„Thermal Laser Separation – Simulation Approach for Analysis of Stress Induced Crack Propagation“

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PV-Days Halle 24.10.2017

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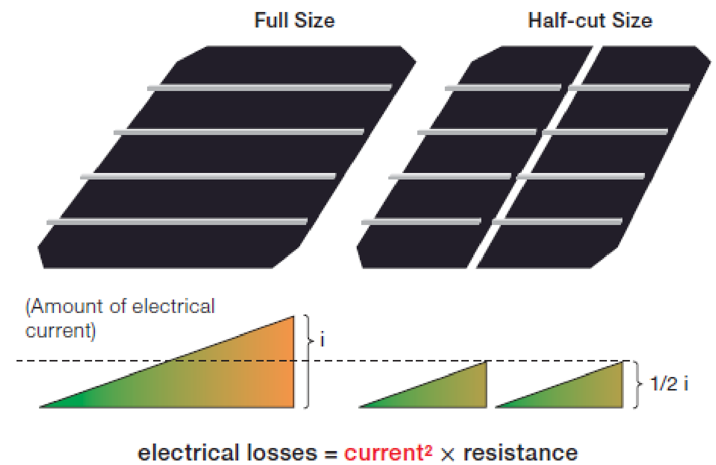
Anhalt University of Applied Sciences

Agenda

- Half cell modules
  - Concept and benefits
  - Performance and yield
- Comparison of cell cutting processes
- Simulation Approach Thermal Laser Separation
- Simulation Results so far
- Summary

Half-cell modules
Concept and state of the art

- Technology concept
  - Production of full size cells
  - Dicing into two (or more) cells
  - Module assembly
- Reduction of resistivity
  - Electrical losses scale with I²
  - Reduction of electrical losses by using half cells

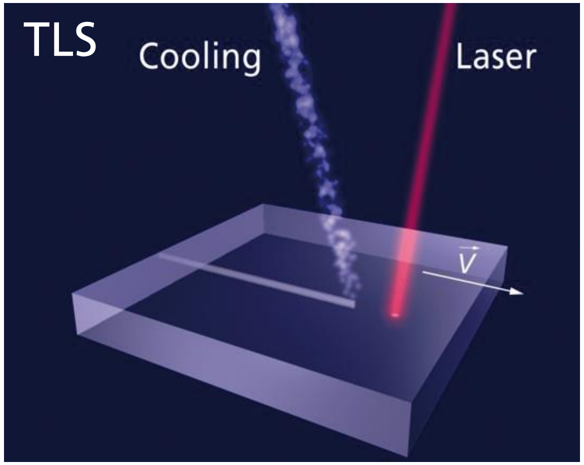


[1] mitsubishi

	standard	half cells
Uoc (v)	45,97	46,05
Isc (A)	9,08	9,36
Pmpp (W)	315,16	**330,04**
Umpp (V)	36,98	37,71
Impp (A)	8,52	8,75
FF (%)	75,51	76,58

Processes for solar cell separation

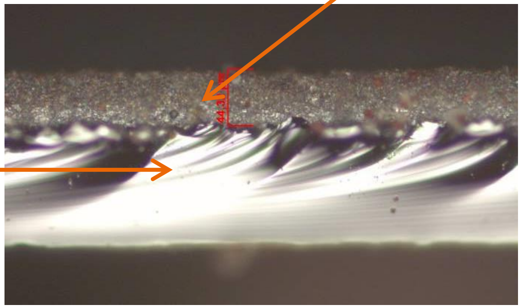
- Standard process:
  - Laser cutting up to 1/3 wafer thickness -> manual breaking
- TLS process
  - Crack propagation by thermally induced mechanical stress



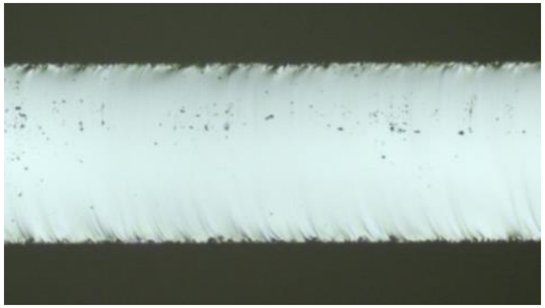
Principle thermal laser separation (source 3D micromac)

Laser affected region

crack



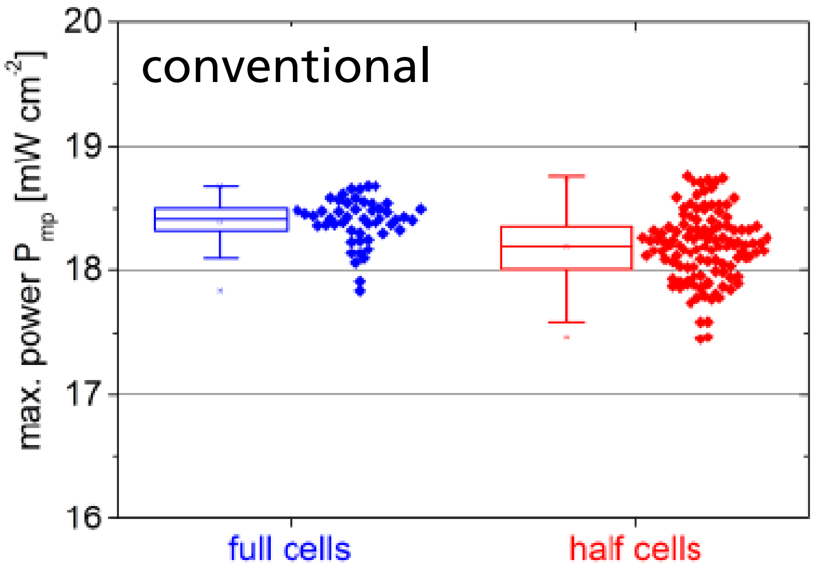
Edge of a separated Si Wafer (standard process)

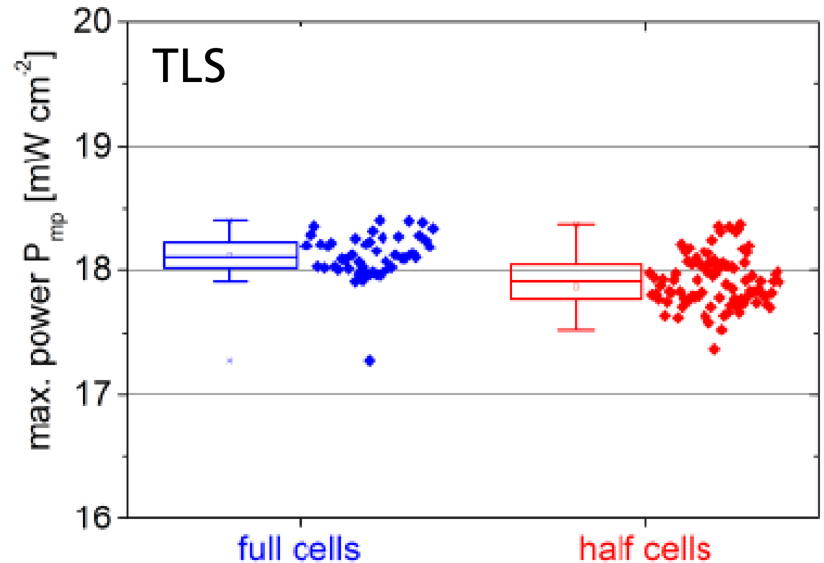


Edge of a separated Si Wafer (TLS process)

Electrical losses or losses in mechanical strength?

I. Electrical characterization
Conventional vs. TLS

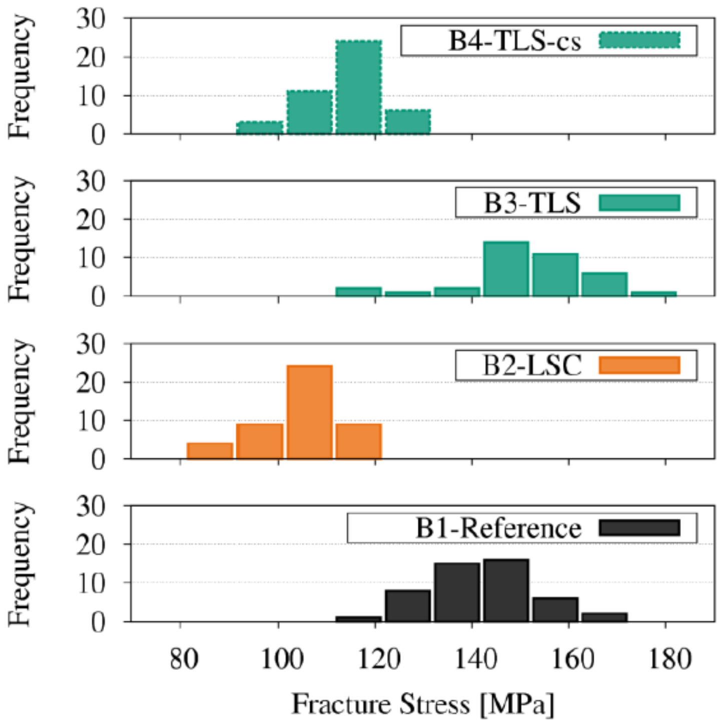




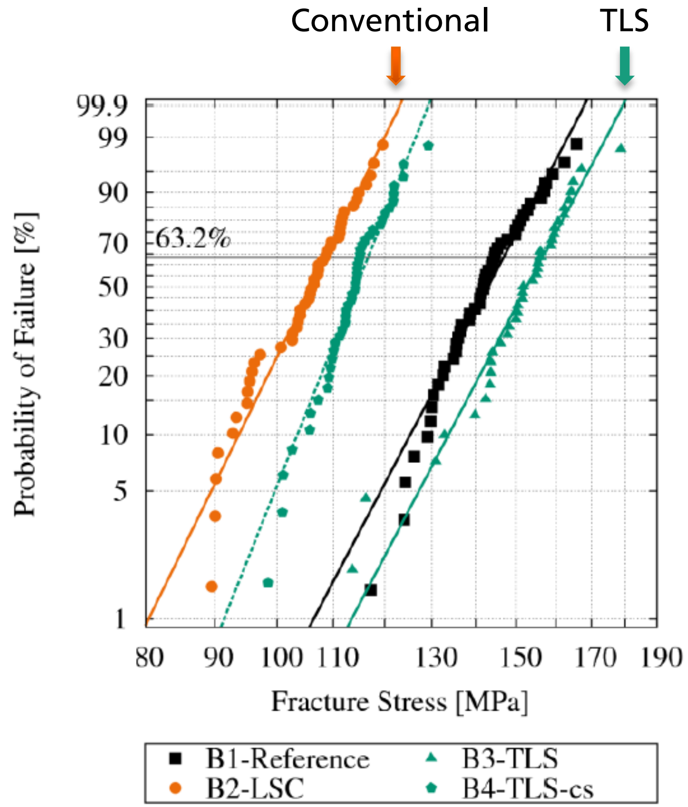
Comparison of max. power P_{mp}, conventional vs TLS

