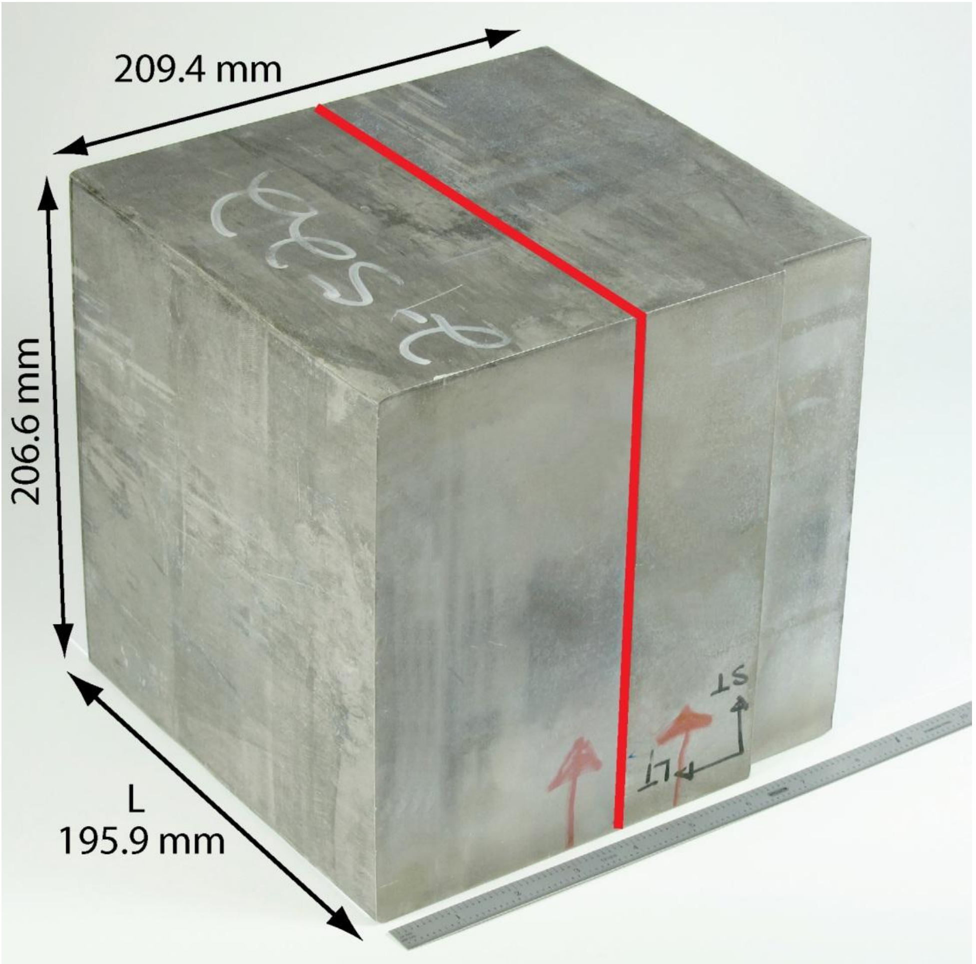
- THE CHALLENGE ✓
- What are residual stresses and why do we care? ✓
- ➢ **The failed specimen**
- THE SOLUTION
- Application to our failed specimen
- Independent validation
- Final thoughts

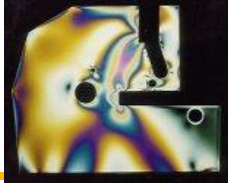


Specimen from aluminum forging

- **AA 7050-T74 hand forging**
  - 209 mm × 207 mm x 1.8 m piece was forged from 0.58 m diameter cylindrical billet
    - 84% reduction
  - Working with section196 mm long
- **Process history**
  - 890 °F for 15.5 hr
  - Water quench (144 °F)
    - Source of stress
  - Artificial age (6 hr @ 250 °F)
  - Artificial age (6 hr @ 350 °F)
- **No stress relief!**
  - Part of a process study

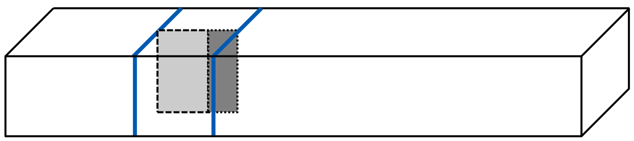






Fracture

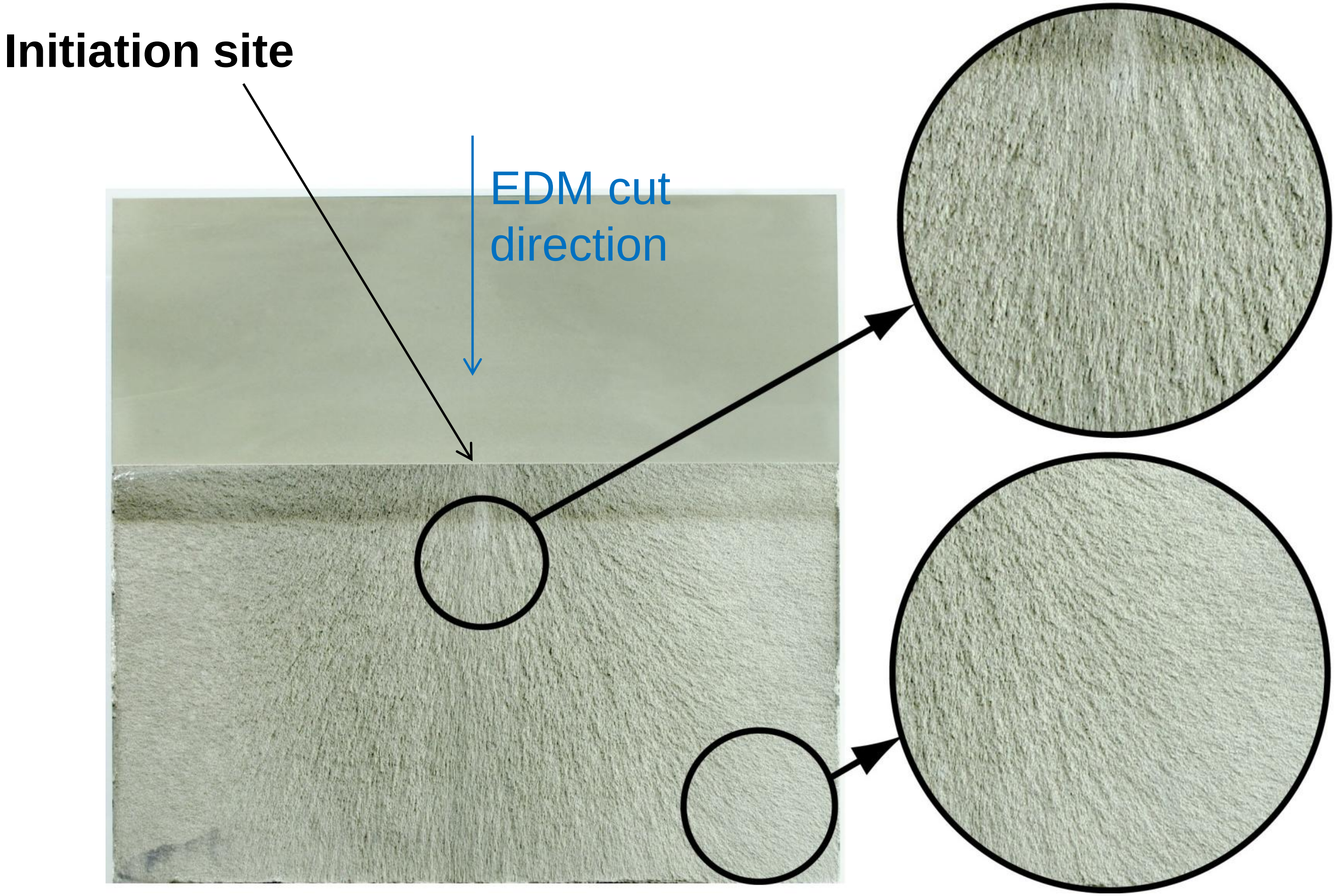
- **Attempt to split block into two using wire EDM cut**
  - Cut to 76.5 mm (~40%), the fast fracture occurs
  - Not intentional
  - Fracture is very planar



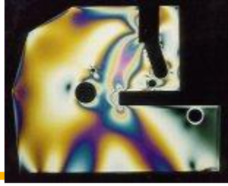
Orientation of cut/fracture relative to original forging

- **Residual stresses released during cut were so high that part spontaneously fractured**

Fracture Surface



Outline

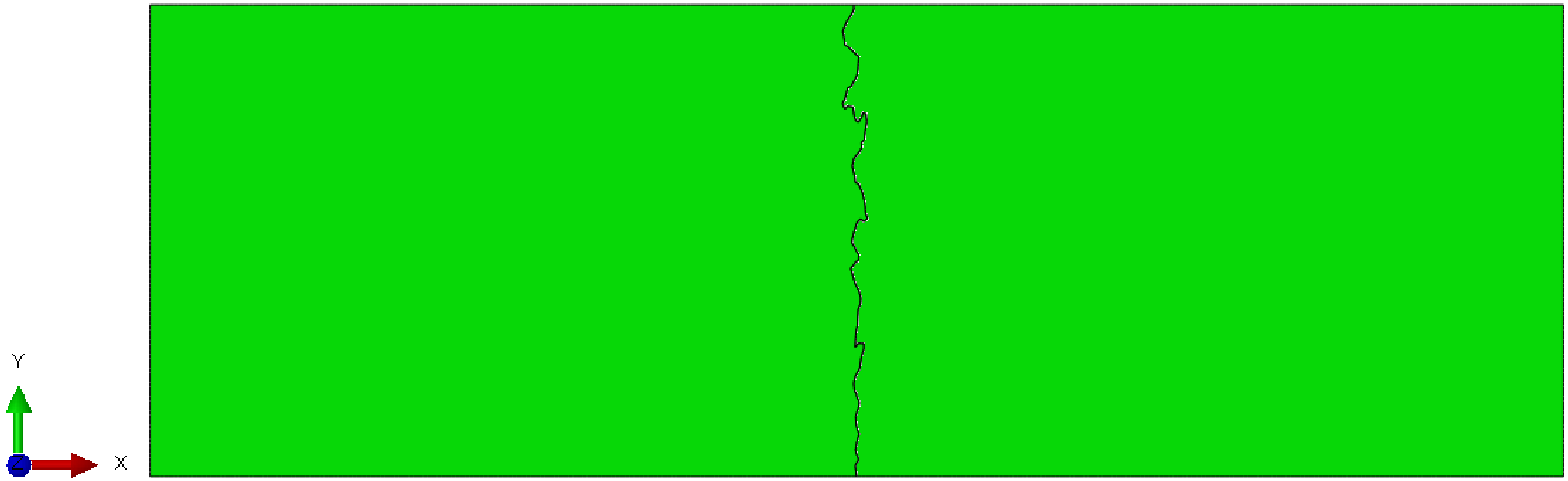


- THE CHALLENGE ✓
- What are residual stresses and why do we care? ✓
- The failed specimen ✓
- ➢ **THE SOLUTION**
  - (Aside – FEM model)
  - What we measure
  - How to calculate stress
- Application to our failed specimen
- Independent validation
- Final thoughts

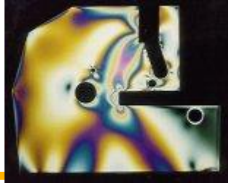
FEM demonstration

I am using an ABAQUS finite element simulation to illustrate and test the principles

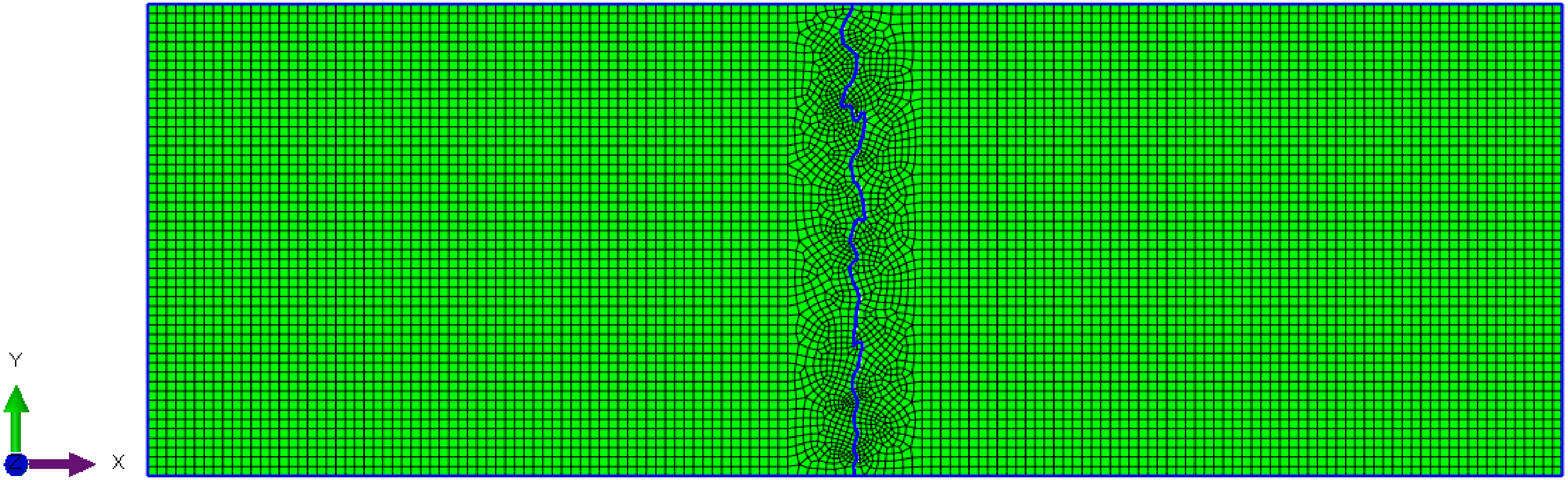
- **Start with a 2-D, 3×1 beam**
- **Divide roughly in half by a *pre-determined* crack**

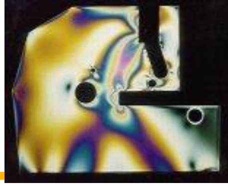


FEM mesh



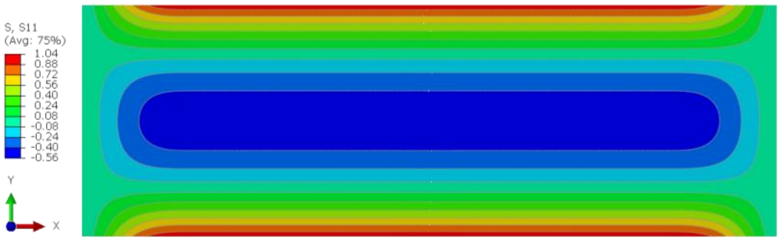
- **2-D plane strain mesh**
  - 50 CPE8R elements through the thickness
- **Initially bond nodes together on crack surface**
  - Can remove bonding during simulation



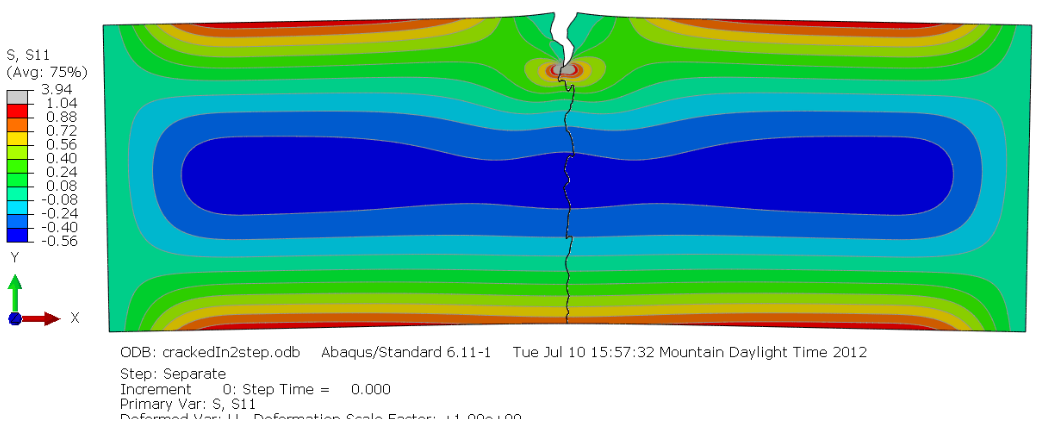


FEM stresses and elastic behavior

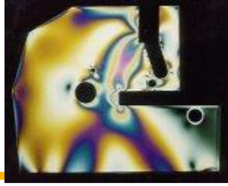
- **Initial stresses parabolic through the thickness**
  - +1 at top and bottom, -½ at mid-thickness
  - Smoothly satisfies stress-free end condition



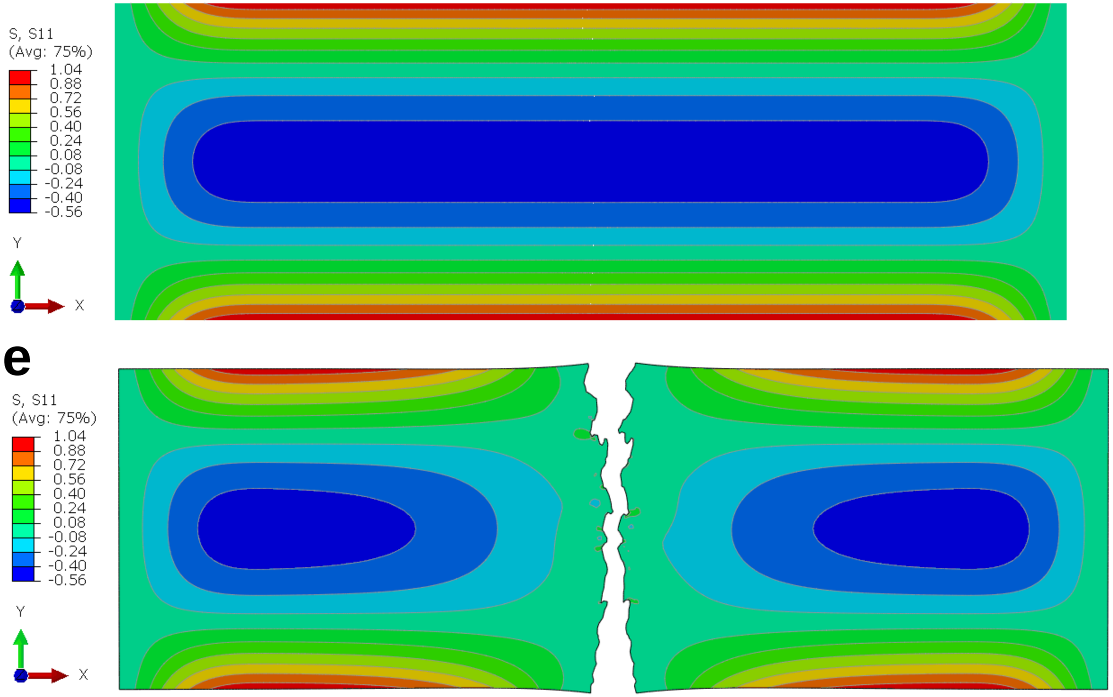
- **Elastic with *E* = 10, ν = 0.3**
  - σ/E = 1/10 gives visible deformation but for metals should really be 1/1000
- **Debond all or part of crack surface as desired**
- **Model *elastic* relaxation of stresses**



The solution



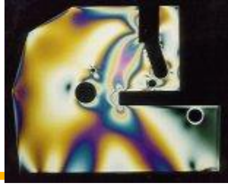
- **When a part with residual stress fractures …**
- **The surfaces do not fit together perfectly, because of stress relaxation**
- **In a brittle fracture, the relaxation is elastic**

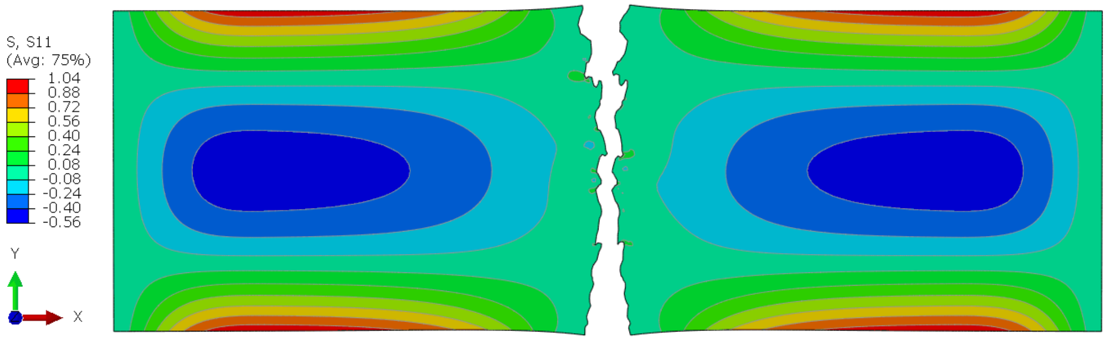


So ⇨

- **The misfit uniquely determines the original residual stress**
  - Remember that the elastic problem is path independent
  - I will discuss more later

How to exploit this idea?

