



Zerstörungsfreie Prüfung polymerer Verbundwerkstoffe mittels aktiver Thermographie

By: DI. J.Sekelja

Anwendungen und Partner



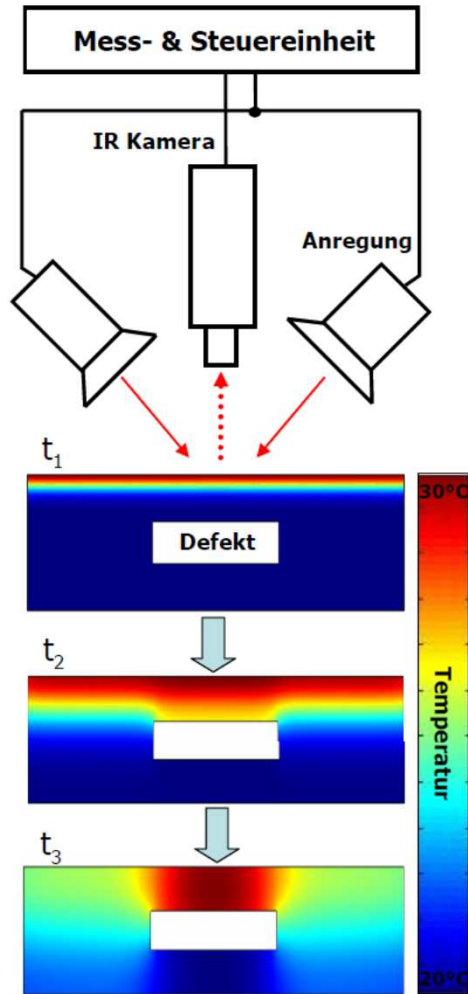
- Porosität in CFK Laminaten
- Delaminationen in CFK Laminaten
- Disbonds zwischen Laminaten und Wabenkernen
- Disbonds zwischen CFK Laminaten und Metall
- Verteilung der Fasern in Glassfaserlaminaten
- Folien und Fremdkörpereinschlüsse
- Impactschäden am CFK
- Risse im Aluminium und Stahl
- Lunker im Stahl
- Finite Element Simulation



Inhalt

- Einleitung
- Theorie
 - Allgemeine Thermographie
 - Anregungstechniken
 - Auswertelgorithmen(PPT, LDF, TSR)
- Anwendungen für optisch angeregte Thermographie
- Anwendungen der Induktionsthermographie
- Zusammenfassung