- Drop in efficiency of about 1.1%$_{rel}$
- **Losses similar for TLS and conventional scribing and cleavage**
- R_{shunt} increased for both processes
  - Increase does not lead to efficiency drop
- Losses mainly due to increased recombination on laser edge

II. Mechanical strength
Fracture stress



Representation as histogram



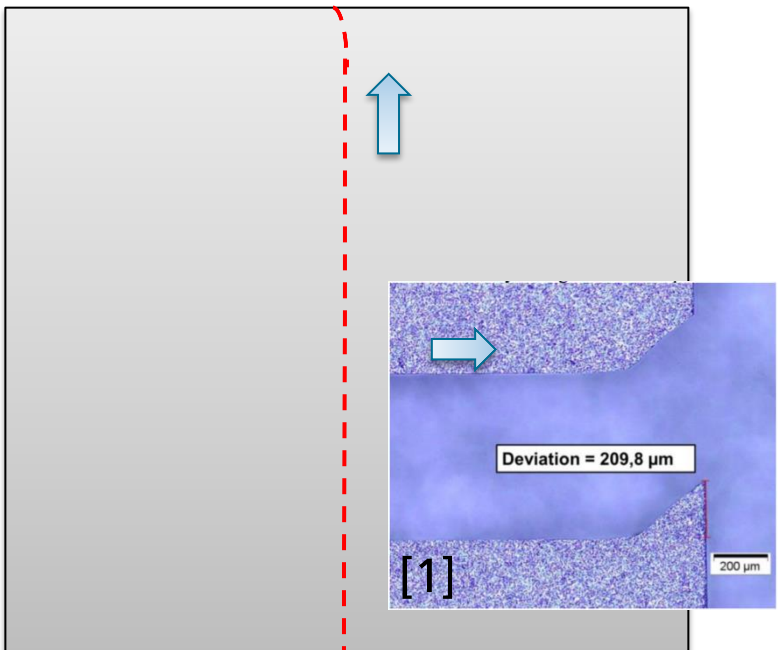
Size dependent Weibull distribution

- Highest mechanical strength for TLS cut cells
- **Reduced mechanical strength for conventional cut cells**

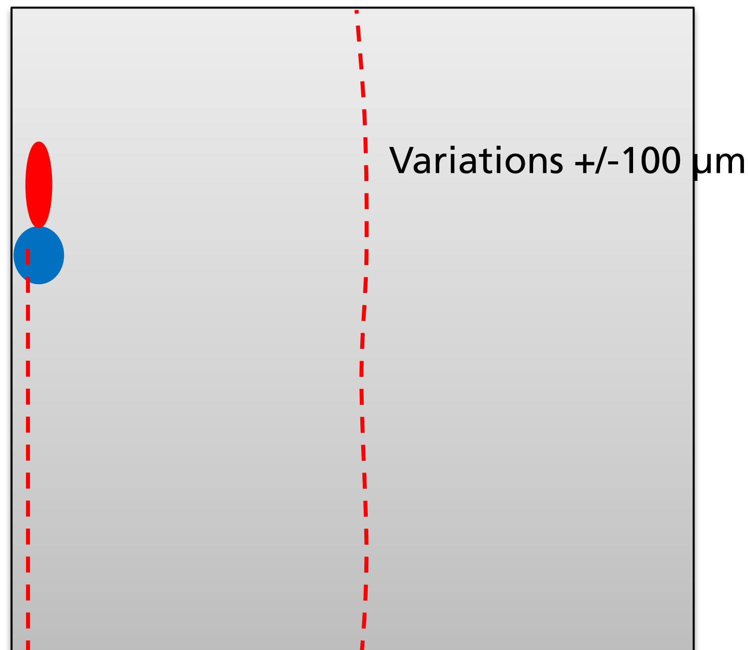
TLS-Problems

- TLS is the better option for cell separation in terms of mechanical strength
- But it has some other problems.

Non ideal crack path at wafer end
1. Crack leaves path near the wafer end



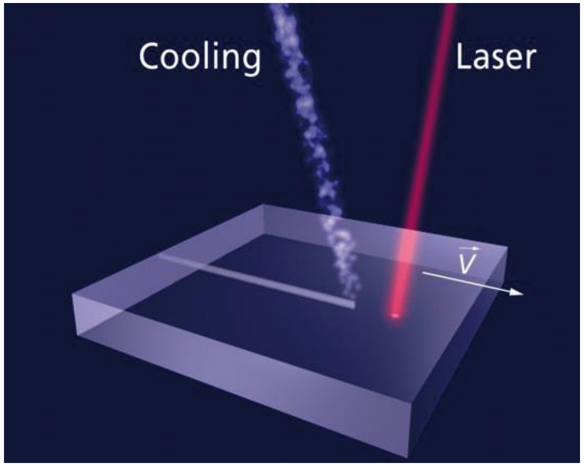
Crack path variations
2. Oscillations
3. Deviation near wafer edge



TLS-simulation better understanding of TLS process and parameter interaction

[1] J. Röth et. al., „Simulation of the thermal laser propagation process (TLS) in relation to the crack propagation at the wafer edge“, Processdings EUPVSEC 2017

Simulation of TLS-processes



Principle thermal laser separation
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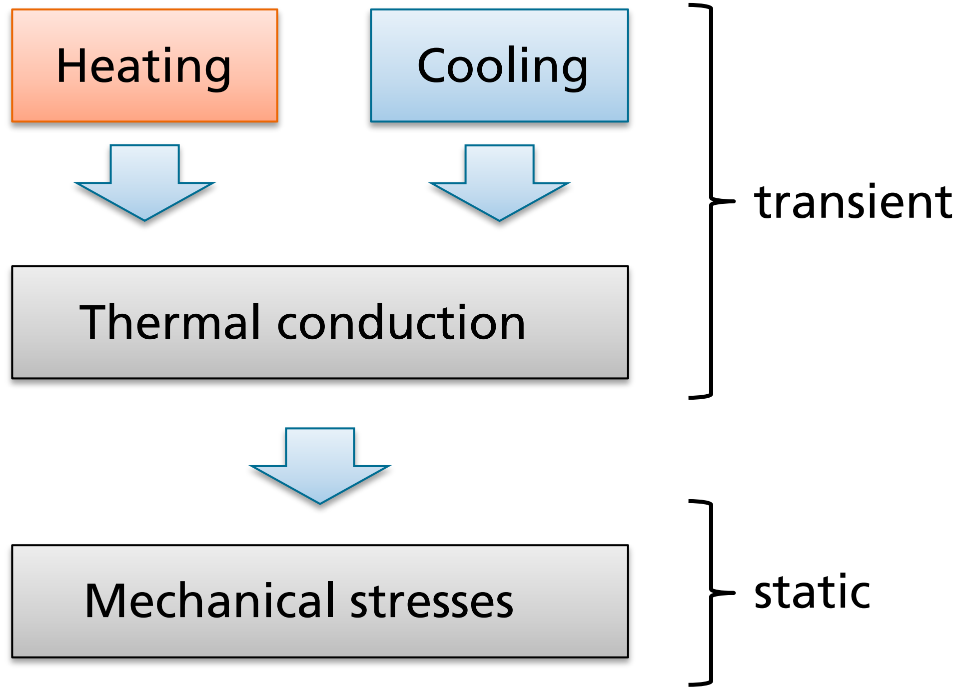


- Done with ANSYS
- Transient model for laser absorption, heating and thermal conduction (TLS-speed, laser power, cooling efficiency)
- Subsequent analysis of mechanical stresses and stress intensities

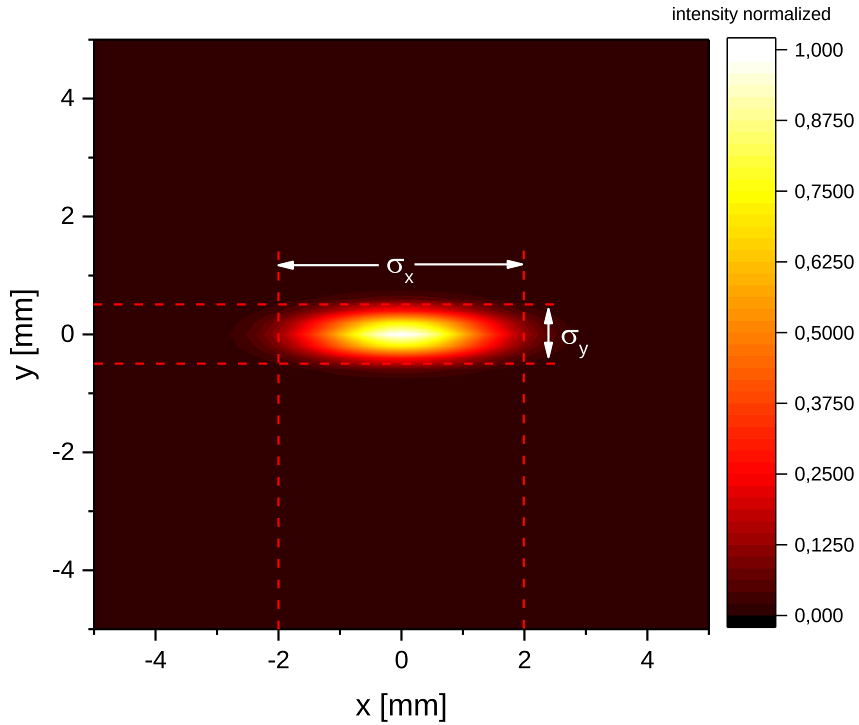
Determination of heat generation rate

σ_x, σ_y…pulse diameter at $1/e^2 * I_{max}$

Gaussian pulse shape:

$$I(x,y) = \exp(-8\left(\frac{(x-x_0)^2}{\sigma_x^2} + \frac{(y-y_0)^2}{\sigma_y^2}\right))$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)dxdy = \frac{1}{8}\pi\sigma_x\sigma_y$$