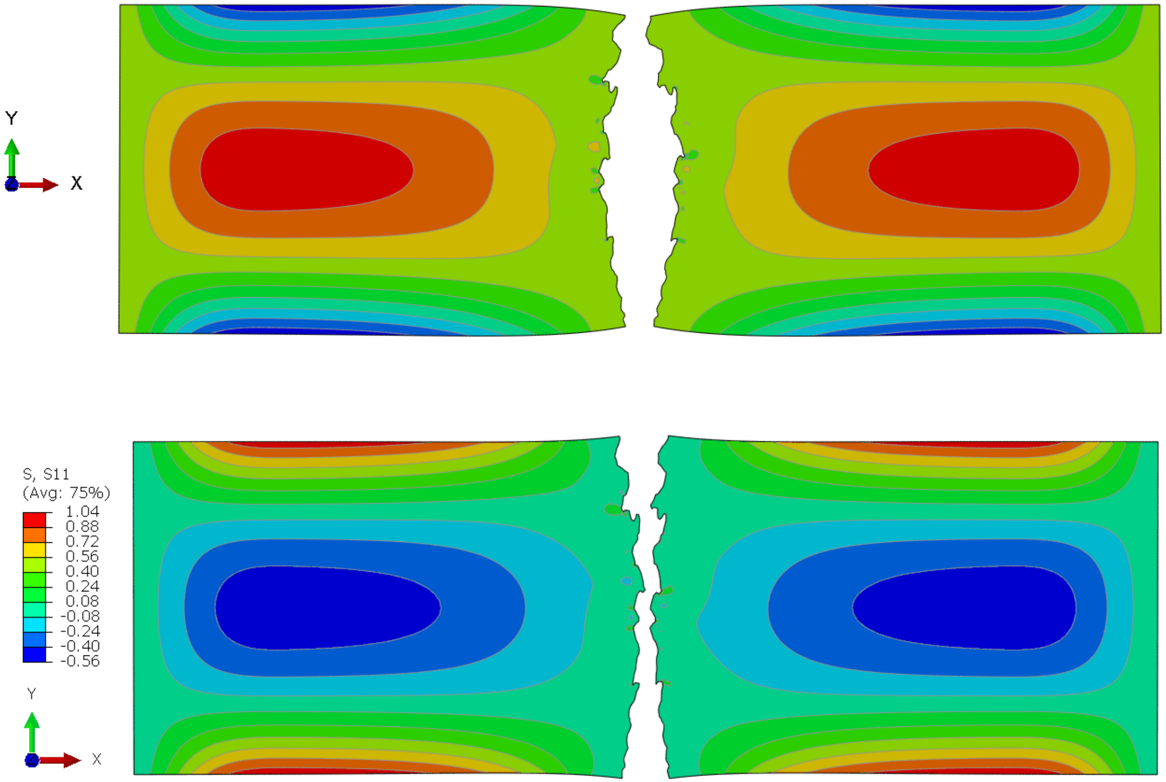


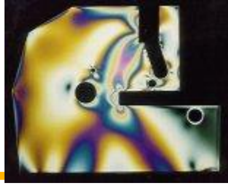


- **How do you measure the misfit? (experimental mechanics)**
- **How do you calculate stress from the misfit? (solid mechanics)**

Measuring misfit

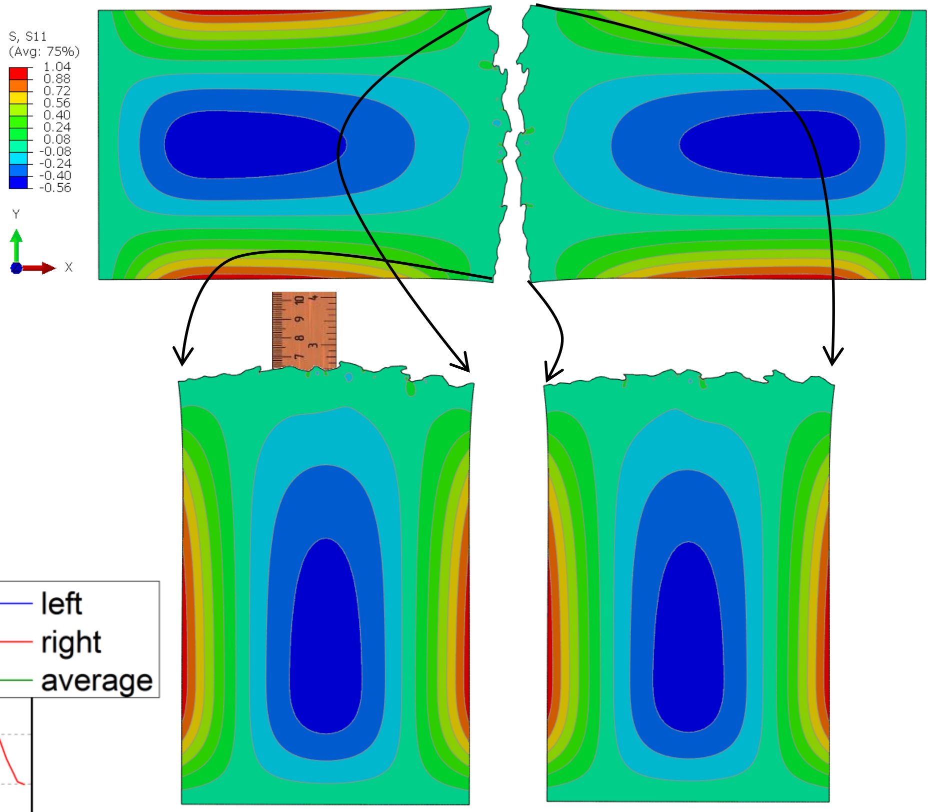
Obviously we are not going to get between two surfaces and measure misfit

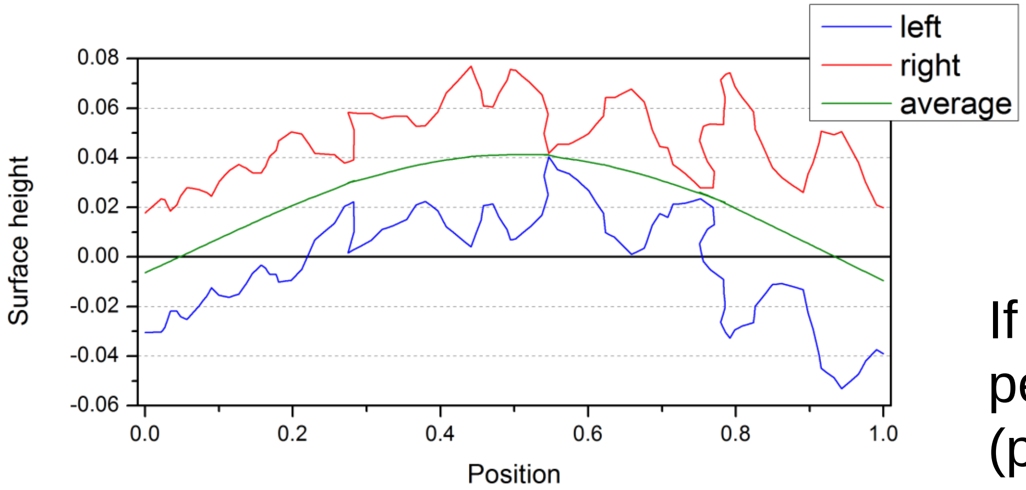




Just average surface contours

- **Measure surface height (contour) of each half**
  - One half is flipped so that material points line up
  - Reference plane is arbitrary
- **Average the two**
  - What remains is the misfit
  - Low values is gap open – from tensile stress

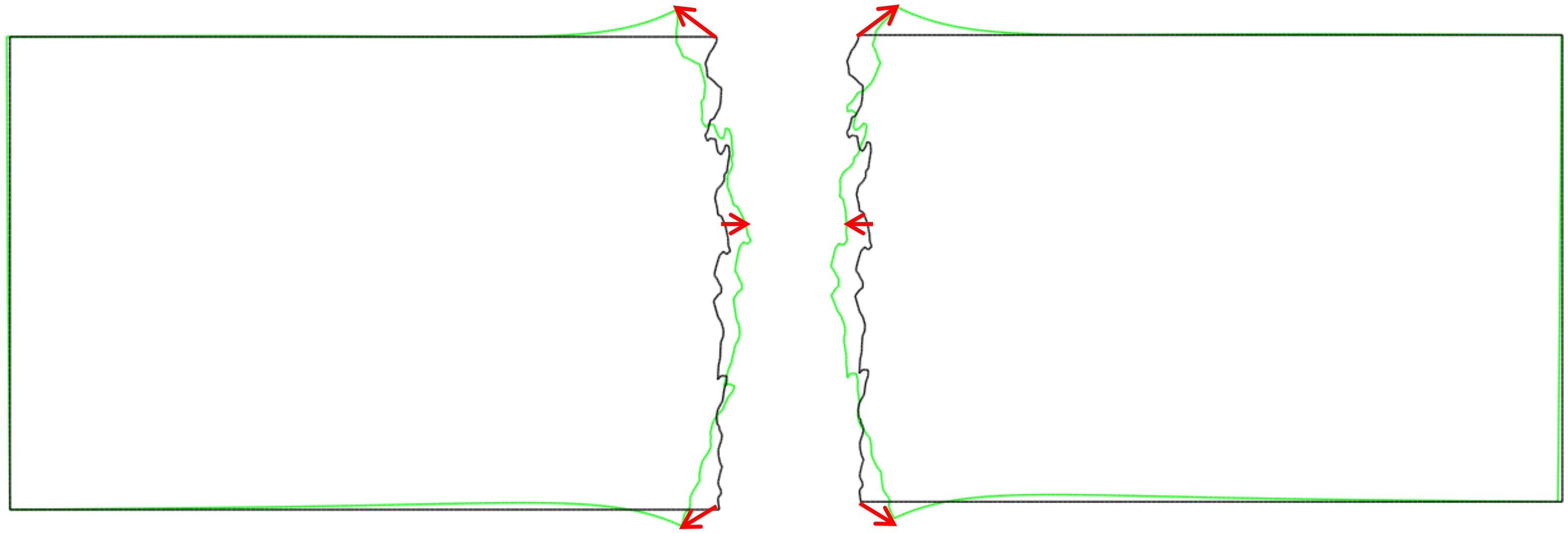




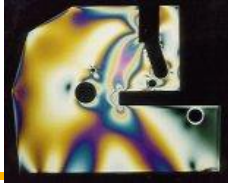
If no misfit, surfaces mate perfectly, average is straight line (plane in 3D)

Misfit = average displacement

- **The misfit = average *x-displacement* of the corresponding points on the two halves**
  - No deformation = no misfit

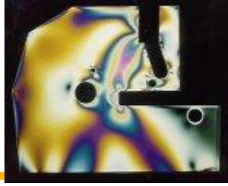


How to calculate stress from the misfit?



- **Lots of residual stress measurements take as their data the deformation measured after creating a free surface**
  - Hole drilling, layer removal, crack compliance …
- **Calculating stresses generally requires an elastic *inverse* calculation**
  - Guess some form for the stresses
    - Pointwise values, polynomial series, …
  - *Solve forward problem*: given the guess, what are the deformations
  - Adjust guess to match measured deformations
    - Linear superposition, so use least squares fit
- **Could do it this way**
- **But can do better**

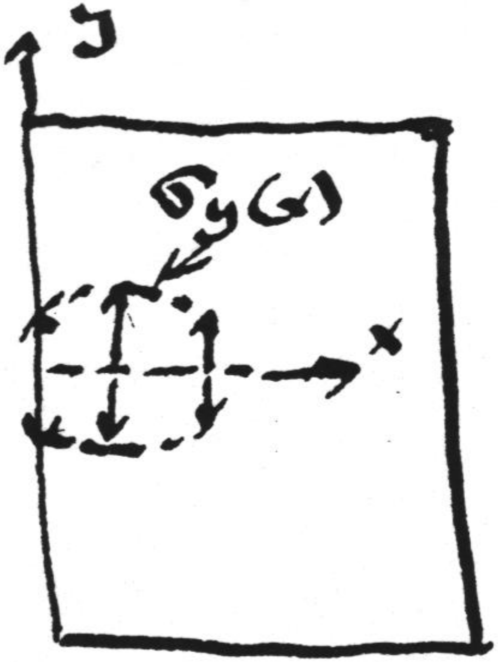
Forward problem



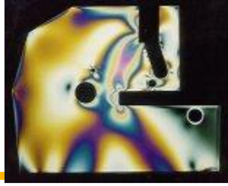
- **Let's start with "easier" forward problem**
- **Not so easy**

As you cut into a part with known residual stresses, what are the deformations?

- **As you cut, the stresses re-arrange**
- **So what are the stresses as you cut deeper and how do you calculate incremental deformations?**
- **(This was solved before you could just put initial stress into FE model)**

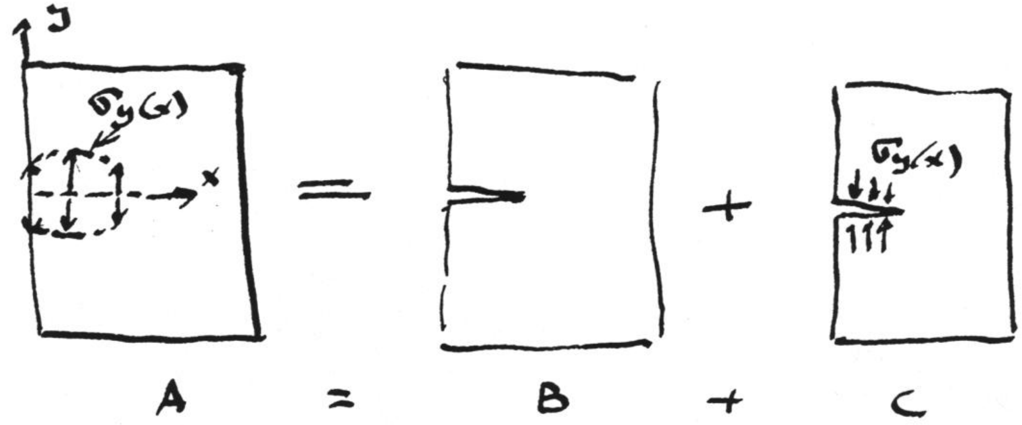


Bueckner's superposition principle



Conceptual order: A = B + C

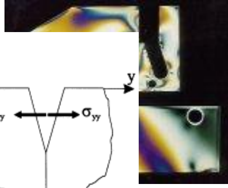
- A: undeformed body with original residual stresses
- Start with body with crack and resulting deformations (B)
- Apply *original* residual stresses as tractions on crack faces (C)
- You get back to original stress state and no deformations (A): **A = B + C**

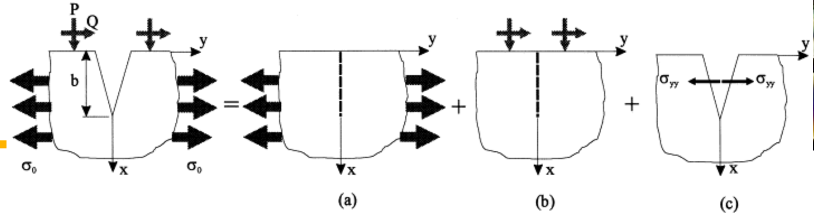


- **Forward problem: deformations in B**
- **How do we get deformations, etc from introduction of crack?**
  - B = A – C
  - So apply opposite of original stresses to face of crack
  - Deformations in A are zero
    - So B is all we need!