Aktive Thermographie Prinzip



IR Cameras

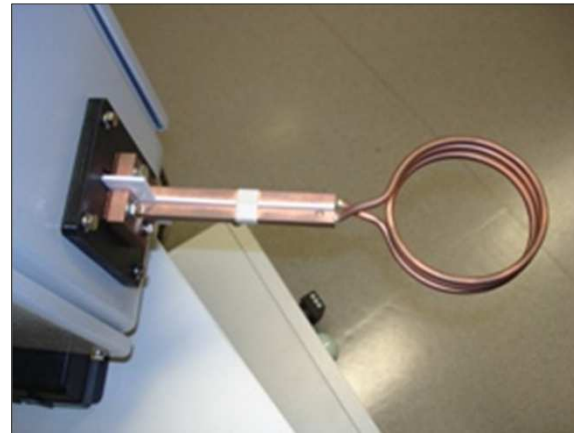


Heat Sources





Optische Anregung



Induktions Anregung



Quelle: isi-sys

Ultraschall Anregung

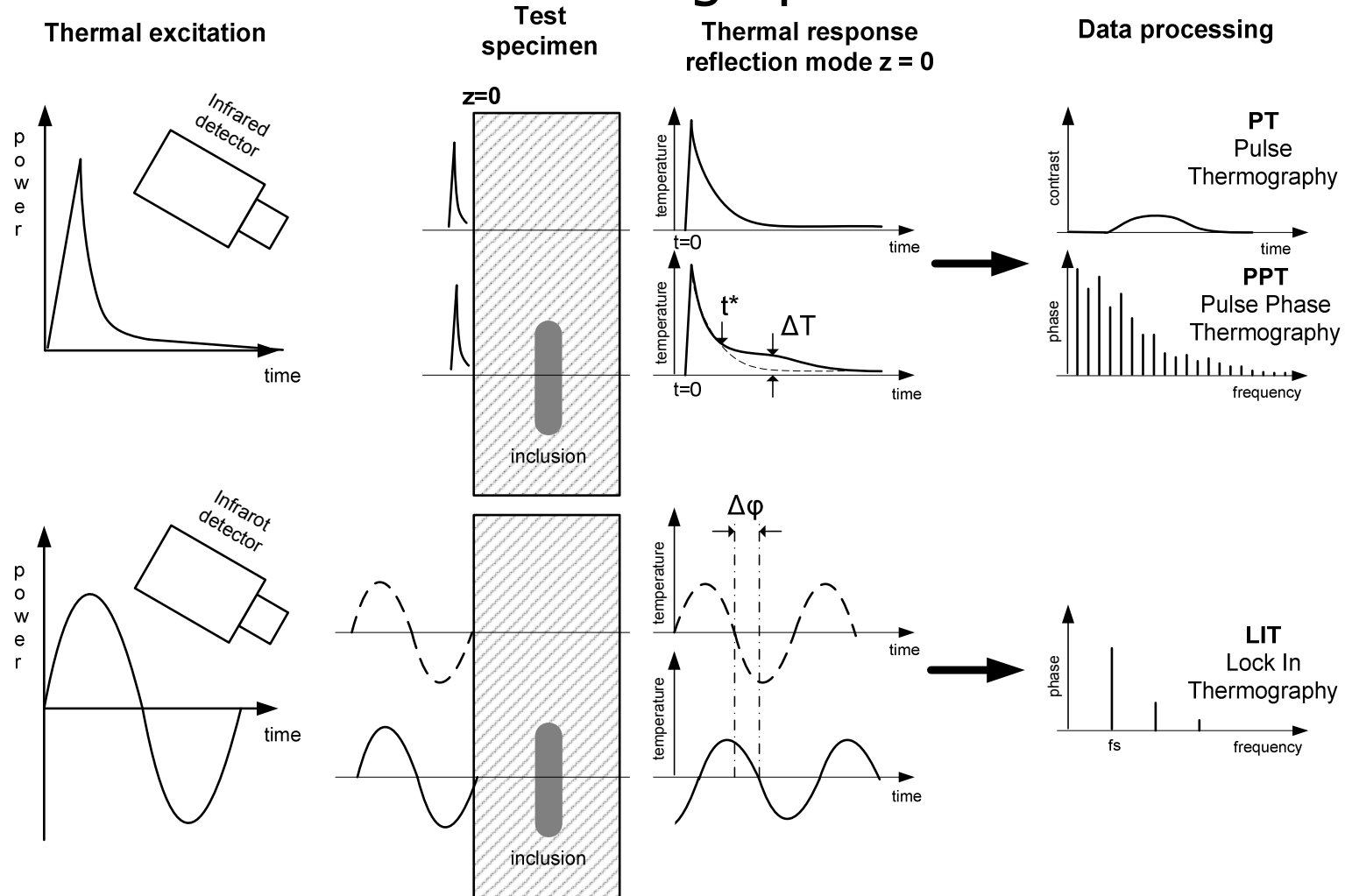


Quelle: Meggitt



Heißluft

Fehlercharakterisierung Puls- und Lock-In Thermographie



Heat conduction in Sound Solids

Semiinfinite Body

Fourier diffusion equation (x, y and z dimension):

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

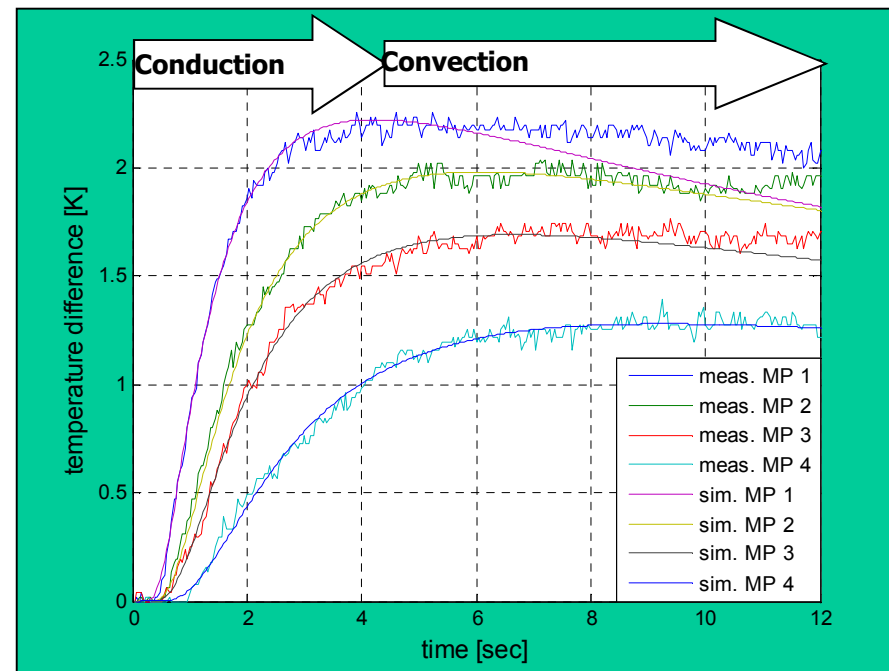
$$\alpha = \frac{\lambda}{\rho \cdot c}$$