2D-Gaussverteilung, σ_x = 4 mm, σ_y = 1 mm

Mean laser power: P_{mean}
Energy per time step: $E_{\Delta t,total} = P_{mean} * \Delta t$
Energy per node (for one element in z-direction):

$$E_{\Delta t,node} = \frac{8}{\pi\sigma_x\sigma_y} I(x,y)\Delta x\Delta y E_{\Delta t,total}$$

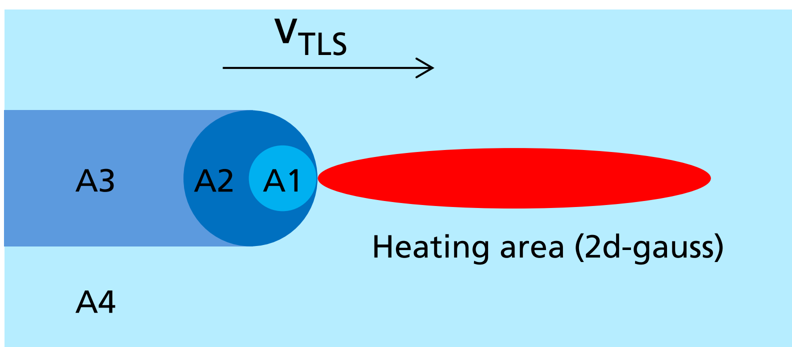
Power per node (for one element in z-direction):

$$P_{HGR,node} = \frac{8}{\pi\sigma_x\sigma_y} I(x,y)\Delta x\Delta y P_{mean}$$

Cooling

- Cooling is realized with convection
- Convention is added to surface elements

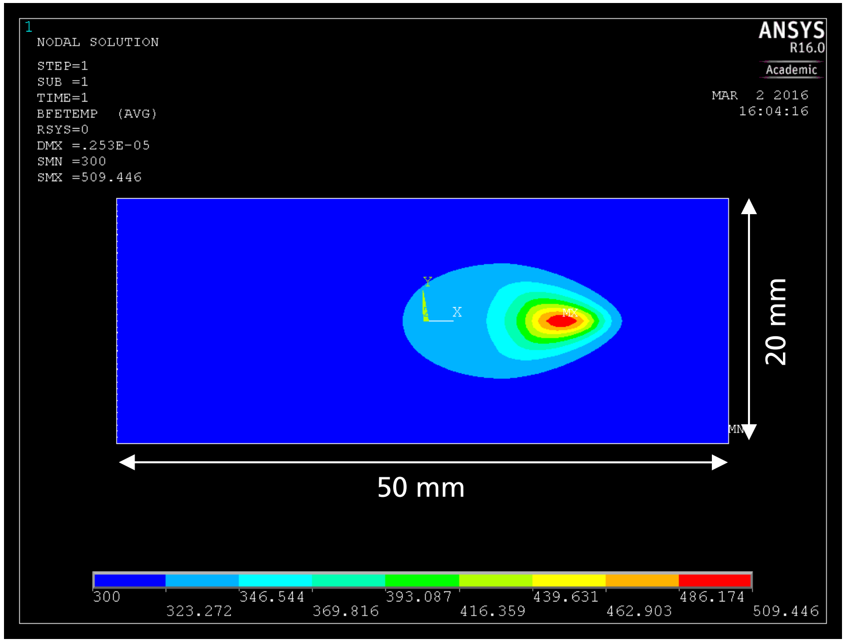
- Definition of „cooling areas“*
  - A1 cooling by evaporation (**when T > 100 °C**) $\alpha_1 \sim 10^4$
  - A2 cooling moving/streaming fluid $\alpha_2 \sim 10^3$
  - A3 cooling stationary fluid $\alpha_3 \sim 10^2$
  - A4 cooling by ambient air $\alpha_4 \sim 10^1$

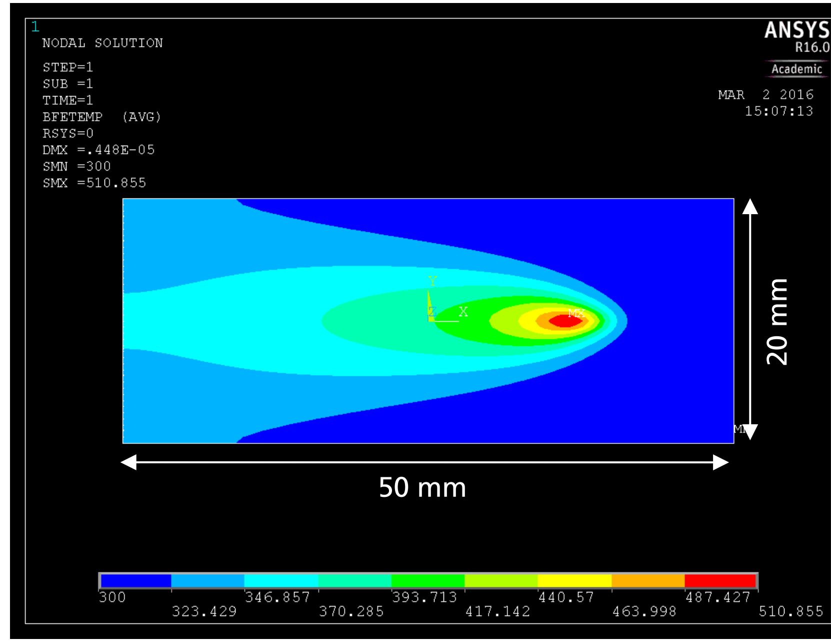


*free convection

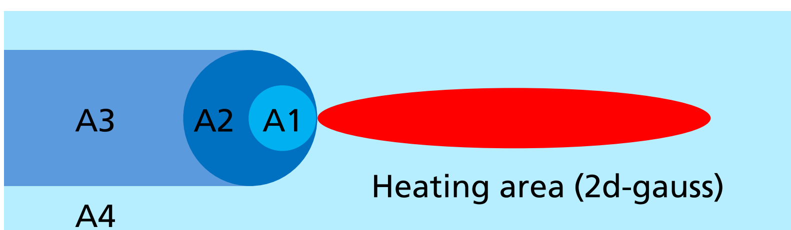
$$\frac{Q}{A} = \alpha * (T_1 - T_2) * \Delta t$$

Temperature distribution with/without cooling

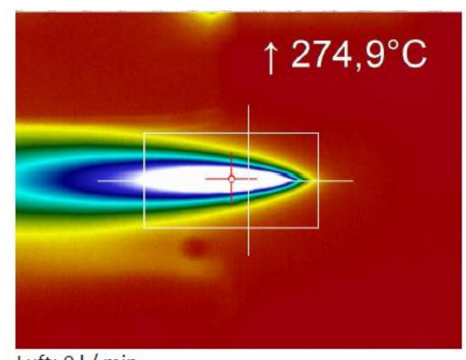




- With cooling
- $d_{A1} = 2$ mm, $\alpha_{A1} = 25000$ W/(m²K)
- $d_{A2} = 6$ mm, $\alpha_{A2} = 5000$ W/(m²K)