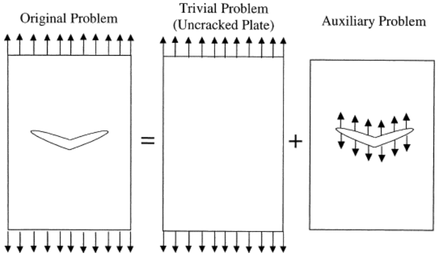
Sketch: Iain Finnie, U.C. Berkeley, ME 224, Fall 1991

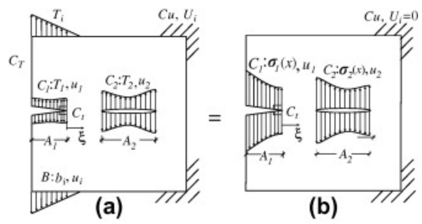
Aside on Bueckner's





- **Bueckner's principle used all the time in fracture mechanics**
  - With weight function also by Bueckner





- **But the figure that we use never appears in Bueckner's papers**
  - e.g., Bueckner, H., 1958, "The propagation of cracks and the energy of elastic deformation," Transactions of the American Society of Mechanical Engineers, 80, pp. 1225-1230.
  - In text: " .. Any [elastic] crack or notch problem can be *reduced* to one where the external load appears in the form of tractions distributed over the faces of the crack"
- **First figure appearance (that I can find) attributed to Bueckner**
  - Barenblatt GI. *The Mathematical Theory of Equilibrium Cracks in Brittle Fracture*. In: H.L. Dryden et al. (eds.) Advances in Applied Mechanics, Volume 7. Elsevier, 1962 p.55-129.
- **Unproven idea was in use before that**
  - (I am interested in more information)

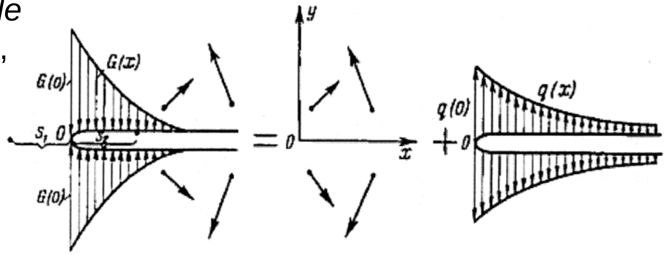
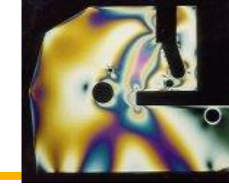
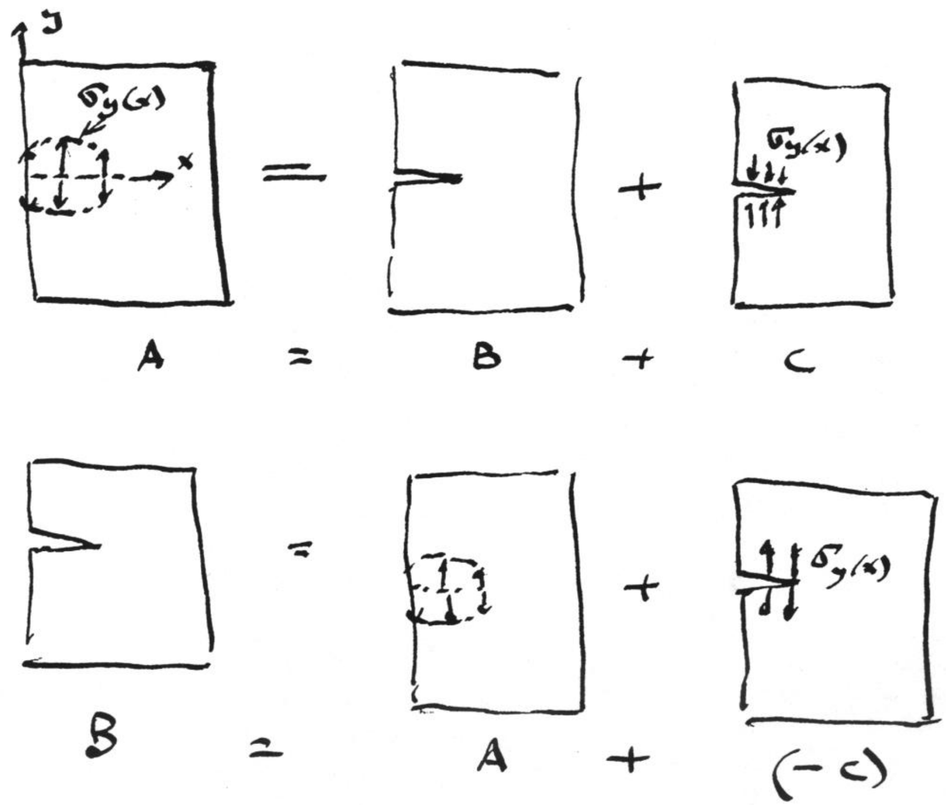


FIG. 8.

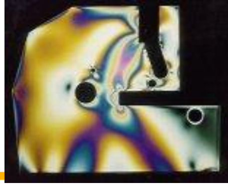
A more direct solution?

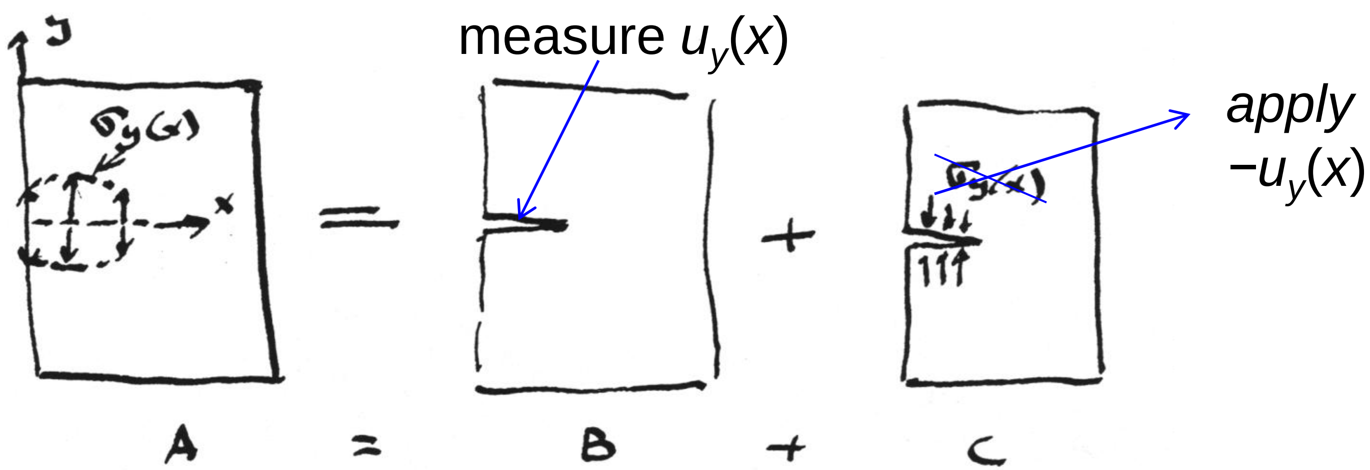


- **We use this to calculate forward solution:**
  - If we knew stress, what would be deformations
- **Can we somehow use this to measure/determine stress directly?**
  - Which state are we trying to calculate?
  - How can we solve for A without knowing the residual stress?

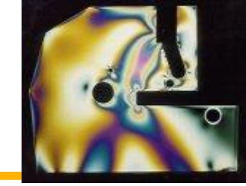


Change around superposition principle

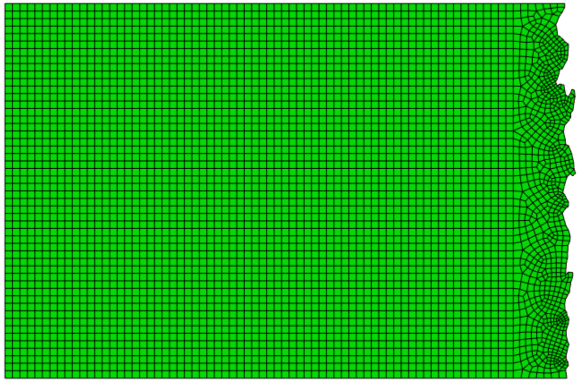




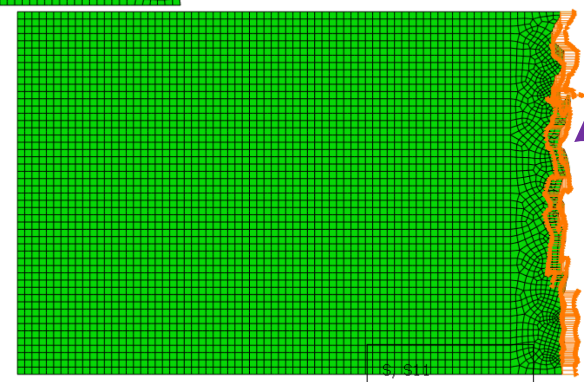
- **We can measure the *shape* of the crack (slit) in B**
  - From *shape* we are inferring displacements
- **Apply opposite of these displacements in C**
  - Kirchoff boundary value problem: stress or displacement boundary condition is OK
- **But what about stress in B?**
  - σ_y = 0 on crack (free surface), so C is all we need

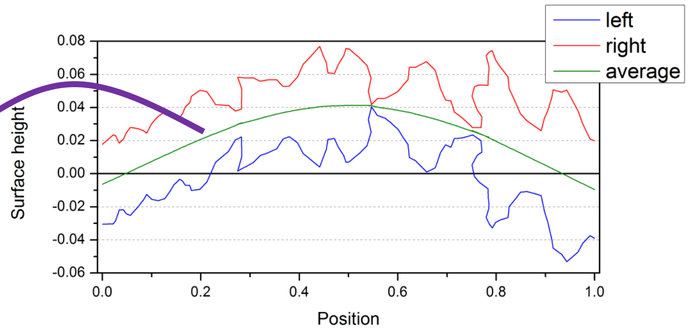


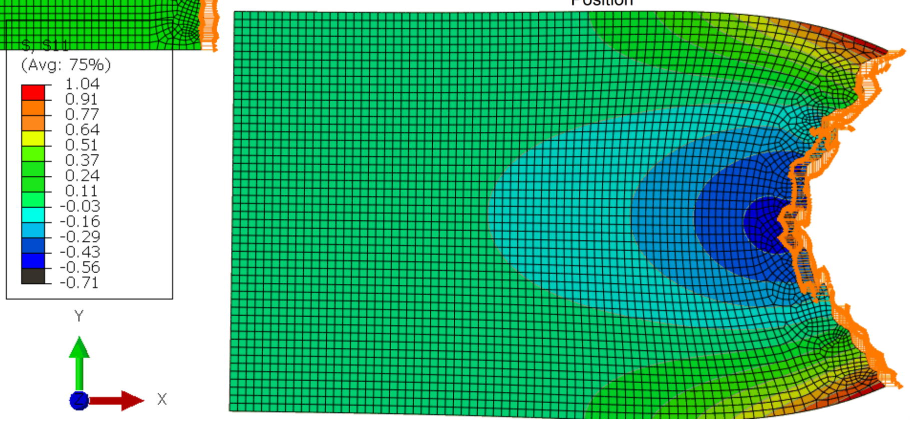
Demonstrate on FE: Applying BCs



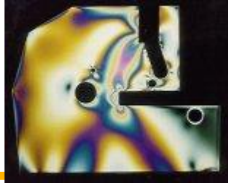
- Start with undeformed mesh of half of he part
- Apply our misfit (average contour) as displacement boundary conditions
- Calculate stress

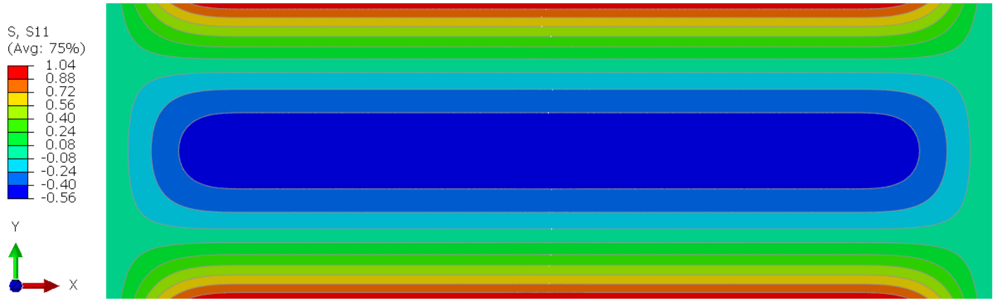




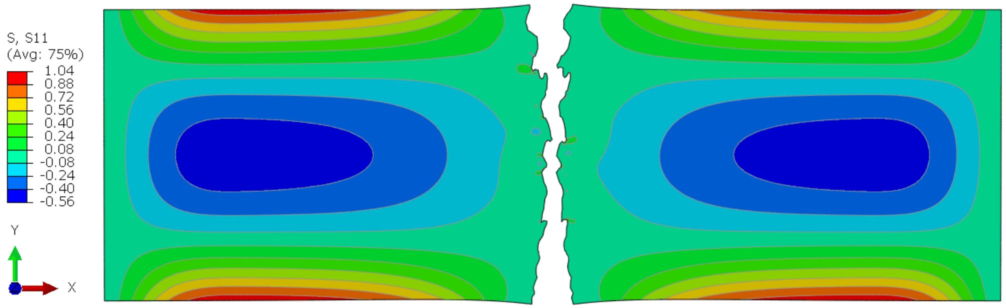


Bueckner's: A = B + C demonstrated by FEM





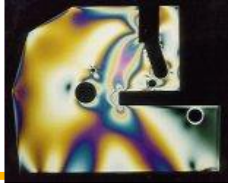
- **A = initial stress**
  - From FE model 1



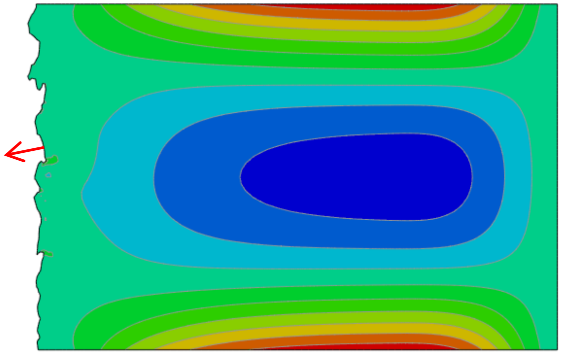
- **B = relaxed stress**
  - From FE model 1

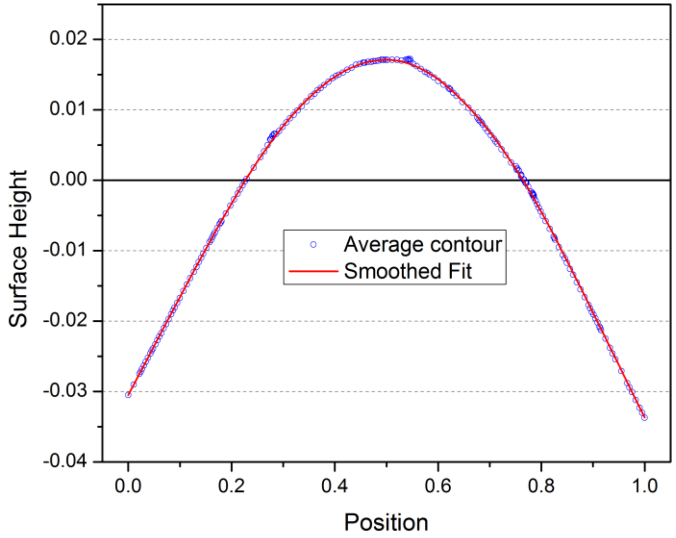
- **C = stresses**
  - FE model 2: applying displacements
- **≈ original stress!**
  - Slight difference because x-direction is not always normal

Make it a little easier



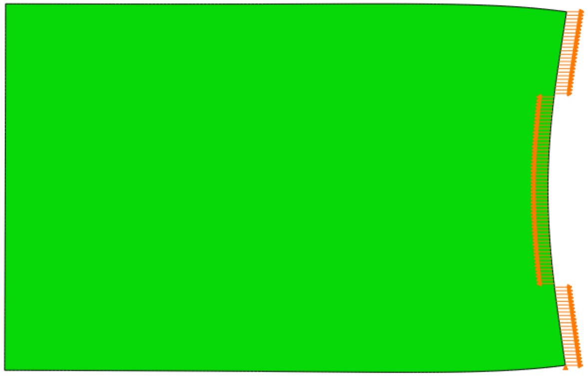
- The effect of local mis-orientation of fracture surface should ≈ average away over whole surface



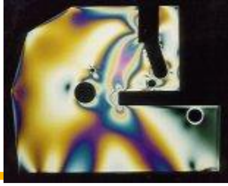


- So let's take misfit
- And smooth out jagged portions

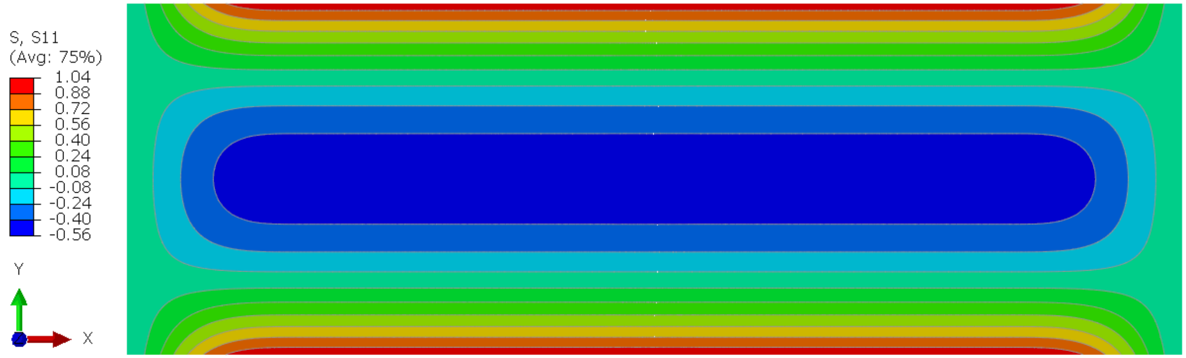
- And apply as boundary condition to model with flat surface