... Thermal Diffusivity

1D Solution of the fourier equation for a DIRAC impulse

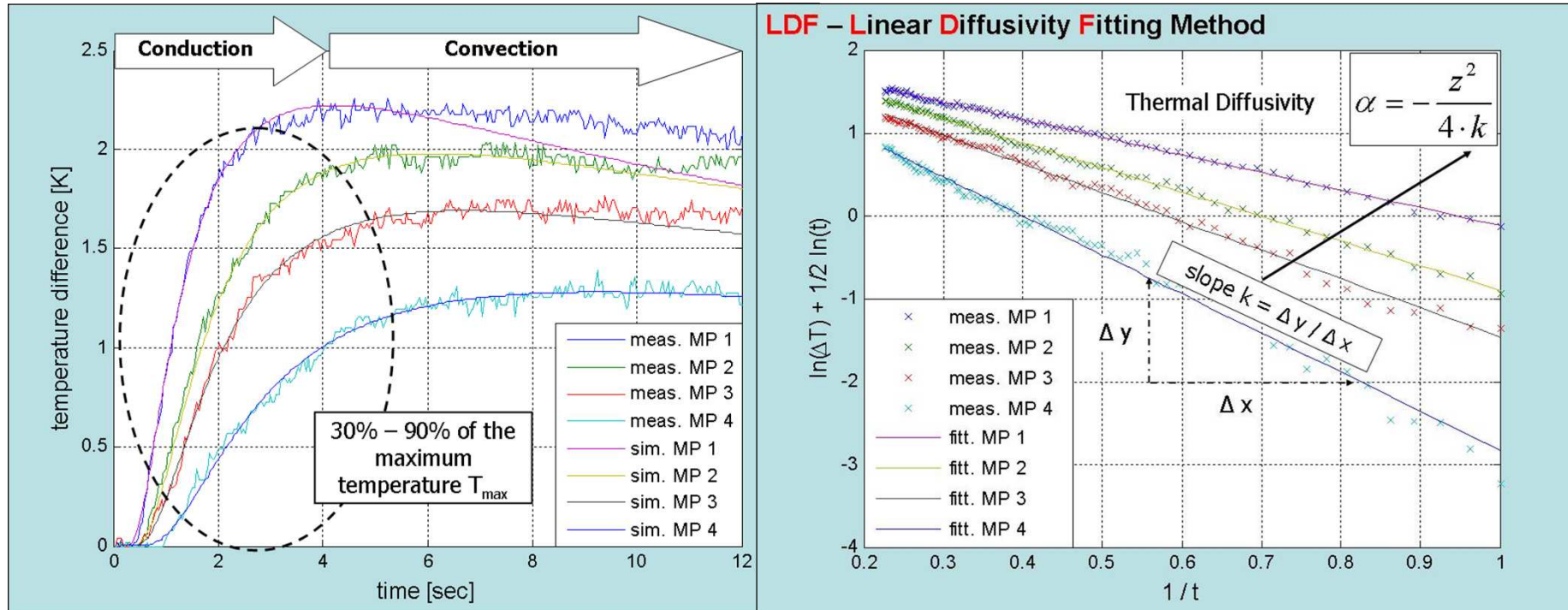
$$T(z, t) = T_0 + \left[\frac{Q / A}{\rho \cdot c \cdot \sqrt{4\pi \cdot \alpha \cdot t}} \right] \cdot e^{-z^2 / (4 \cdot \alpha \cdot t)}$$

- Adiabatic heating
→ No Convection and Radiation!
- Thermal thick specimen
→ Semi-infinite Body
- Isotropic material
→ $\lambda_x = \lambda_y = \lambda_z$ (thermal conductivity)



Linear Diffusivity Fitting – LDF

Fast method for the characterization of materials



Solution of the heat diffusion equation for a Dirac pulse excitation

$$T(z, t) = T_0 + \left[\frac{Q / A}{\rho \cdot c \cdot \sqrt{4\pi \cdot \alpha \cdot t}} \right] \cdot e^{-z^2 / (4 \cdot \alpha \cdot t)}$$