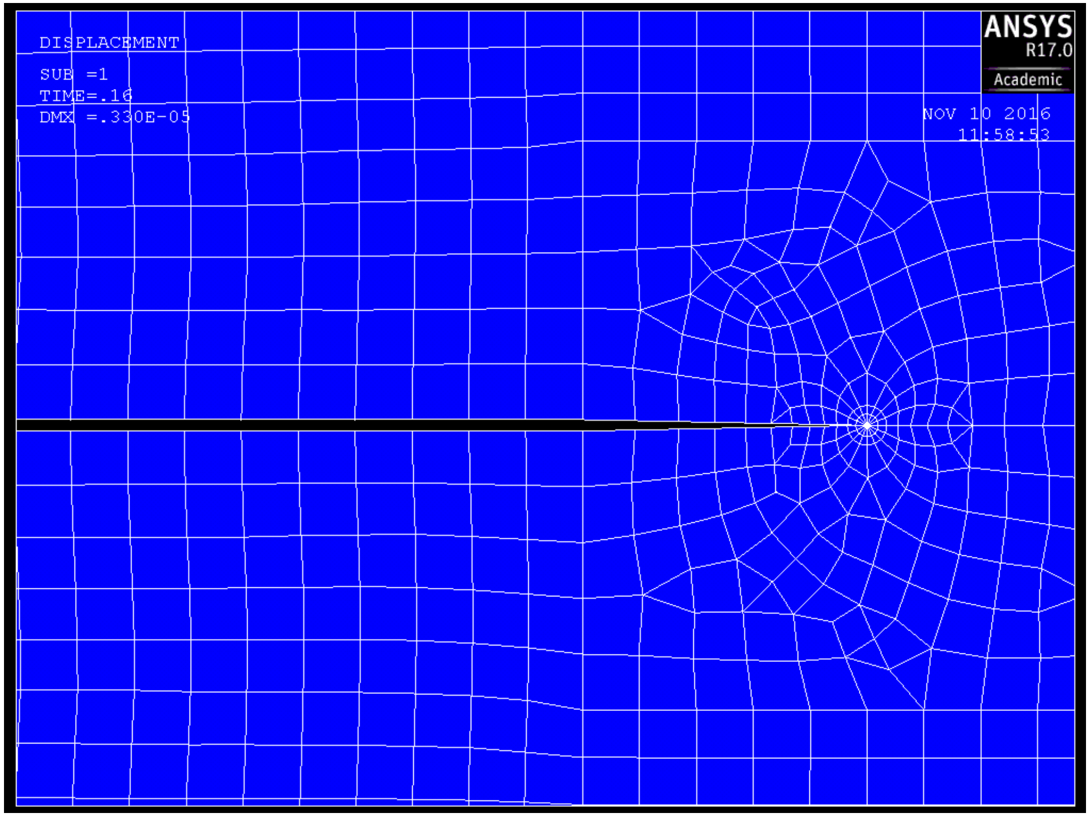


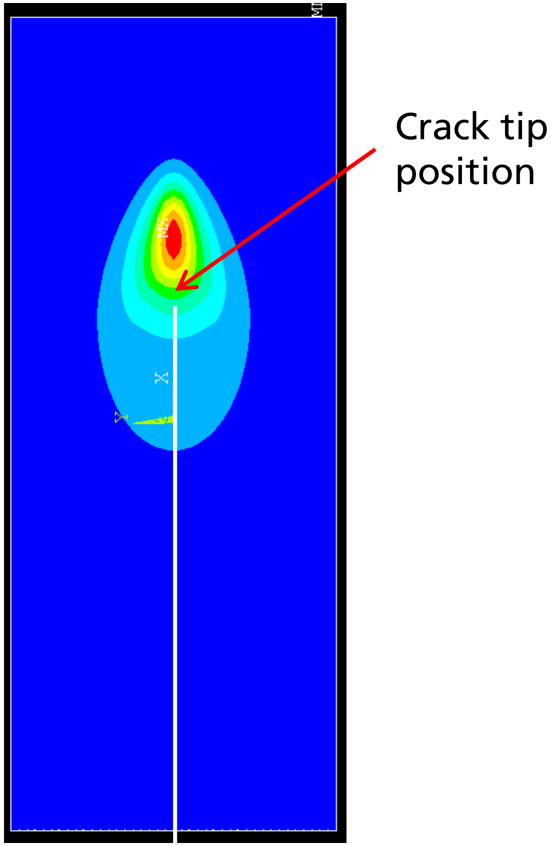
Without cooling



Thermography measurement

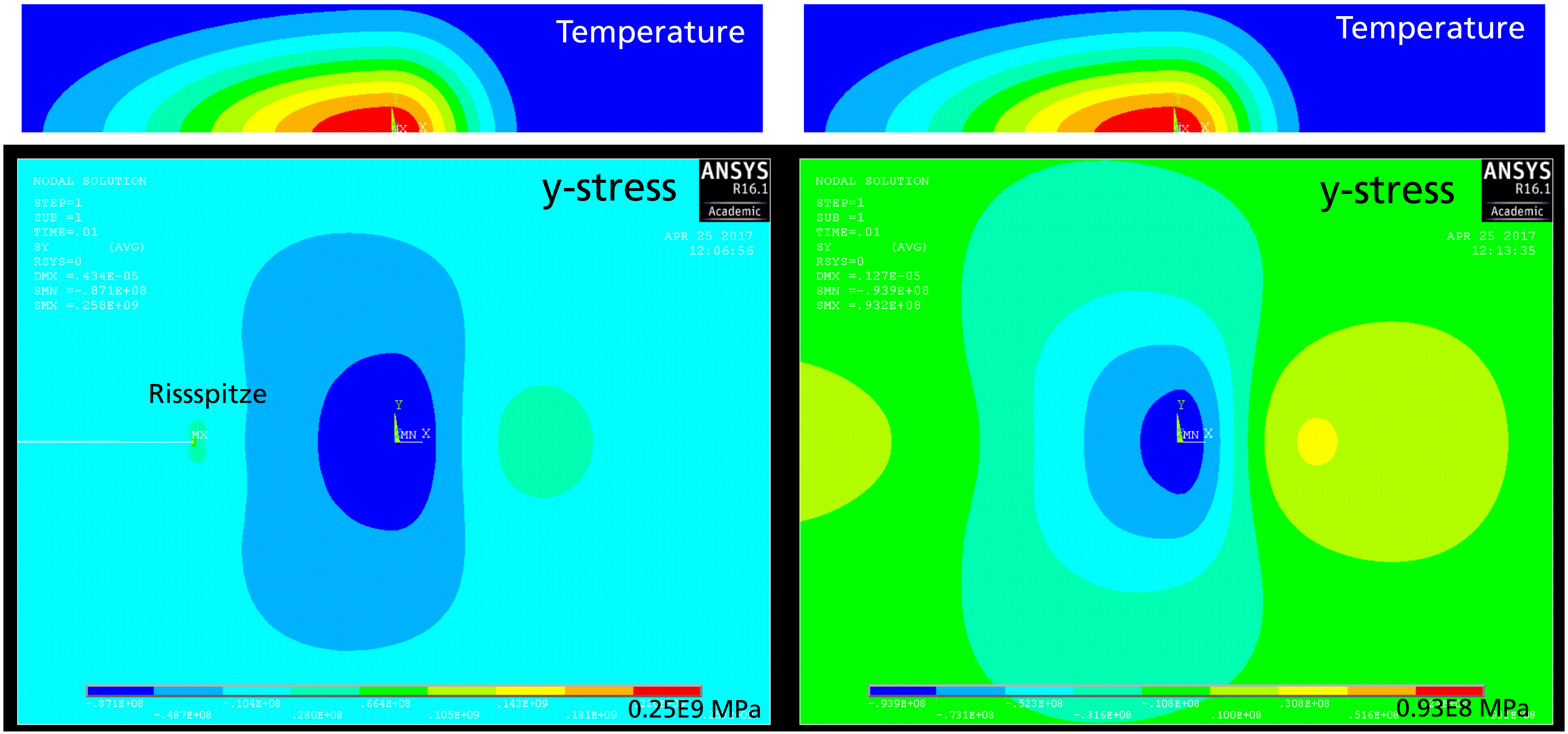
Incorporation of a crack tip





- Modeling with „crack tip elements“
- Modelled as a zero gap with contact elements
- Variation of crack tip position -> evaluation of stress intensities

Incorporation of a crack tip



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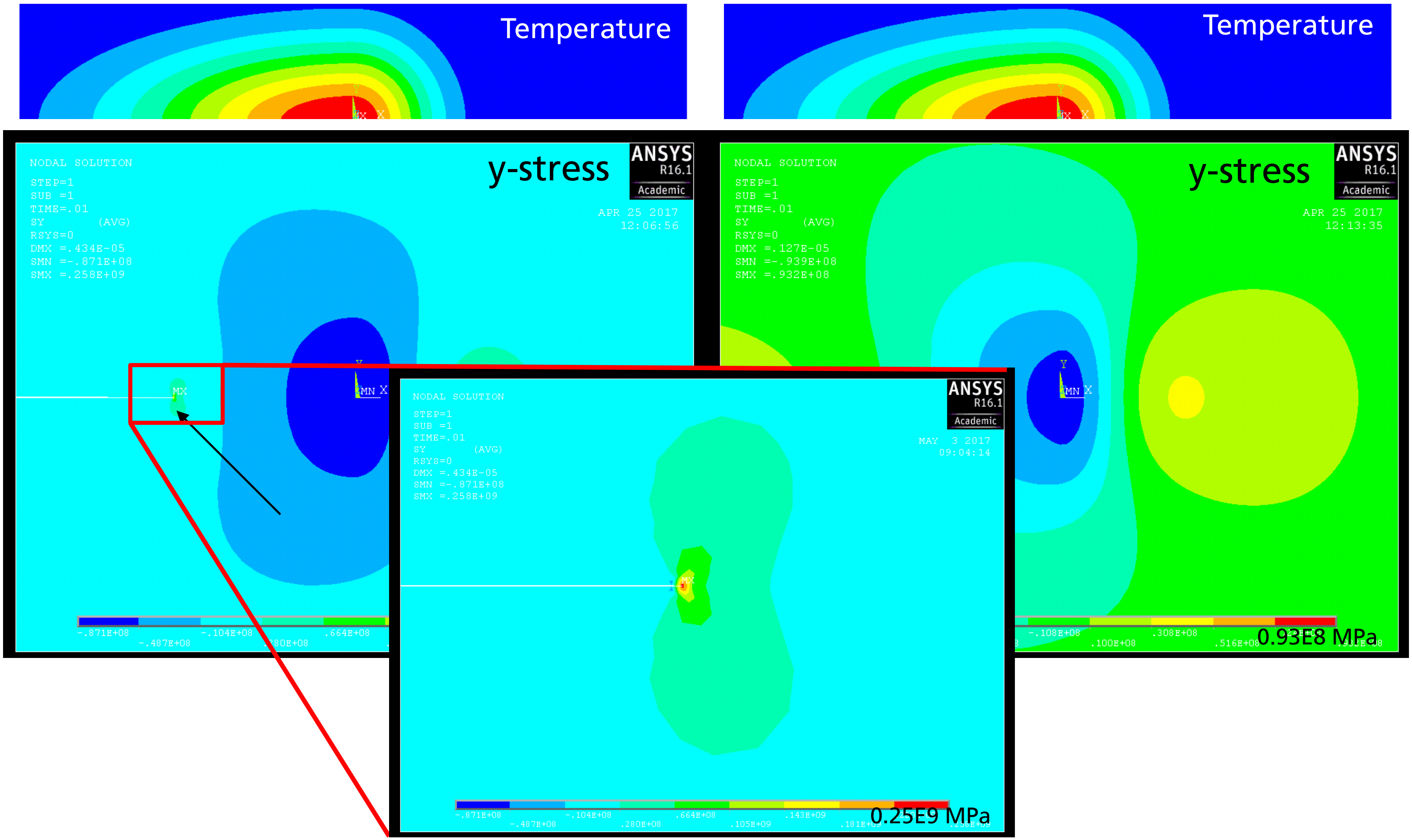
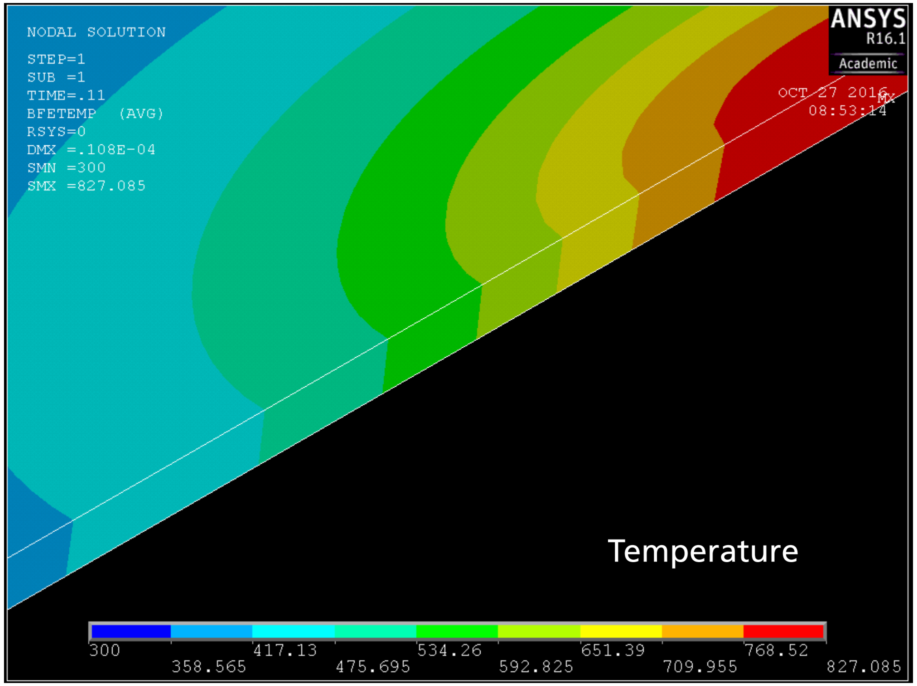
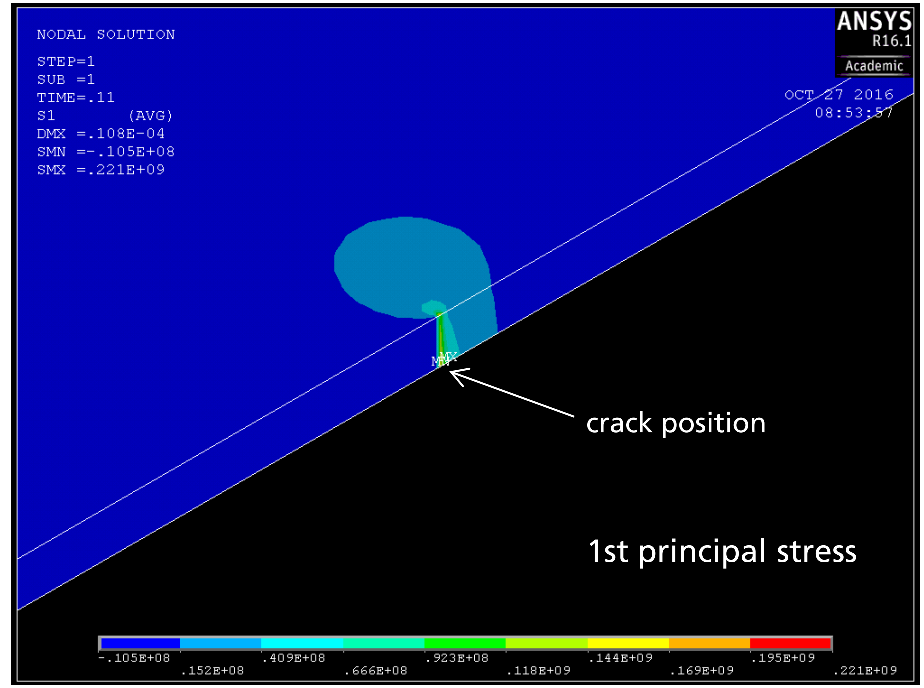
Incorporation of a crack tip