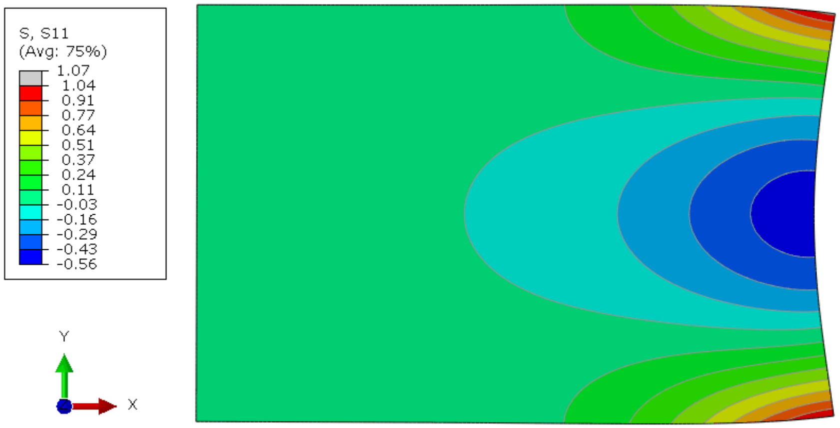


Los Alamos NATIONAL LABORATORY EST.1943 NNSA Hill Engineering, LLC Solutions for Aircraft Structures www.hill-engineering.com UCDAVIS

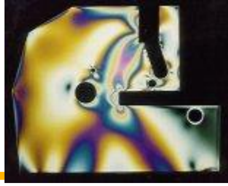


Just mesh flat surface



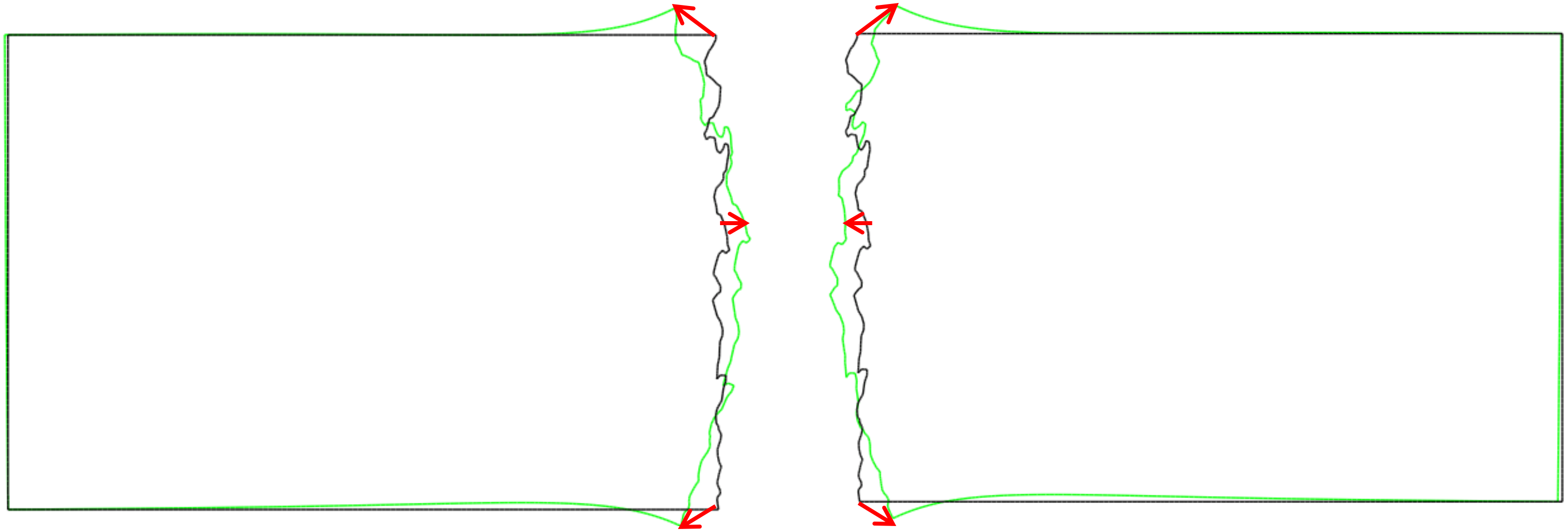


- **Matches original stresses almost perfectly**
- **So we can just use mesh of flat surface**



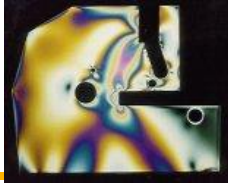
Transverse displacements

- ***If* we could measure the transverse (y) misfit**
  - We would determine residual shear stress τ_{xy}
  - (Transverse misfit zero in this example:)



- **Released shear stress does effect normal *displacement* but not *misfit***
  - *Anti-symmetric effect – it averages away*
- **Fracture tend to occur along path with zero shear stress anyway**

Outline

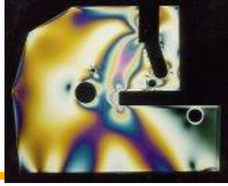


- THE CHALLENGE ✓
- What are residual stresses and why do we care? ✓
- The failed specimen ✓
- THE SOLUTION ✓

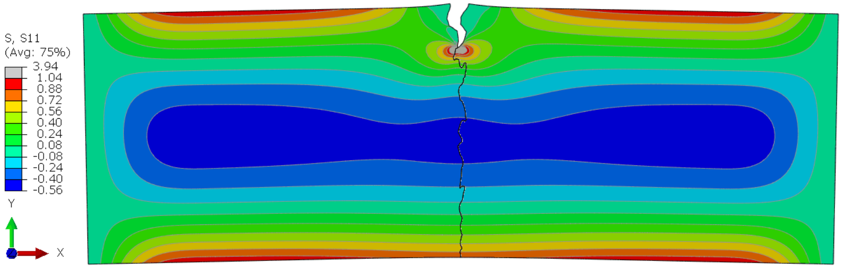
➢ **Application to our failed specimen**

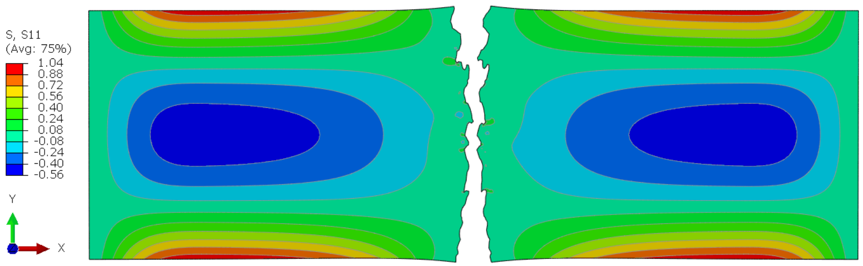
- Independent validation
- Final thoughts

We will determine stresses right before fracture

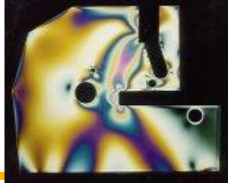


- **Bueckner's principle applied to any two states separated by elastic deformations**
- **Will compare notched state to fracture**

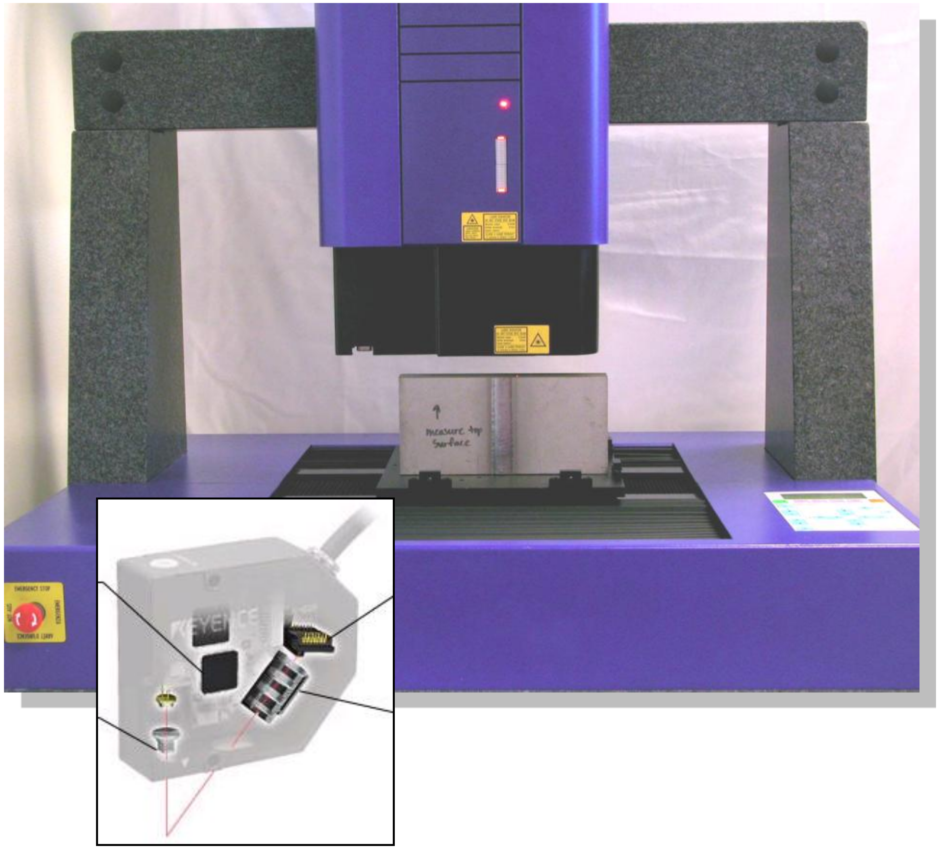




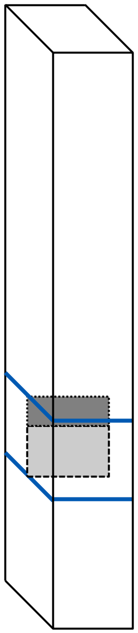
Surface measurement

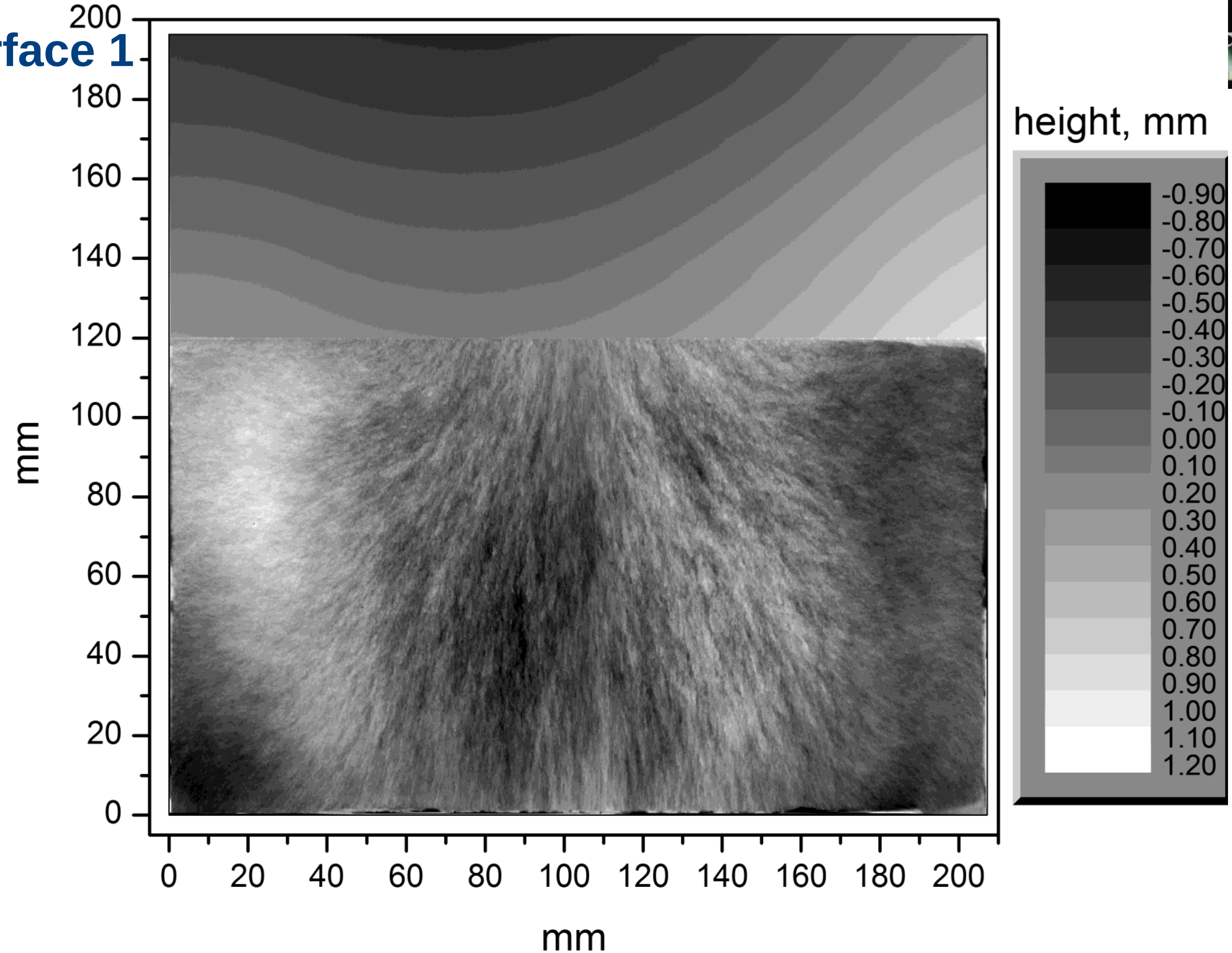


- **Measure contour of fracture surfaces using a scanning profilometer**
  - Taylor Hobson Talyscan 250
  - Keyence laser triangulation probe
    - 2 mm range
    - 30 μm spot size
    - 0.1 μm resolution
  - High-resolution scan
    (100 μm x 100 μm) point spacing
    -> 4 M points



Surface 1





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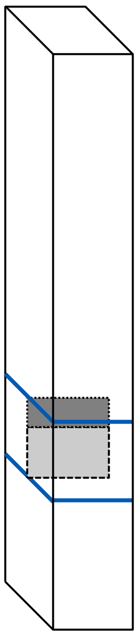
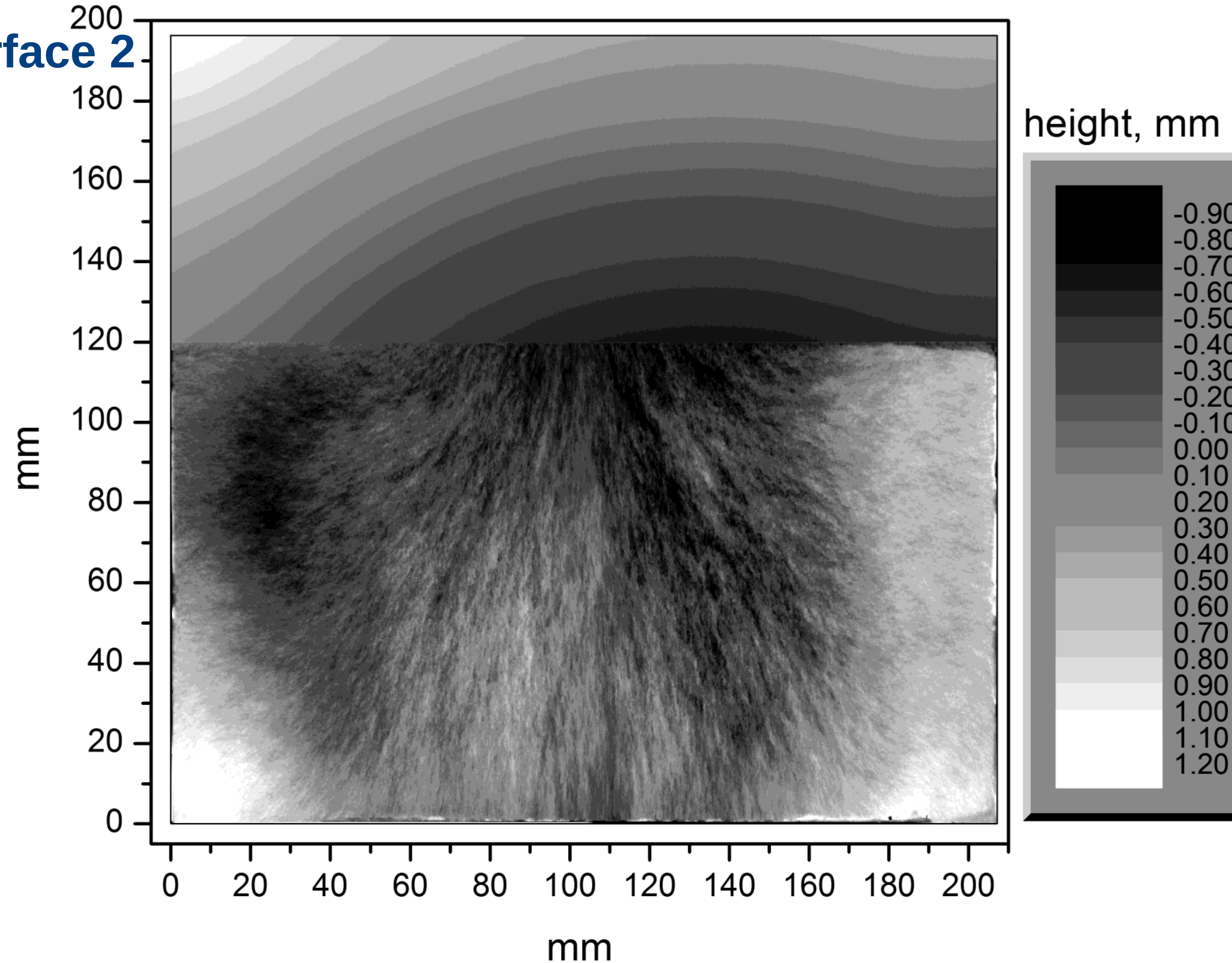
Surface 2

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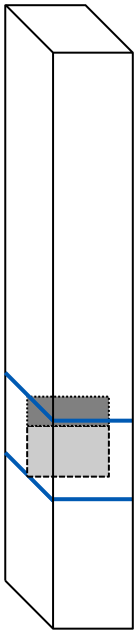
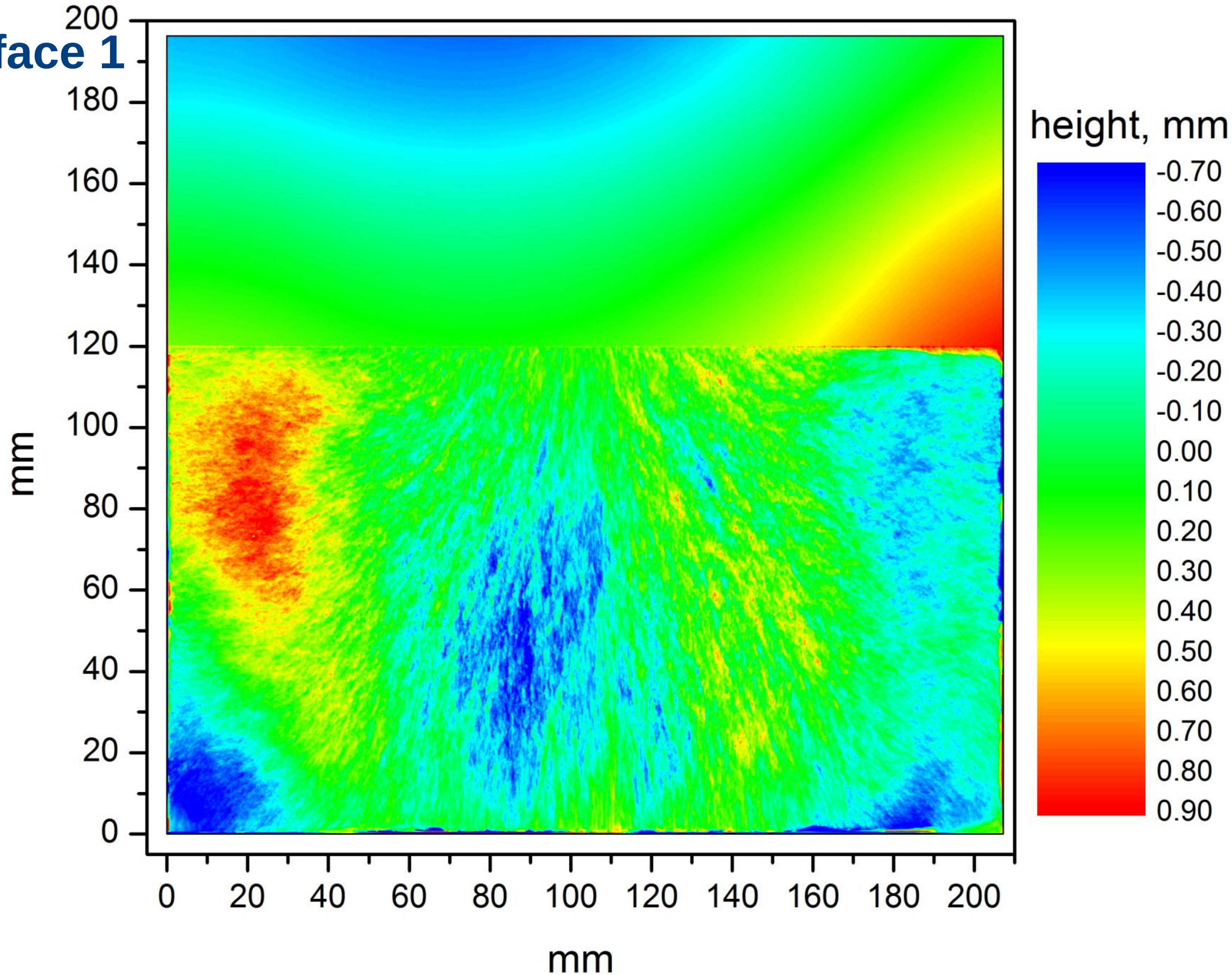
Surface 1





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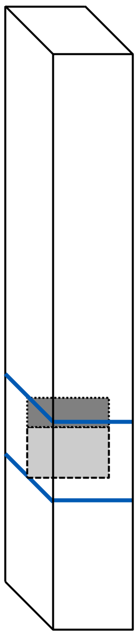
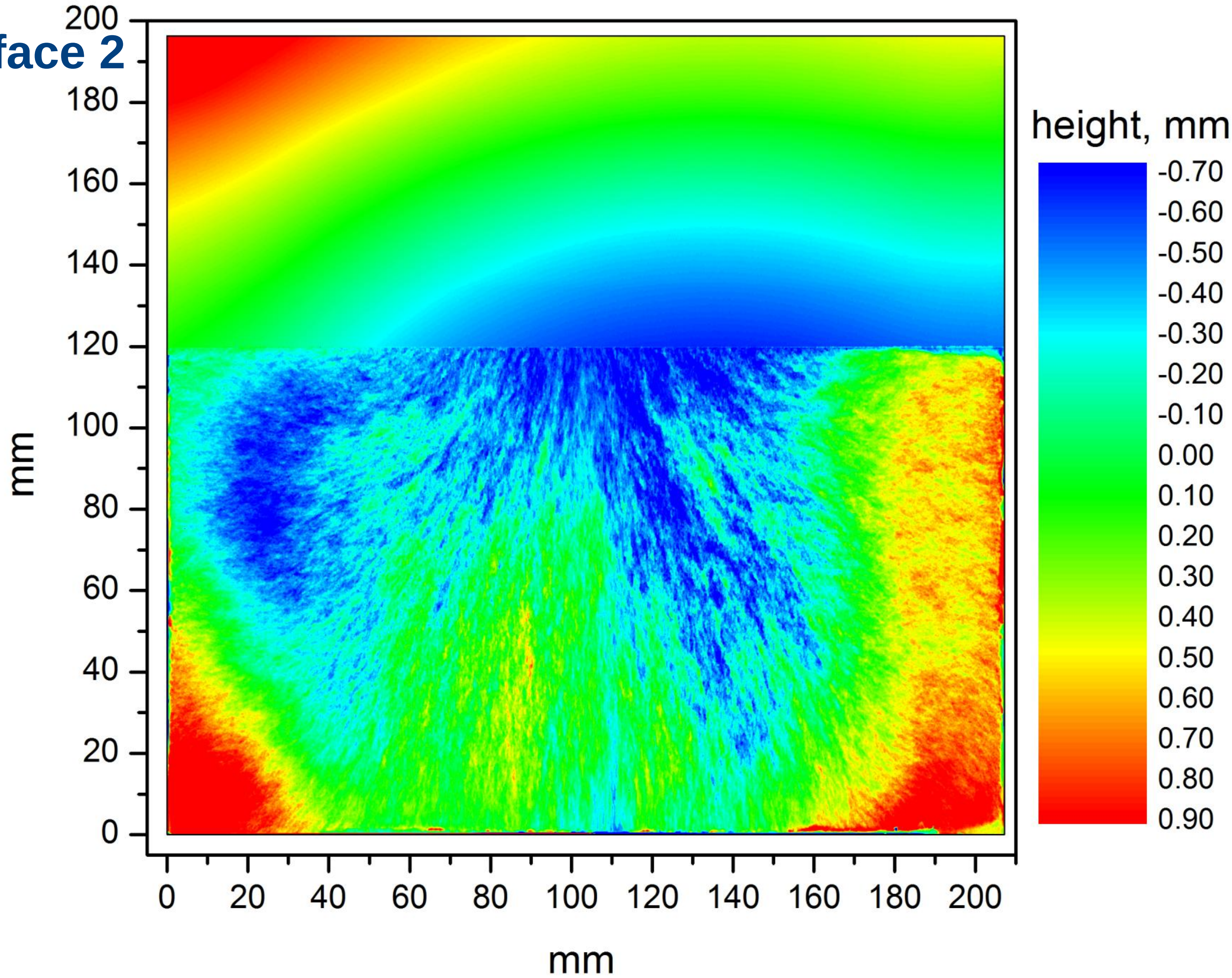
Surface 2

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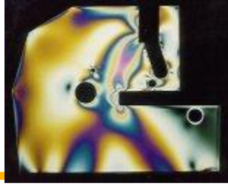
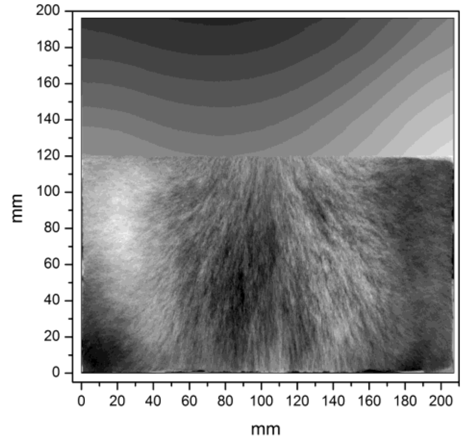
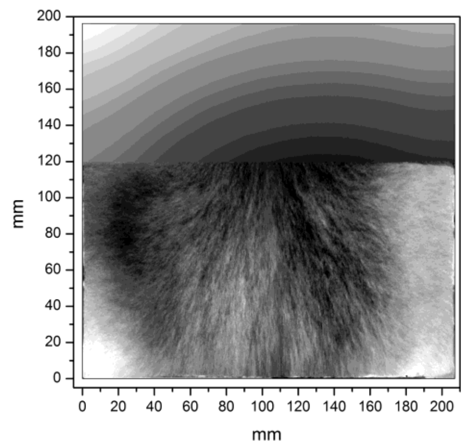
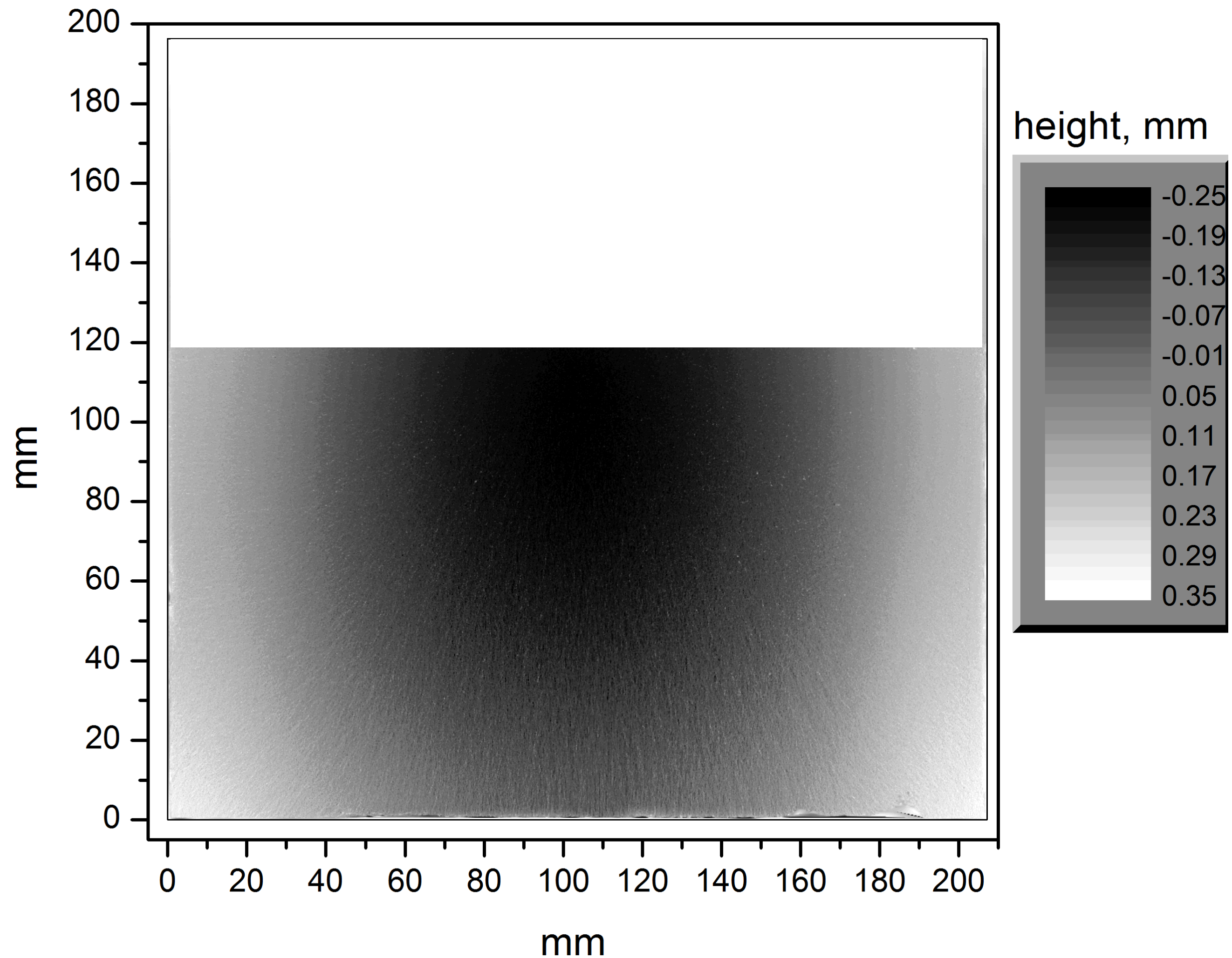
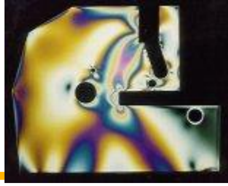


After very careful alignment … average surface!