Incorporation of a crack tip

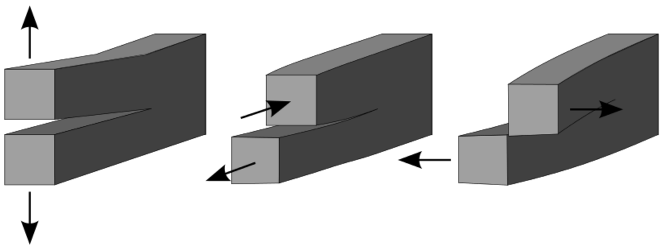




- Strongly localized stress maximum at crack tip
- -> determination of stress intensity factors directly on the crack tip
- -> VCCT (virtual crack closure technique)

Determination of K_1, K_2 and K_3 with VCCT-method

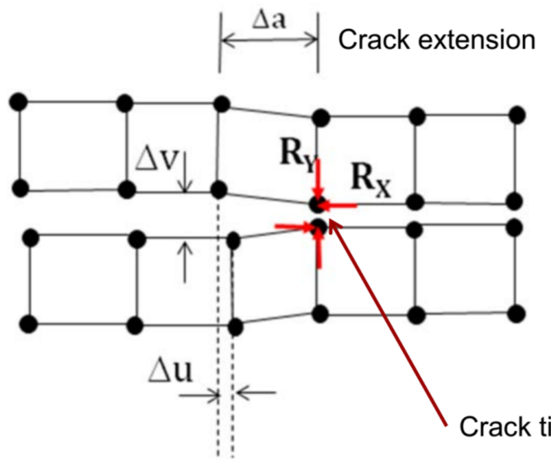
- The mode I and II energy release rate expressions used in VCCT, assuming a 2D crack geometry and lower order elements:
  - Approach can be extended to 3D and higher order elements.



$$G_I = \frac{1}{2\Delta a} R_y \Delta v \qquad G_{II} = \frac{1}{2\Delta a} R_x \Delta u$$

Δu and Δv:

Relative displacements of crack face



R_x and R_y :

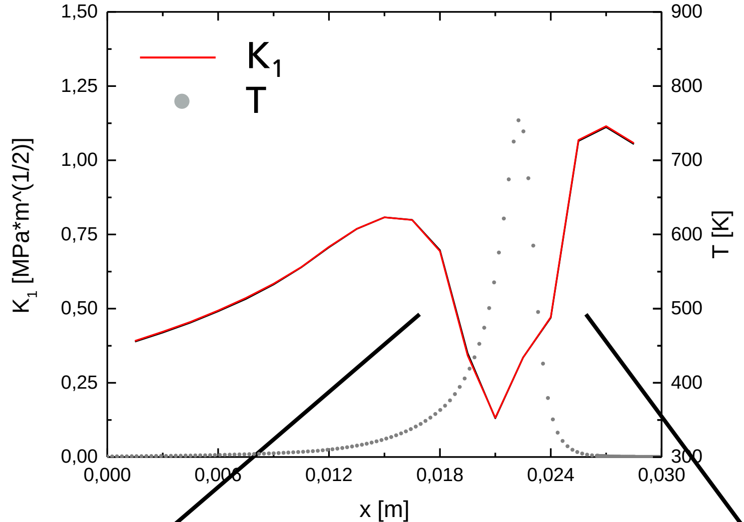
Reaction forces at crack tip node

[1]

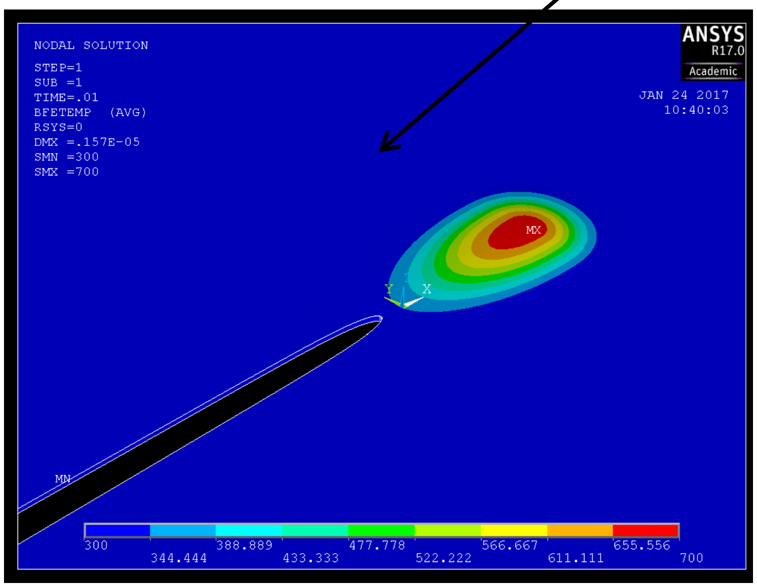
- Determination of G1, G2 and G3 with VCCT-method directly in ANSYS
- Calculation of K_1, K_2 and K_3 ⇨ $$\frac{K_I^{\,2}\left(1-\nu^2\right)}{E} = G_I$$

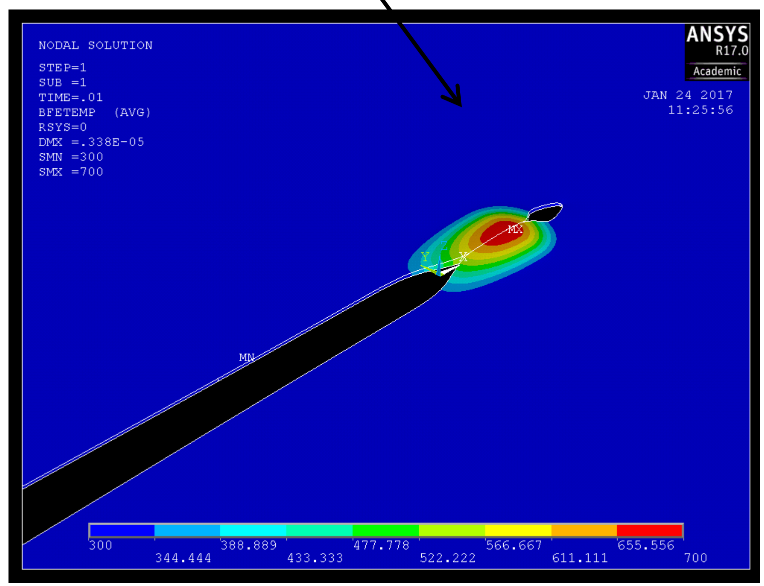
[1] Virtual Crack Closure Technique (VCCT) in ANSYS, 2011 CAU Associates