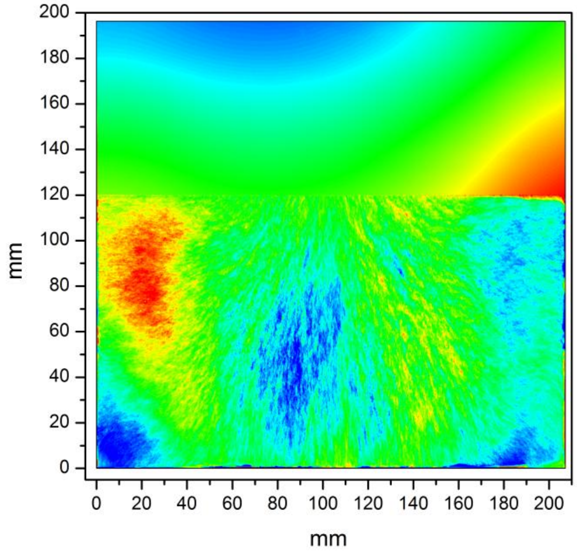


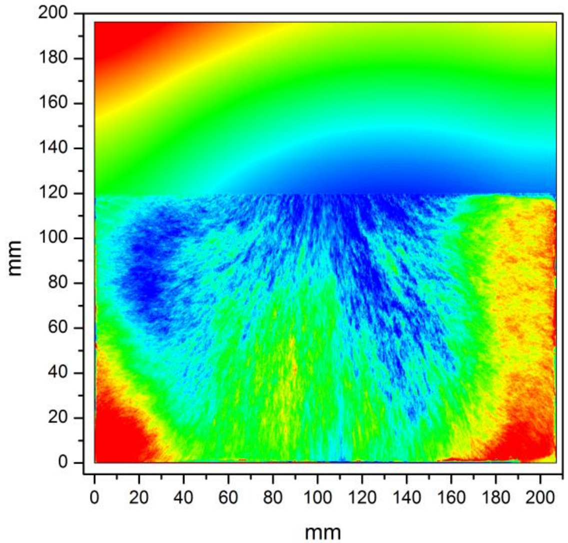


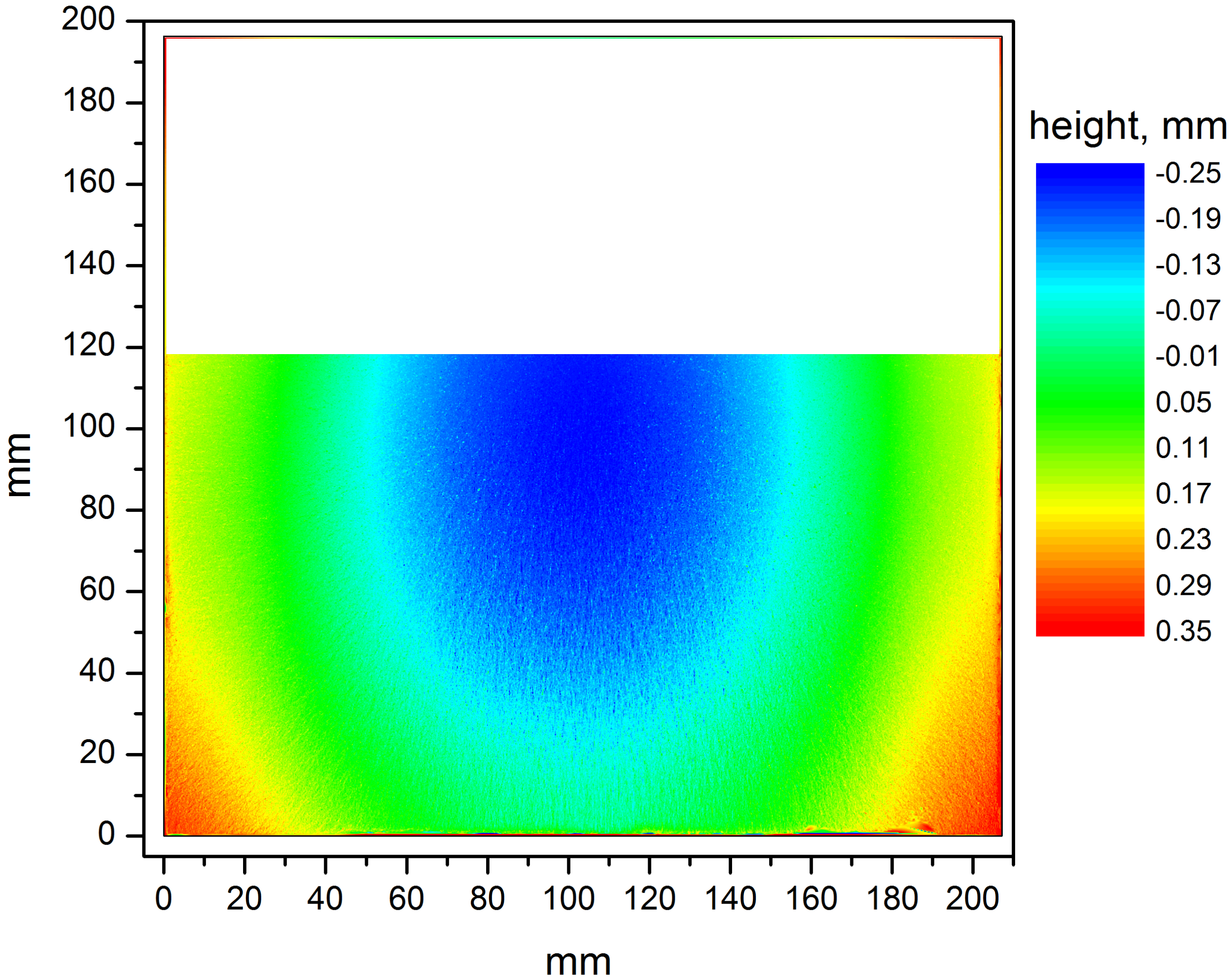




After very careful alignment … average surface

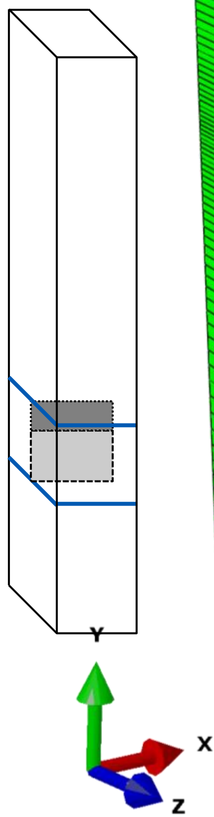


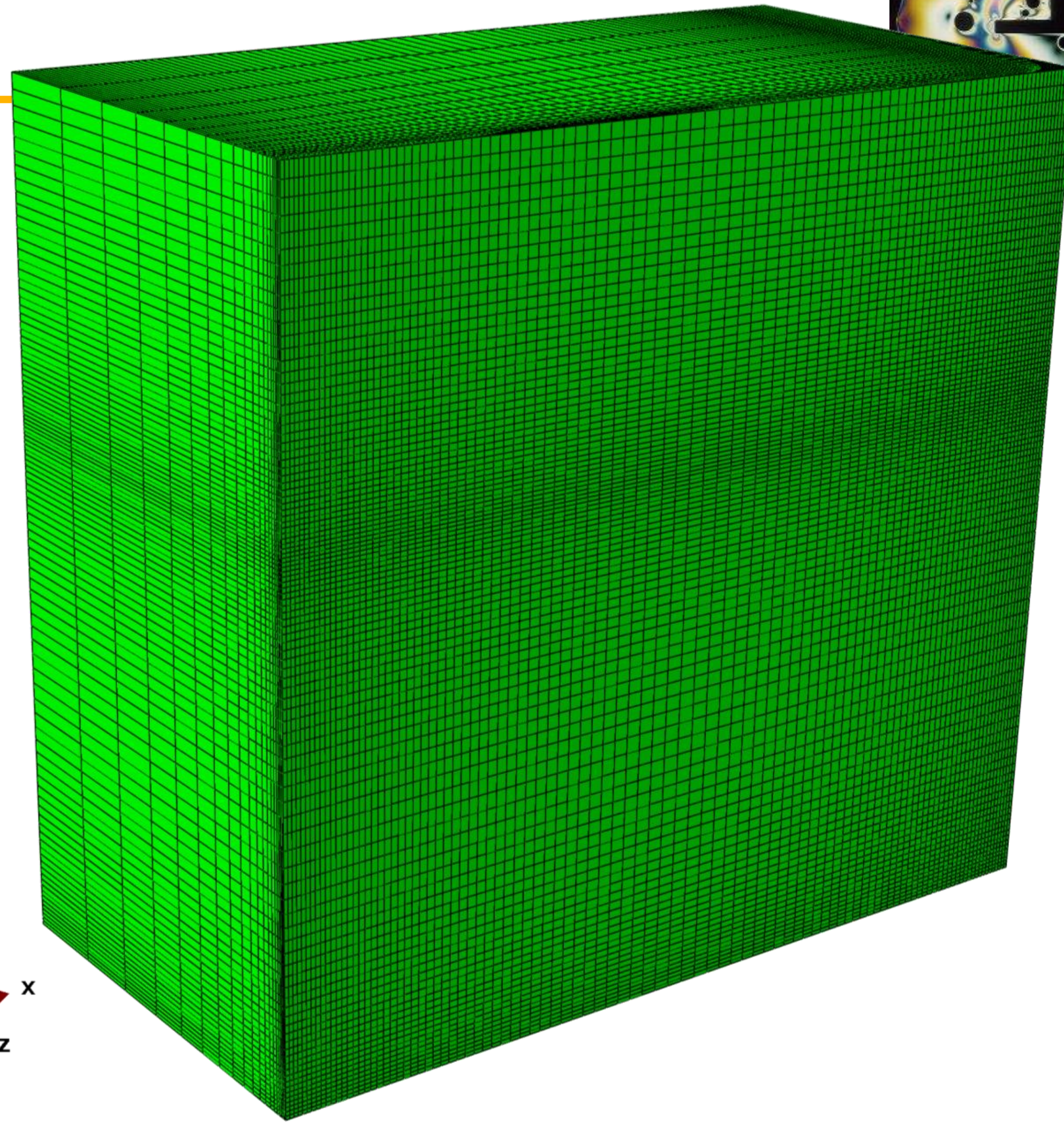




FE mesh

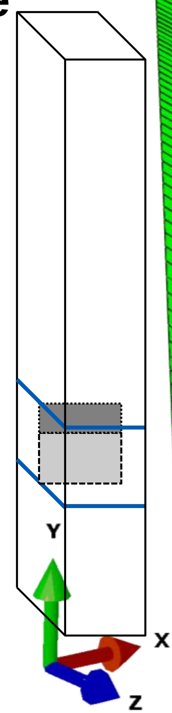
- **3-D mesh of *half* of part**
  - 200,000 C3D8 linear hexahedral elements
- **Elastic**
  - *E* = 71.7 Gpa
  - $\nu = 0.33$

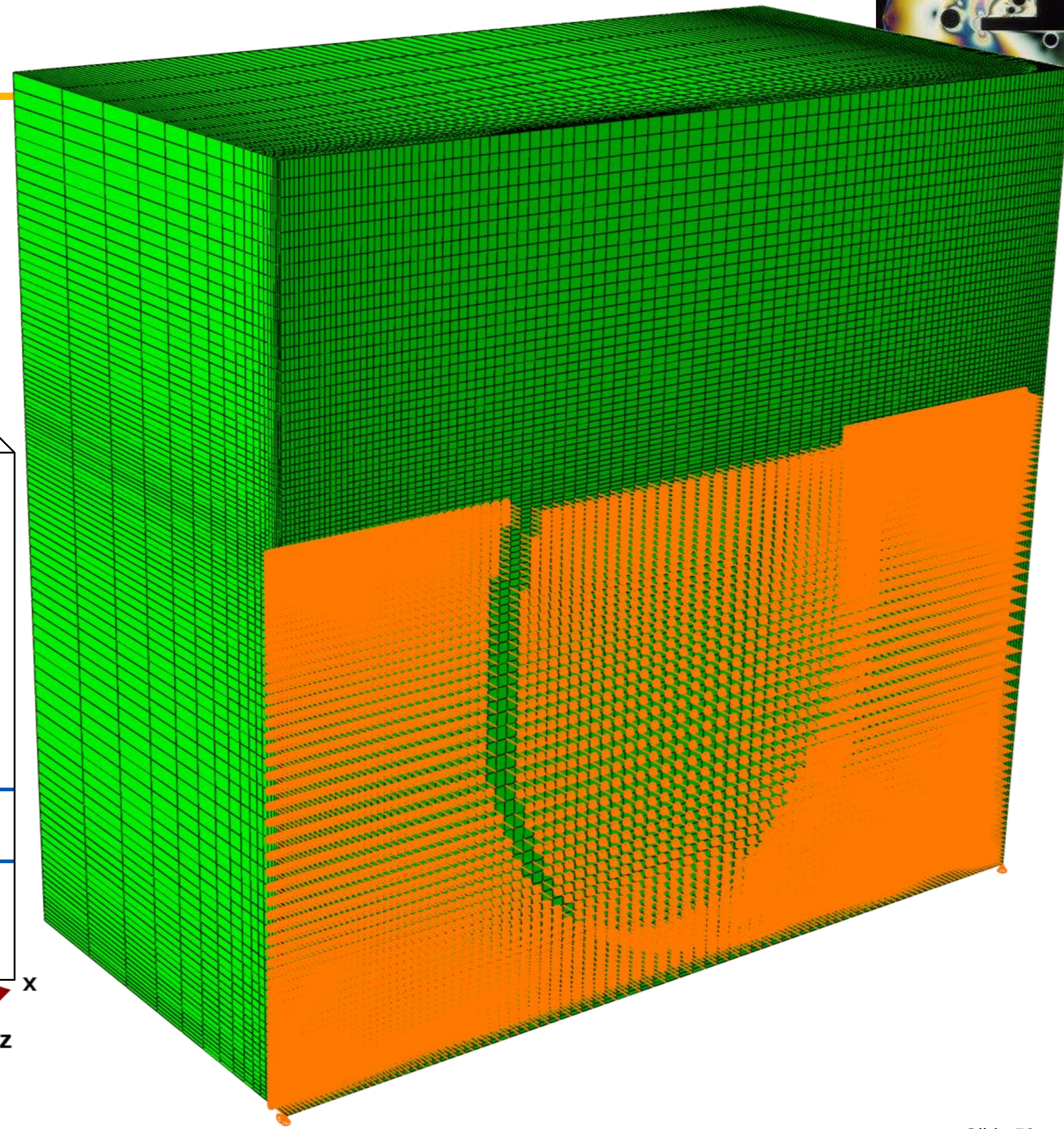




FEM Analysis

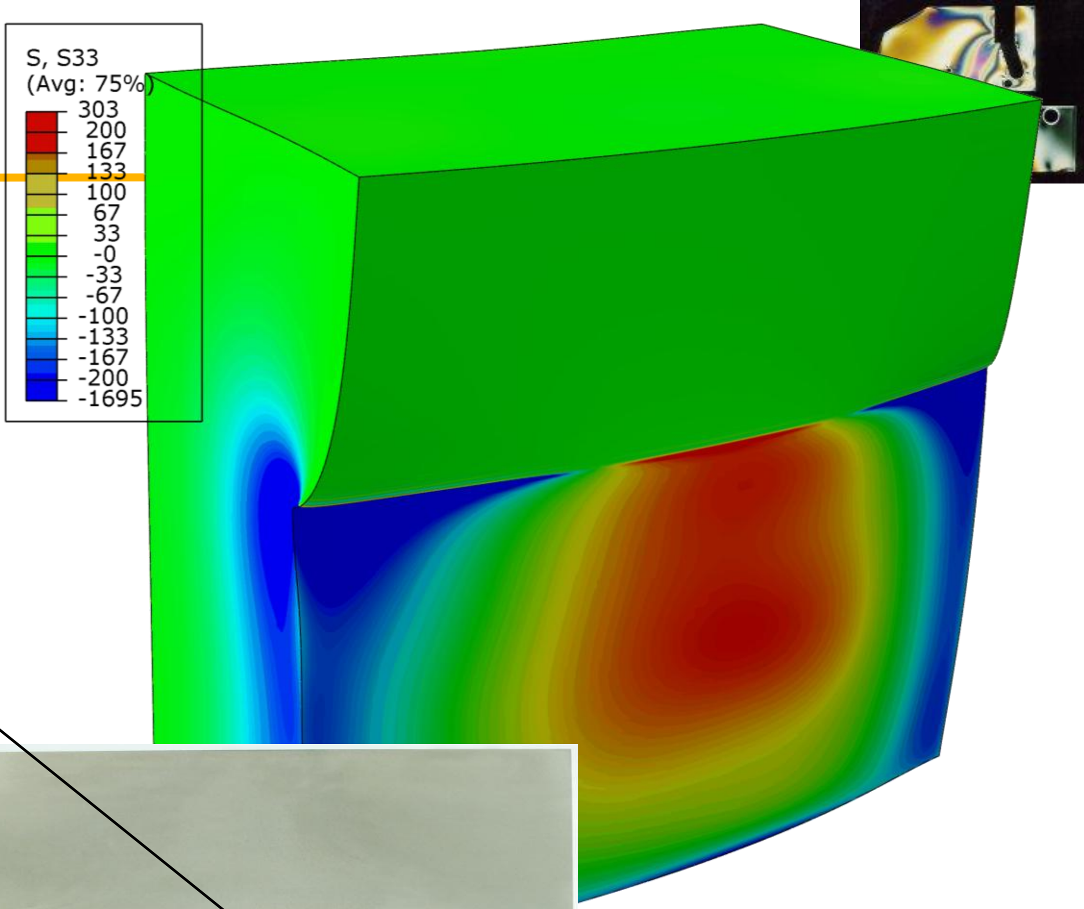
- **Smooth misfit data a little**
- **Apply z-direction boundary conditions along fracture surface**

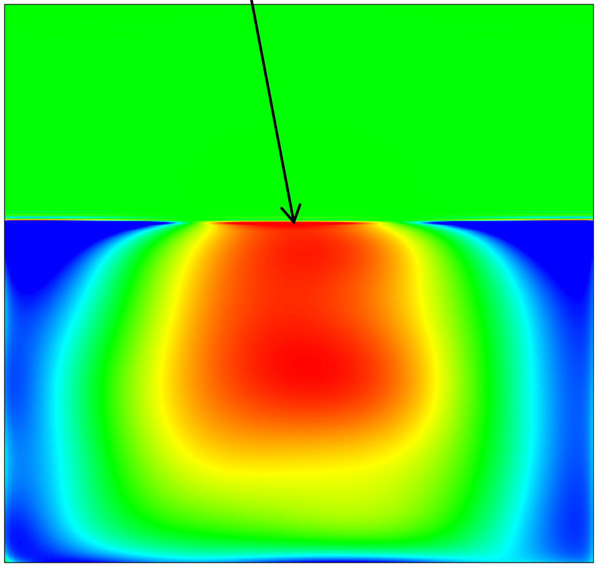


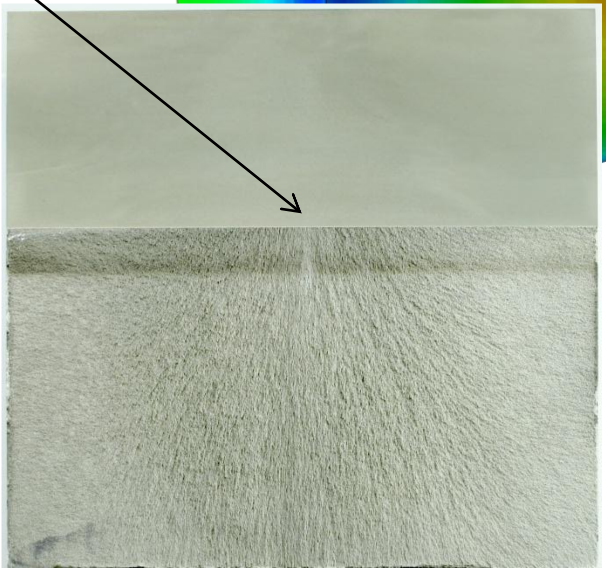


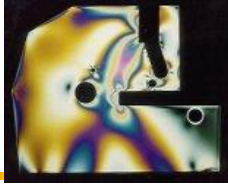
Stresses

- **Crack initiated at peak tensile stress region**



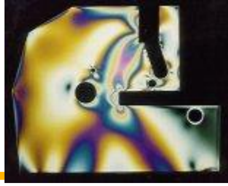






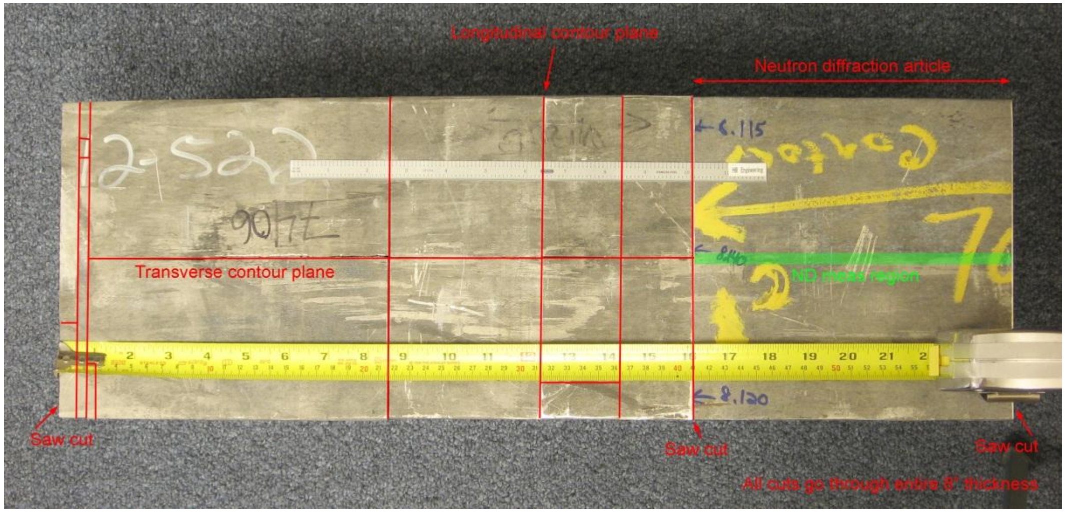
Outline

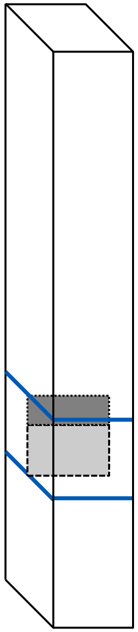
- THE CHALLENGE ✓
- What are residual stresses and why do we care? ✓
- The failed specimen ✓
- THE SOLUTION ✓
- Application to our failed specimen ✓
- ➢ **Independent validation**
- Final thoughts



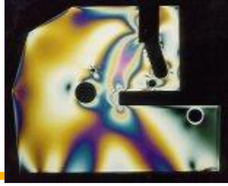
Independent validation

- **Use neutron diffraction for independent validation**
  - Very different assumptions, so truly independent
- **Take adjacent piece from same forging**
  - Same processing and history
- **No EDM cut**
  - It would probably just fracture again
  - We can look at quenching stresses before cut

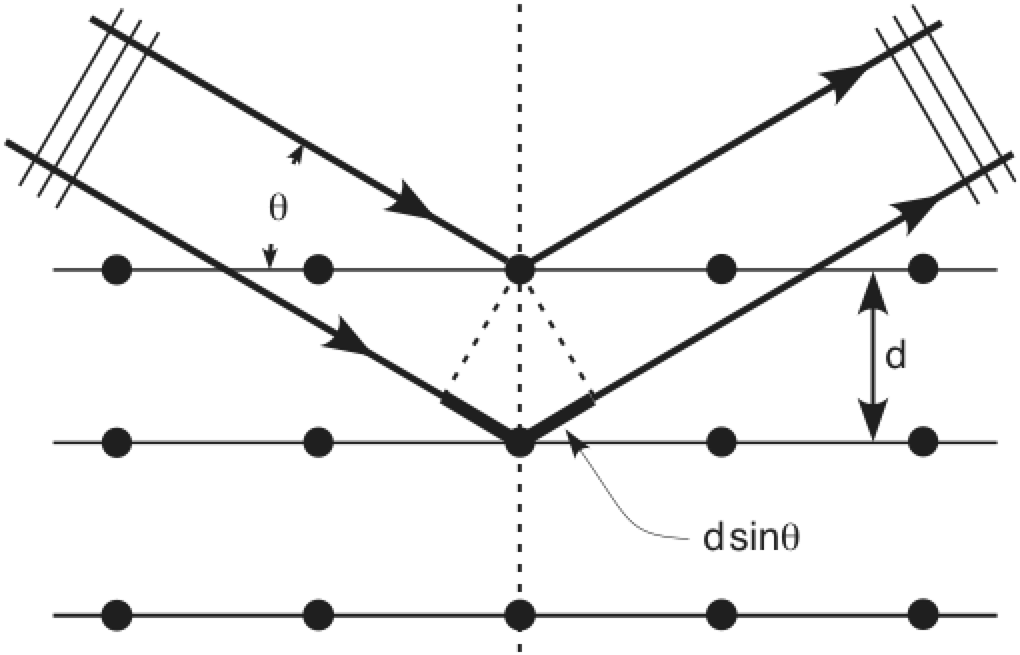




Diffraction methods principle



- **Subject a crystalline material to incident radiation**
- **Radiation will diffract off of crystal lattice planes via Bragg's law**
  - $\lambda = 2d\sin\theta$
- **Gives you lattice spacing d**
- **Compare with unstressed latticed spacing d_0**
- **Get elastic strains**
- **Calculate stress**
- **Requires statistics – average over many diffracting grains**



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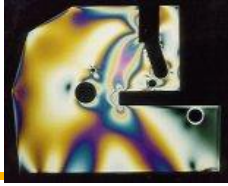
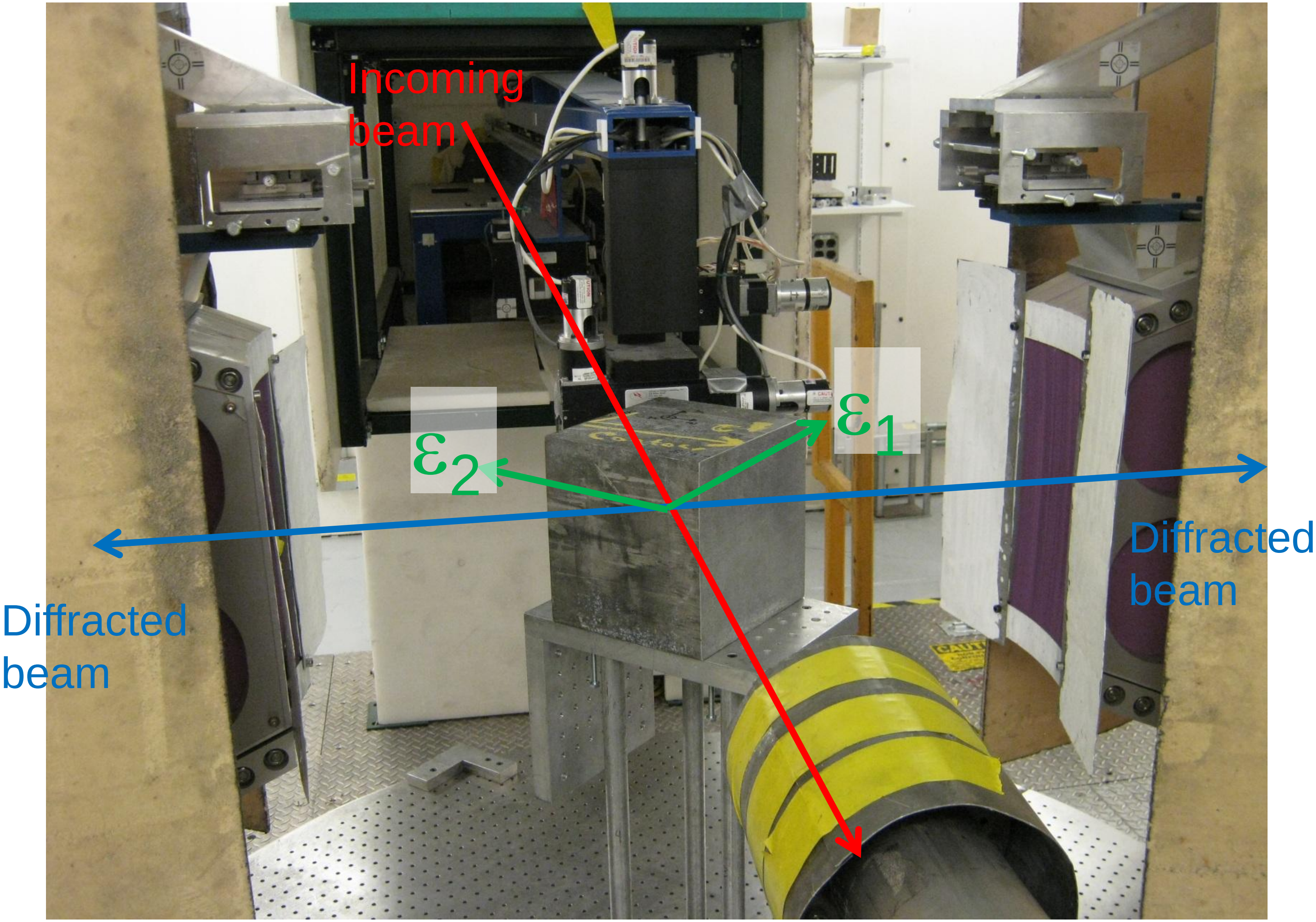
$$\varepsilon_i = \frac{d - d^0}{d^0}$$

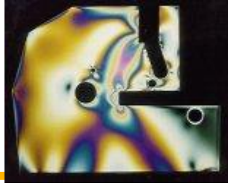
$$\sigma_i = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\left[\varepsilon_i + \frac{\nu}{1-\nu}(\varepsilon_j + \varepsilon_k)\right]$$

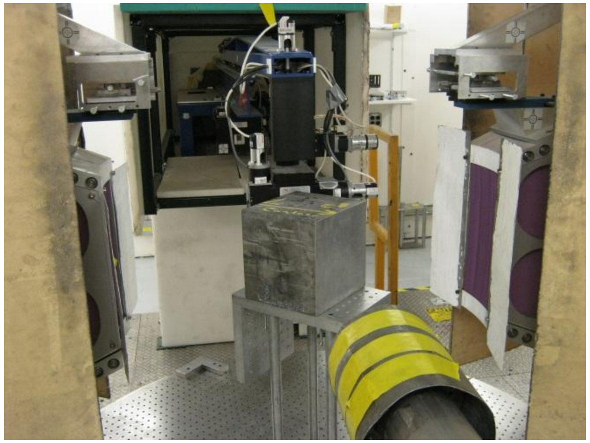
Forging in SMARTS instrument at Los Alamos



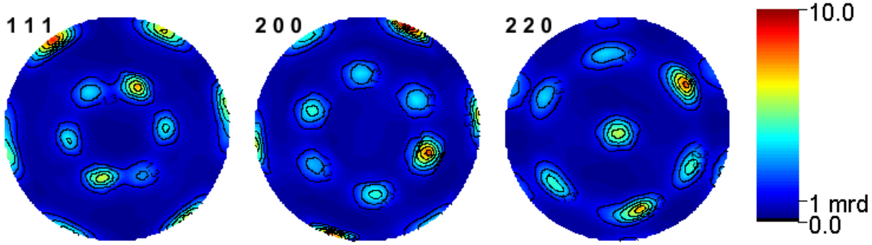


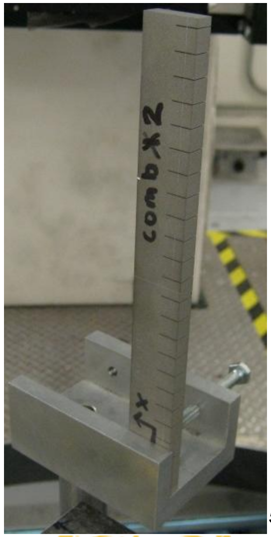
Neutron details

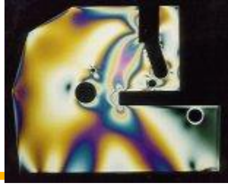




- **Bjørn Clausen and Thomas Sisneros at LANL**
- **Measured 2 orientations to get 3 ε's**
- **5 × 5 × 4 mm sampling volume**
- **Only 5% neutron penetration in thick part**
  - ~120 hours to measure ~80 points along 3 lines
  - Full 2D map not practical
- **Spallation source - multiple reflections, fit to Rietveld refinement**
- **Measured unstressed lattice spacing on comb specimens**
  - Large d_0 variations – adds uncertainty
- **Texture up to 10 × random**
  - Adds uncertainty

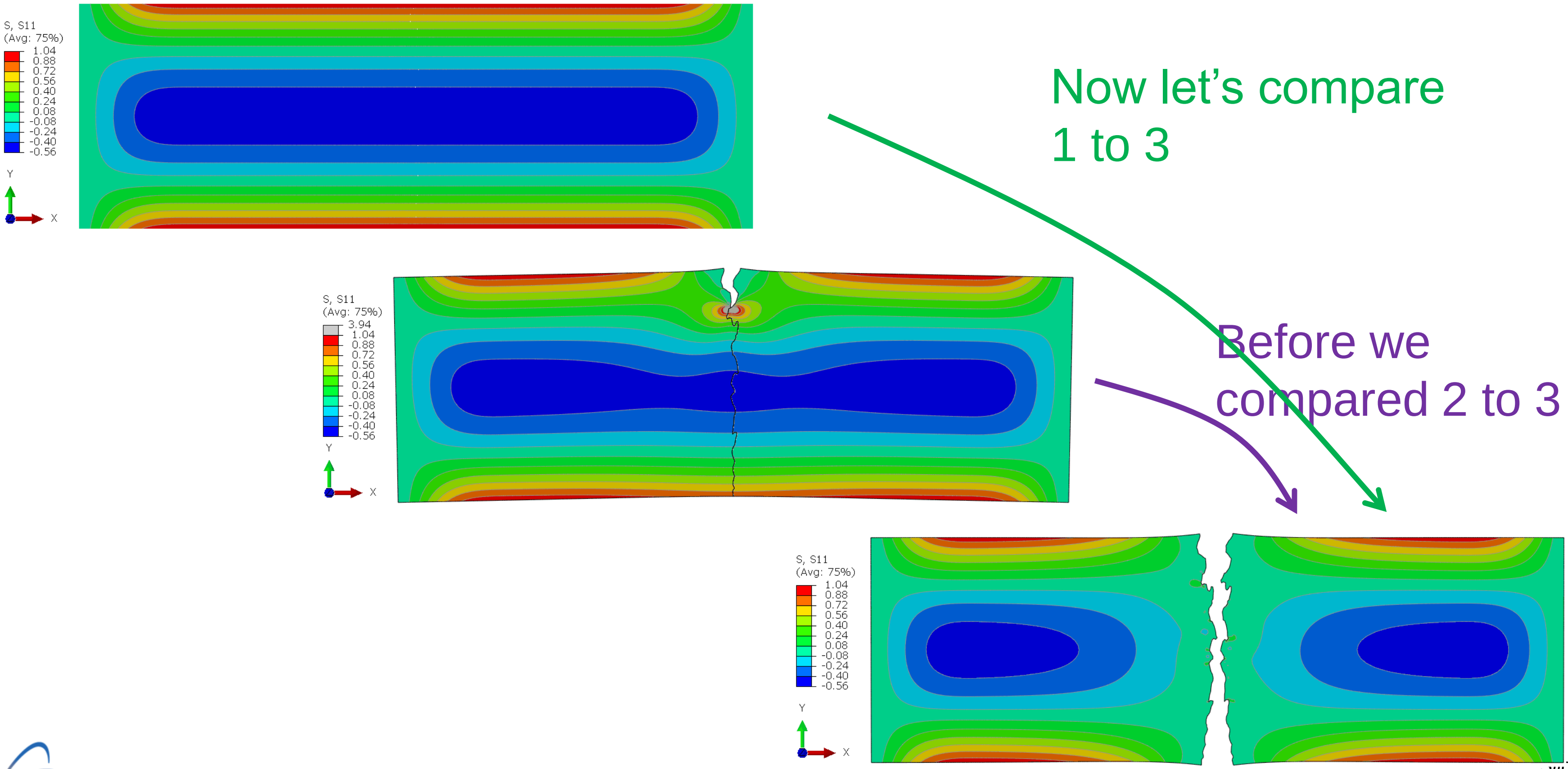




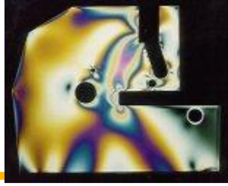


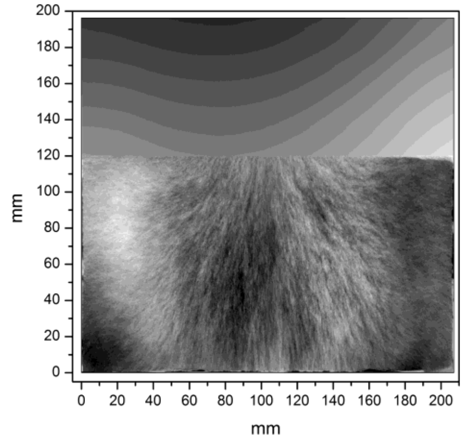
We can apply Bueckner's to whole surface

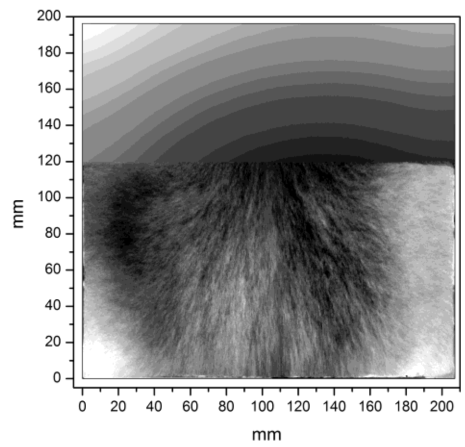
- **Want to compare directly with neutron**
- **Bueckner's principle applied to any two states separated by elastic deformations**