Stress intensity factors for different crack tip positions



- Maximum of K_1 before and after T_{max}

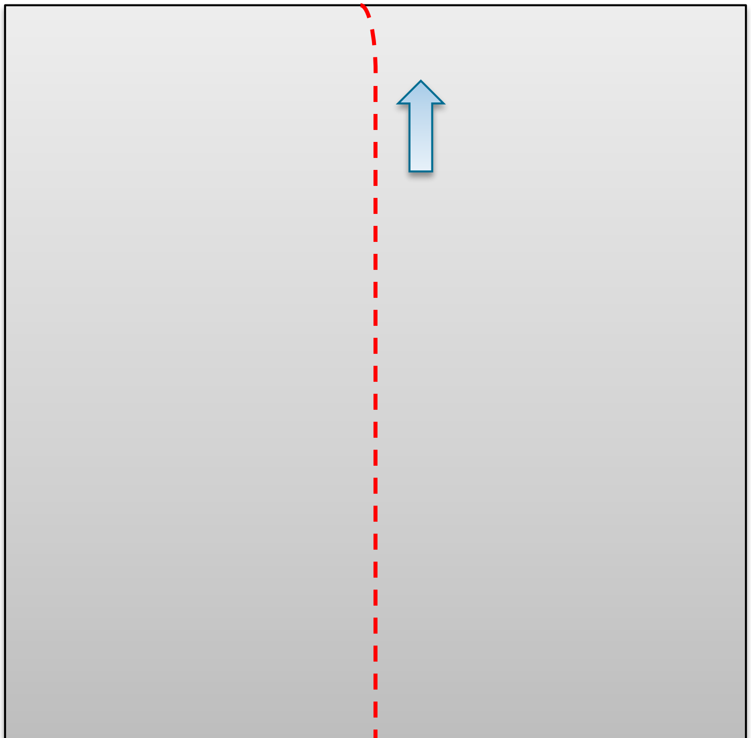




TLS-Problems

Non ideal crack path at wafer end

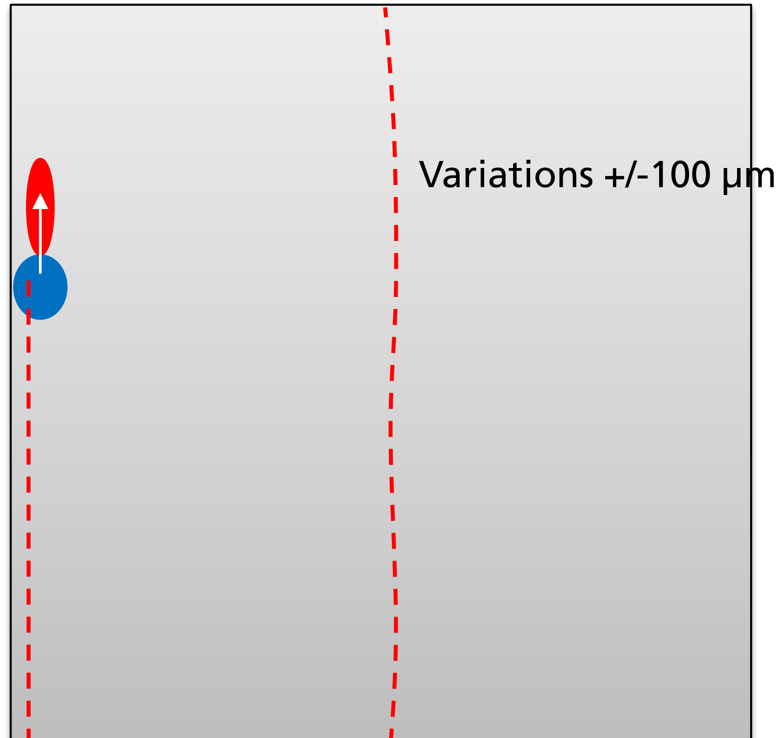
- Crack leaves path near the wafer end



Crack path variations

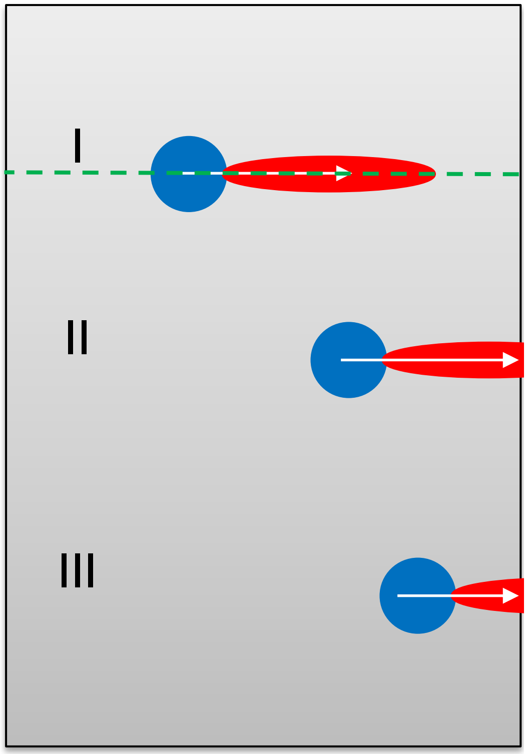
a. Oscillations

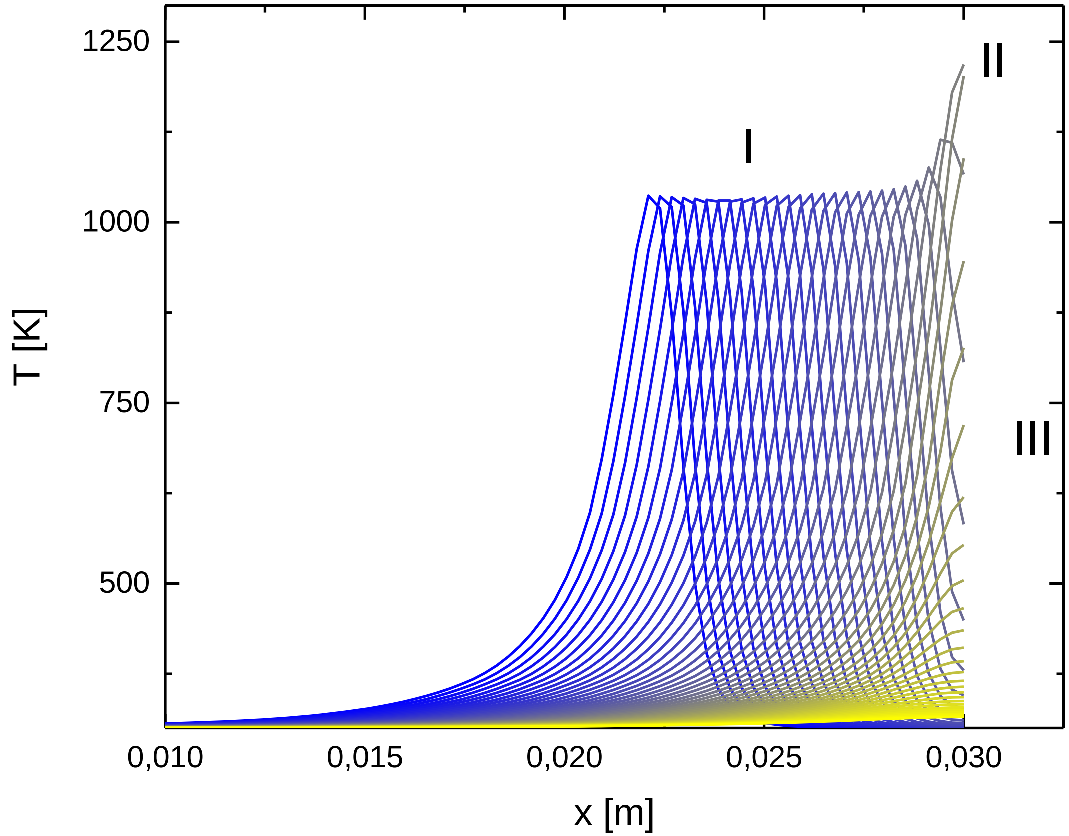
b. Deviation near wafer edge



Can the model be used to reproduce/explain these problems?

Approaching the wafer end: Temperature





- Heat accumulation in case II $T_{max,edge} \sim T_{max,wafer} * 1.15$
- Decreasing temperatures in case III
- Effect on K_1 and crack propagation?