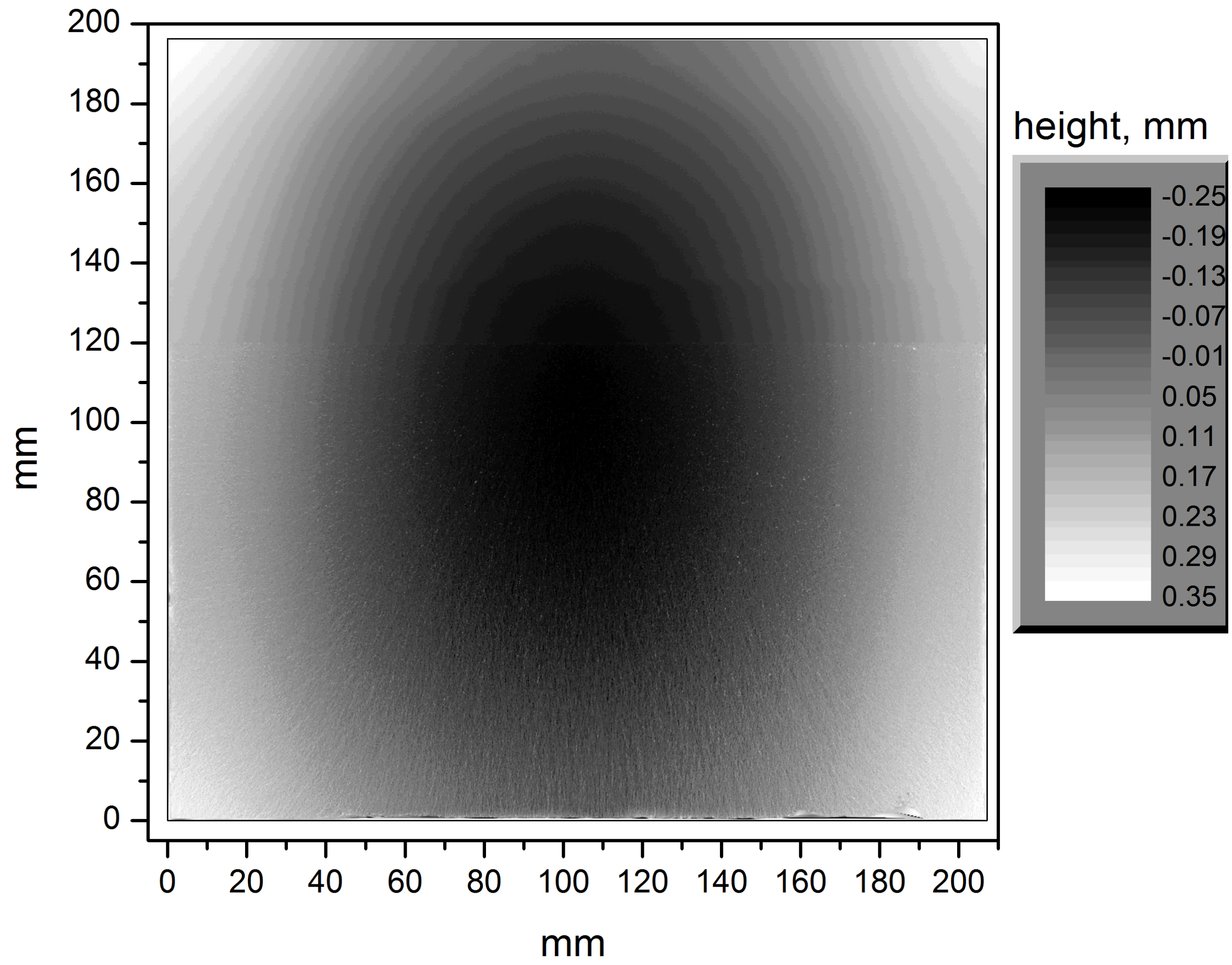


Shift EDM portion of surface by half cut width …









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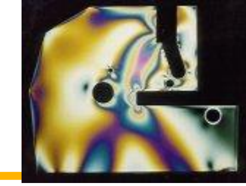
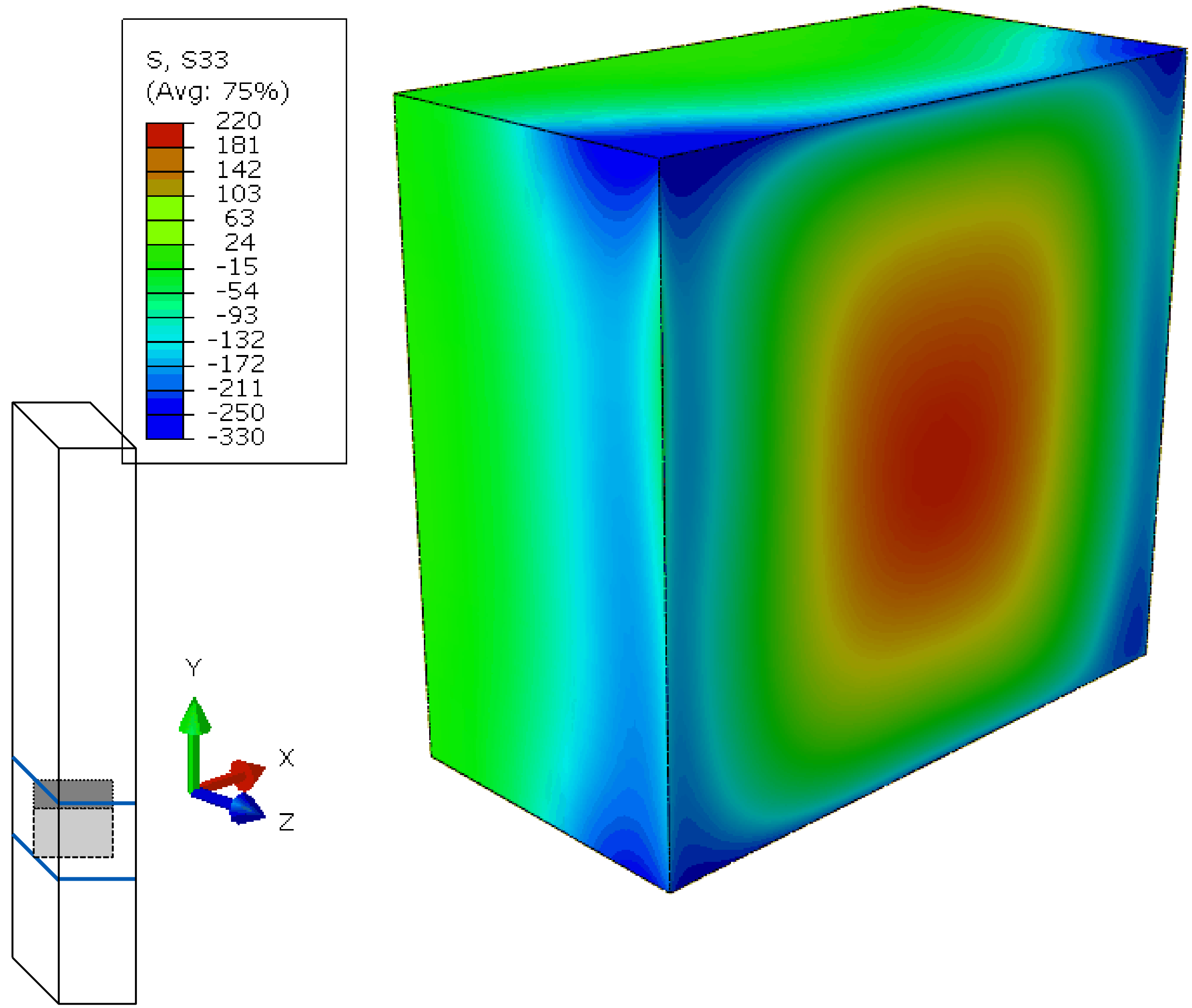
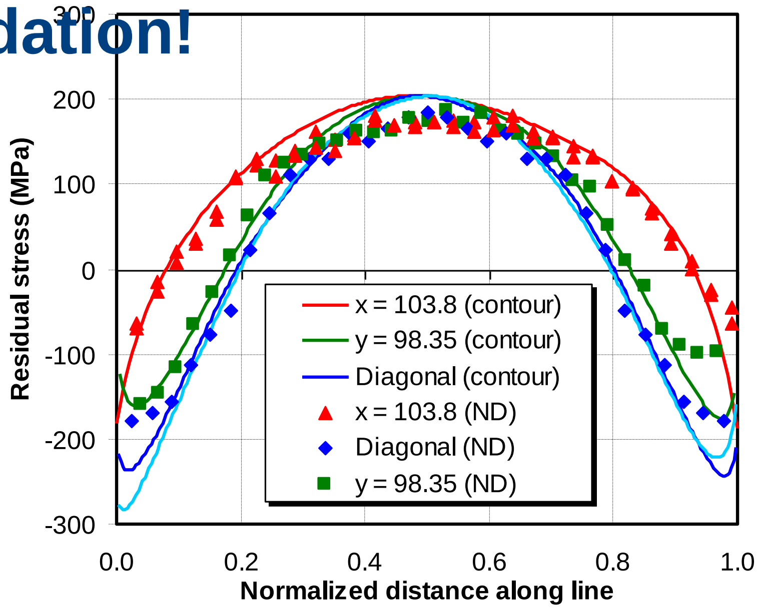


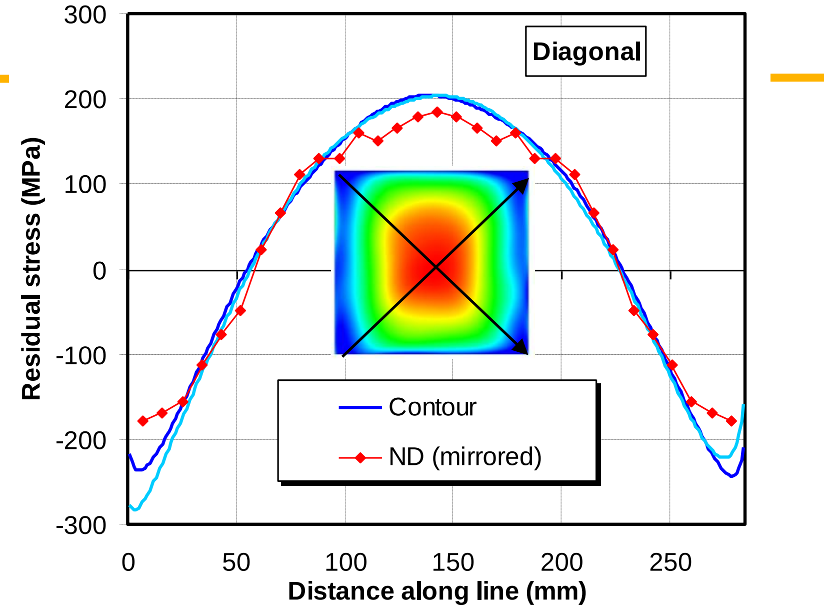
Apply misfit to full surface



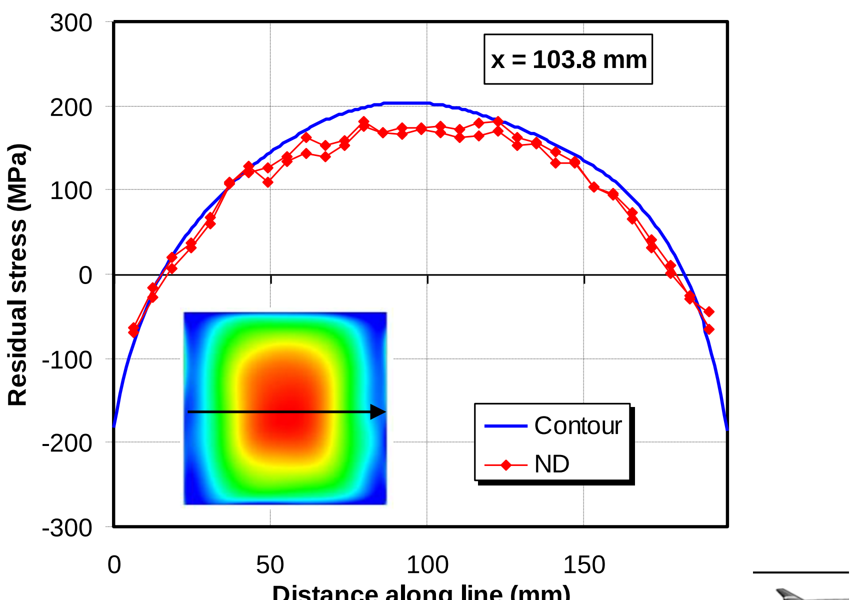
Validation!



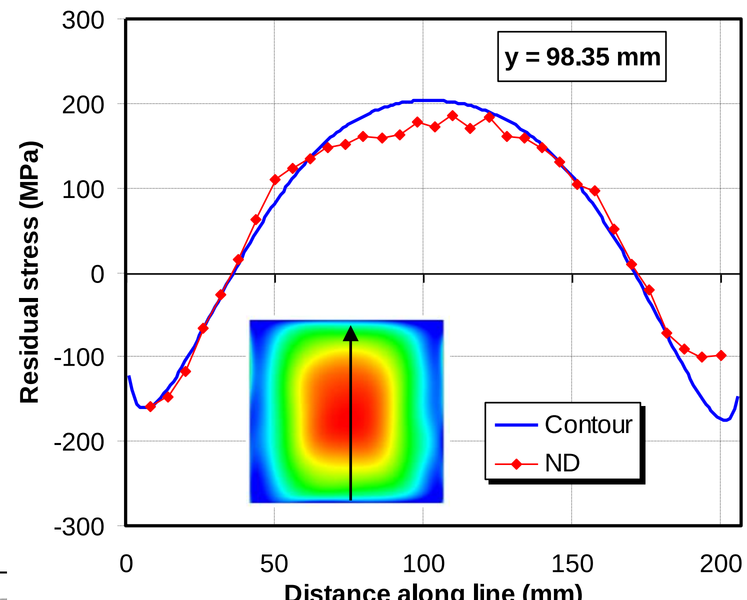
300
200
100
0
-100
-200
-300
Residual stress (MPa)
0.0
0.2
0.4
0.6
0.8
1.0
Normalized distance along line
x = 103.8 (contour)
y = 98.35 (contour)
Diagonal (contour)
x = 103.8 (ND)
Diagonal (ND)
y = 98.35 (ND)



Diagonal
300
200
100
0
-100
-200
-300
Residual stress (MPa)
0
50
100
150
200
250
Distance along line (mm)
Contour
ND (mirrored)



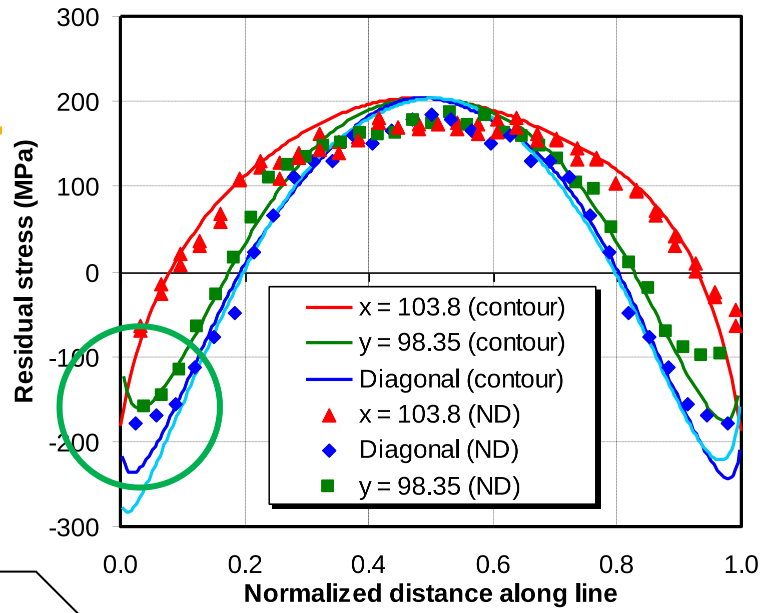
x = 103.8 mm
300
200
100
0
-100
-200
-300
Residual stress (MPa)
0
50
100
150
Distance along line (mm)
Contour
ND

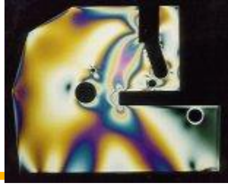


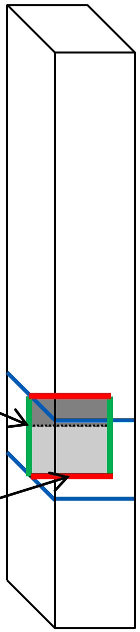
y = 98.35 mm
300
200
100
0
-100
-200
-300
Residual stress (MPa)
0
50
100
150
200
Distance along line (mm)
Contour
ND

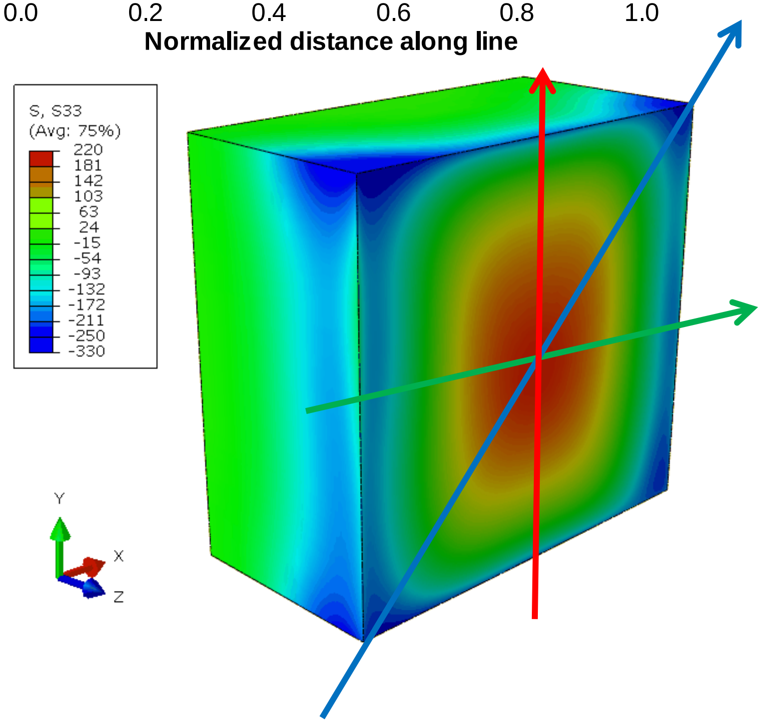
Stress interpretation

- **Typical quenching stress**
  - Core cools last, constrained from contracting ⇨ tensile stress
- **$\sigma/S_y \approx$ 200 MPa / 450 MPa = 44%**
  - Very large, but not usual state of this material
- **Different spatial distribution in compressive regions**
  - Horizontal and diagonal traces have “hooked” stresses near surface
  - These edges have stresses from original quench
  - Vertical trace does not
  - Those edges saw stress change from sectioning the forging

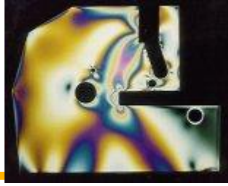








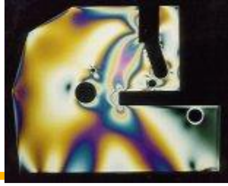
Outline



- THE CHALLENGE ✓
- What are residual stresses and why do we care? ✓
- The failed specimen ✓
- THE SOLUTION ✓
- Application to our failed specimen ✓
- Independent validation ✓

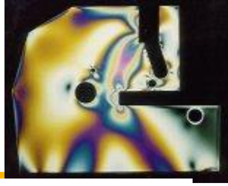
➢ **Final thoughts**

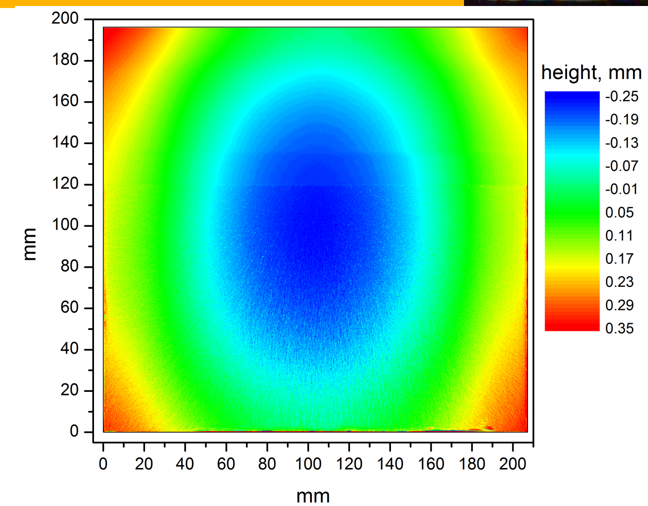
The contour method



- **The “Contour Method” was published in 2001**
  - M. B. Prime, "Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut," *Journal of Engineering Materials and Technology*, **123**, pp. 162-168, 2001.
  - Wire EDM cut, then measure surface contour
- **In many ways, this is just contour method with a fracture for the cut**
  - But if I would have told you that right away, the talk would have been much less interesting
- **Fracture is a near-ideal cut – so expect even better results**
  - Zero cut width reduces errors
  - True brittle fracture has no plasticity
- **Lots of applicable published work on contour method**
  - Shear stress effect, plasticity, calculating stress, …

Is it practical?

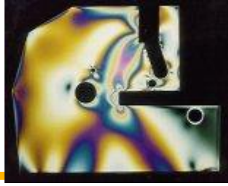




- **This was a very large contour: 0.6 mm +**
  - $\sigma/E \approx 0.003$ and big part
- **But could probably measure down to < 0.05 mm**
- **Need a brittle fracture – minimal plasticity**
  - Remember, dynamic Sy is higher
  - Plasticity has to be fairly large before it significantly impacts misfit
- **There are opportunities for further work**
  - Less planar fractures, fatigue surfaces , ceramics and other non-metals, …
- **Not just for brittle fracture**
  - Fatigue or SCC failures often end in a brittle fracture – we could look at stresses just before fracture

Applications may be limited, but technique is powerful and unique

Final thoughts



- **Real advances in experimental mechanics require innovative theoretical and analytical thinking to go with innovative capabilities**
  - For example, taking full field data (e.g., DIC) and treating it like discrete data (strain gauge) misses a wonderful opportunity
- **Contour and fracture surface methods share a different way of thinking**
  - Residual stress suffers from reference problem – no “before” state
    - And can only measure surfaces deformations not internal
  - So measured shape and inferred internal displacements
    - And novel application of Bueckner’s principle
- **Thanks!**