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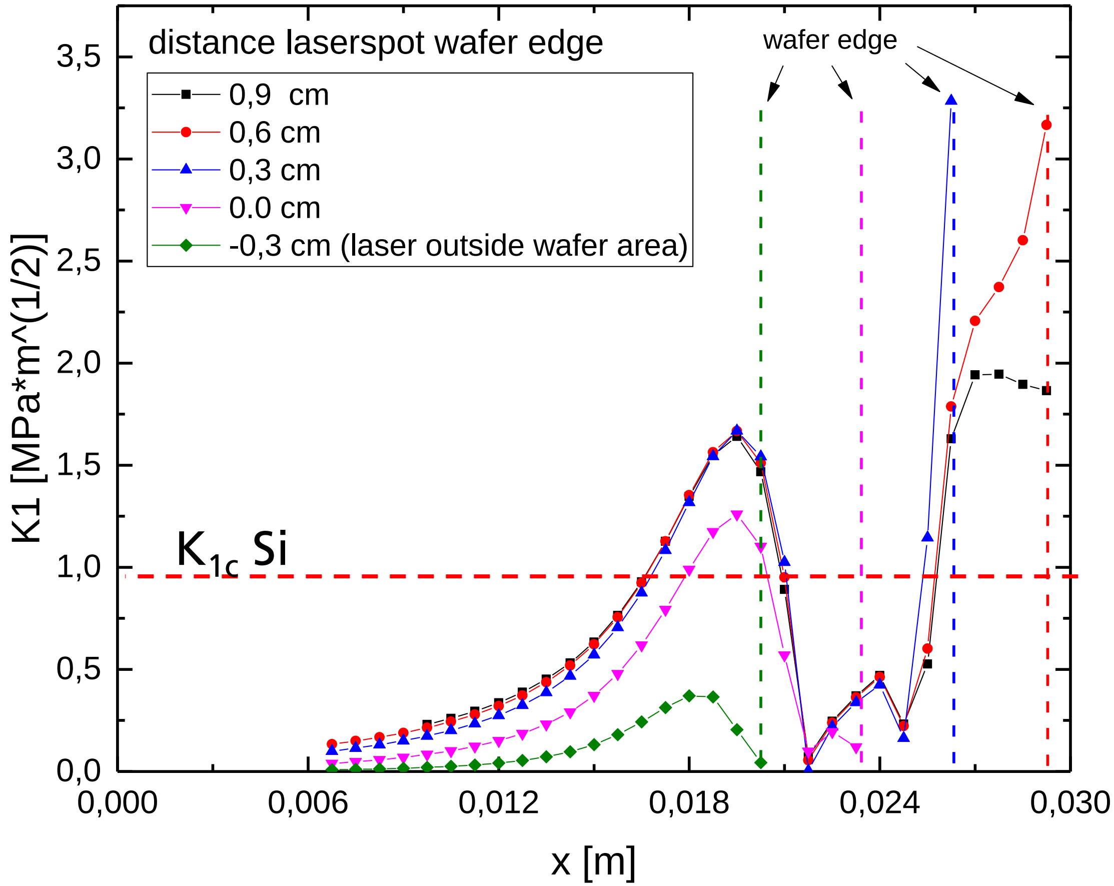
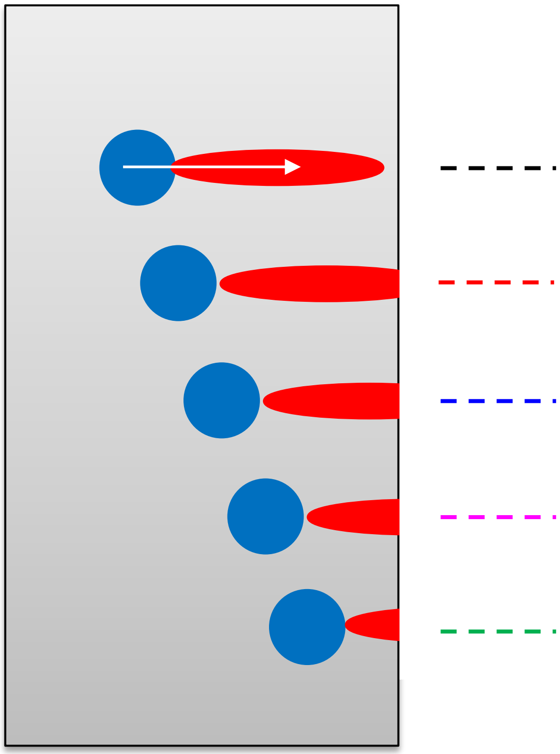
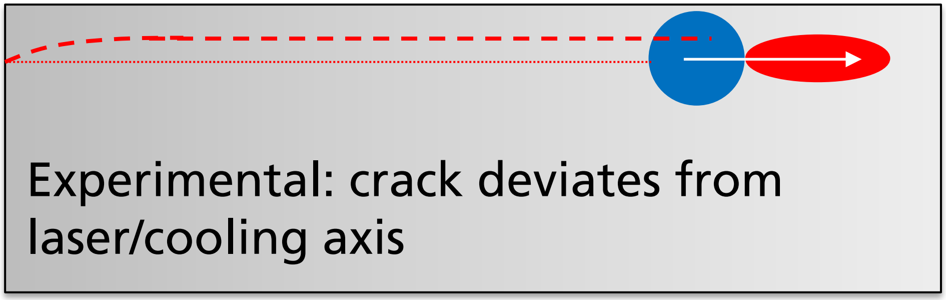
Approaching the wafer end: Stress intensity factor K_1



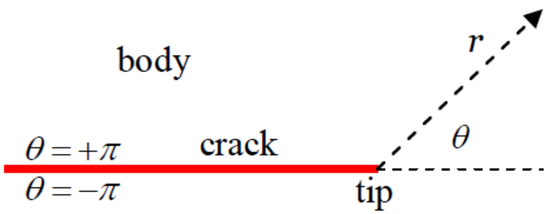


- K_1 decreases -> crack propagation stops
- Possible solution: crack propagation in front of laser spot
  - -> no success so far

Crack propagation near the wafer edge

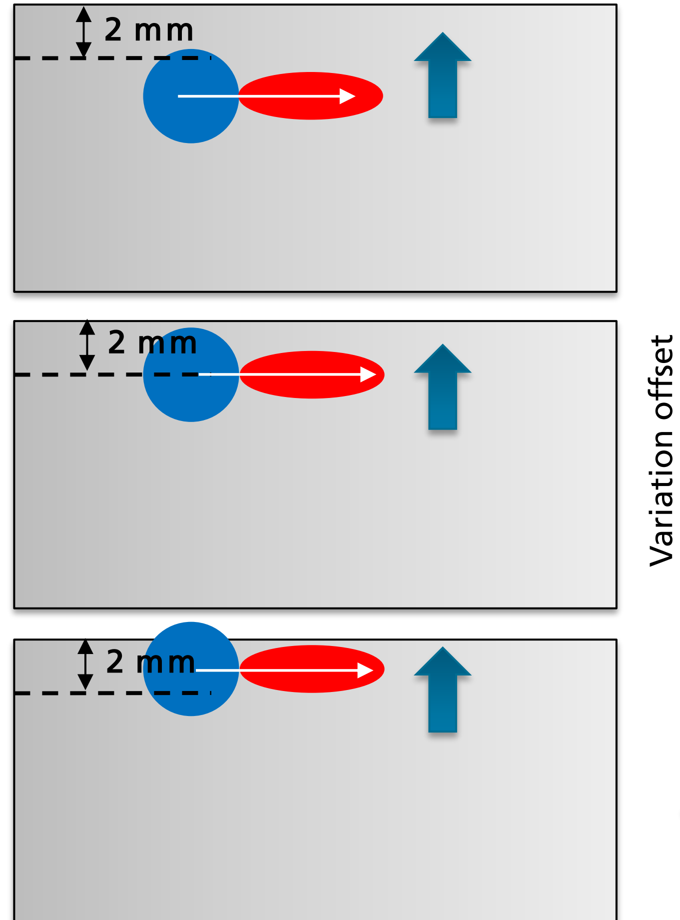


- Maximum circumferential stress criterion (MCSC)



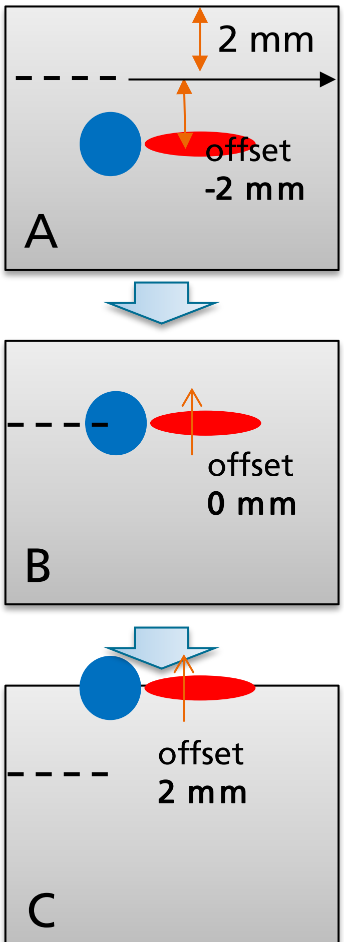
$$\theta = \alpha = 2atan\left(\frac{K_1 - \sqrt{K_I^2 + 8K_{II}^2}}{4K_{II}}\right)$$

Compensation of edge effect possible?

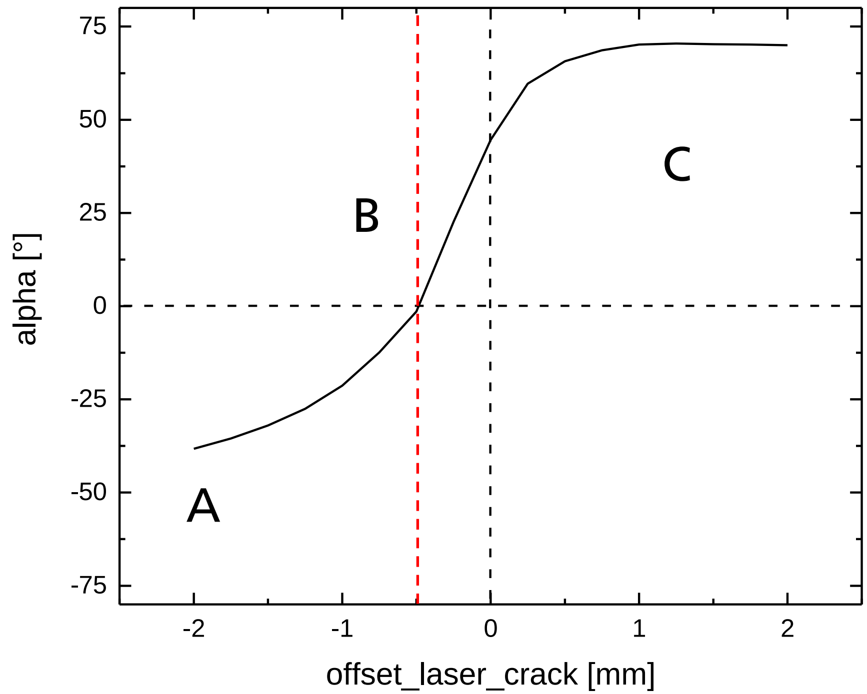


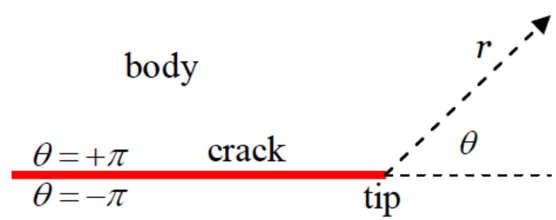
- Approach for simulation

Angle of crack propagation near wafer edge



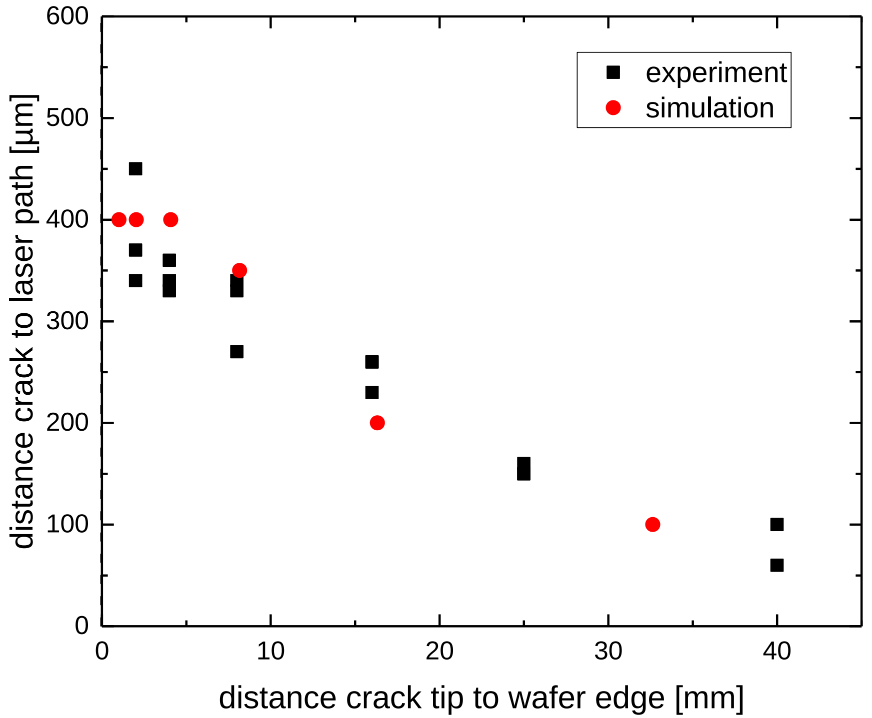
- Near the wafer edge the path of crack propagation deviates from the laser path

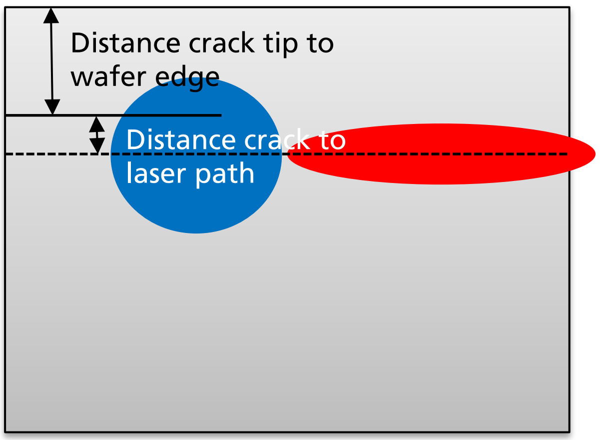




$$\alpha = \theta_p^{(K)} = 2\arctan\left(\frac{K_I - \sqrt{K_I^2 + 8K_{II}^2}}{4K_{II}}\right)$$

Crack path deviations, Experiment vs. Simulation





Comparison of measured and simulated crack path deviations for asymmetric cutting

- The simulation reproduces crack deviations when cutting asymmetric substrates

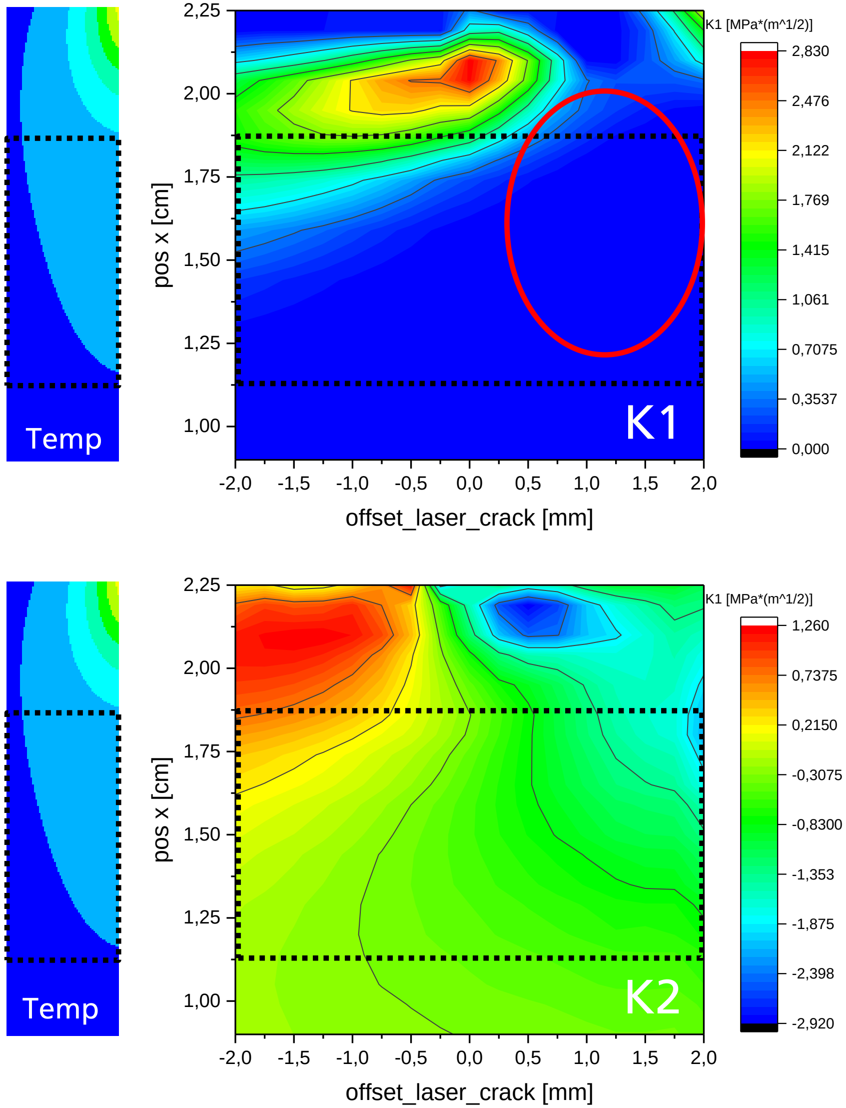
Summary

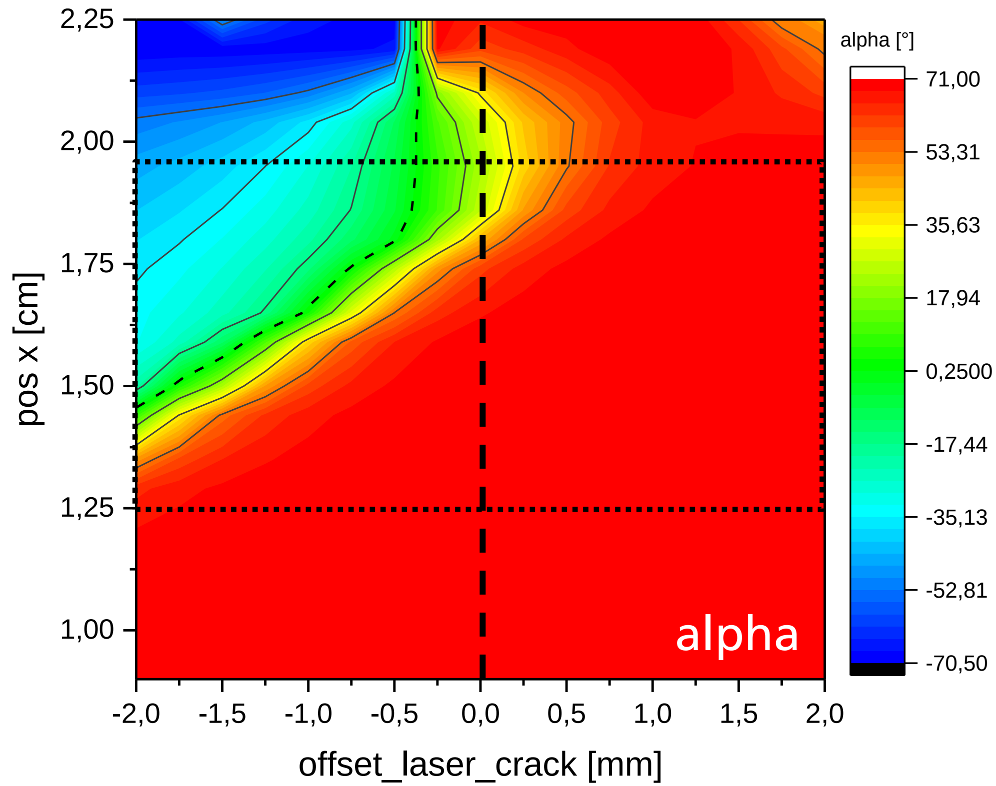
- A **simulation model was set up** including
  - transient laser heating and cooling
  - evaluation of stresses and stress intensity factors

- Model allows for **analysis of TLS disadvantages**
  - Heat accumulation and reduction of K1 lead to crack path bending when approaching the wafer end
  - The dislocation of the crack path near the wafer edge can compensated by an offset of the laser/cooling path

- Open questions:
  - Quantitative comparison with experimental results (ongoing)
  - 100 µm crack path variations (possible causes: asymmetric cooling due to fluid-dynamic processes, asymmetric stress due to sample holder, residual stresses in wafer)

Angle of crack propagation near wafer edge





- Angle of 0° is only reached with negative offset
- -> crack propagation between laser path and wafer edge

Anhang: Wärmestau bei Überfahrt über Waferrand