- **Not sensitive** to inhomogeneous illumination or changes of offsets (reflections of the environment, emissivity variations)
- **Linear fitting procedure** allows a fast implementation (2 sec for a 320x240 image)

Bestimmung der anisotropen Wärmeleitung in CFK

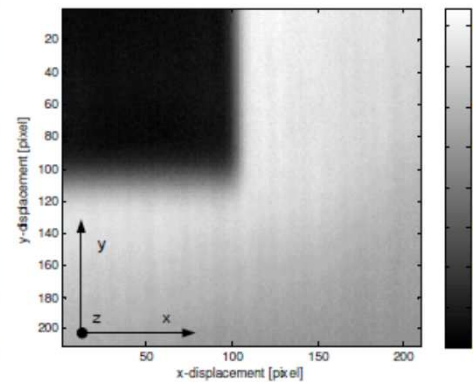
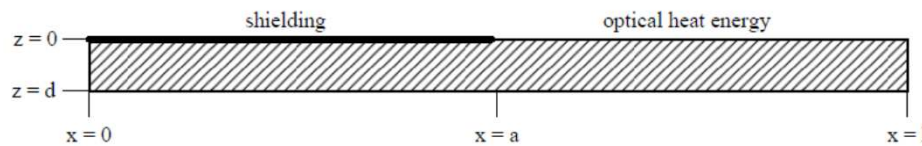
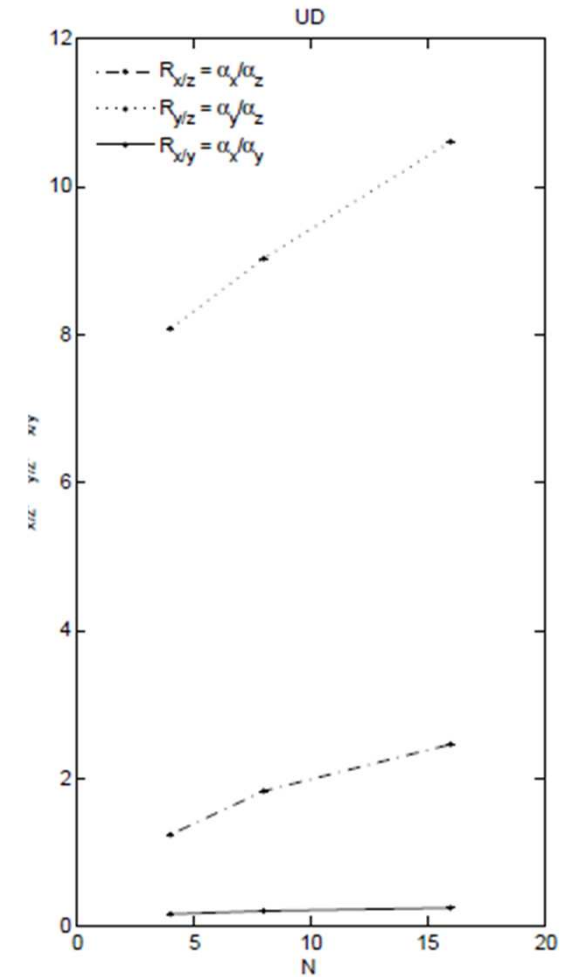


Abbildung: Messaufbau und Thermogramm bei UD8 Probe

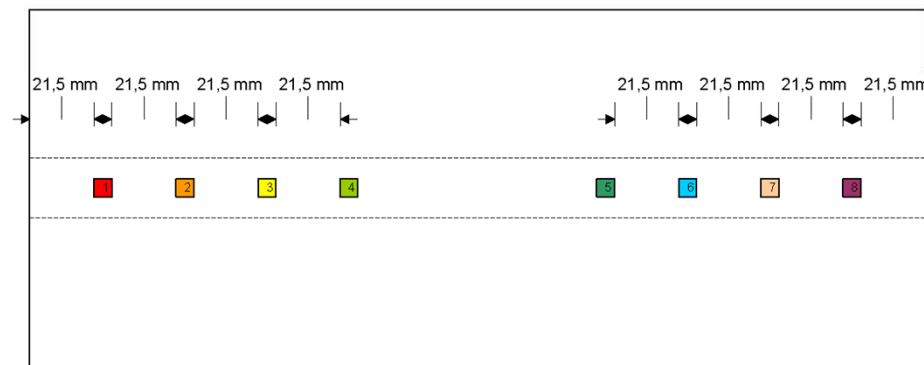
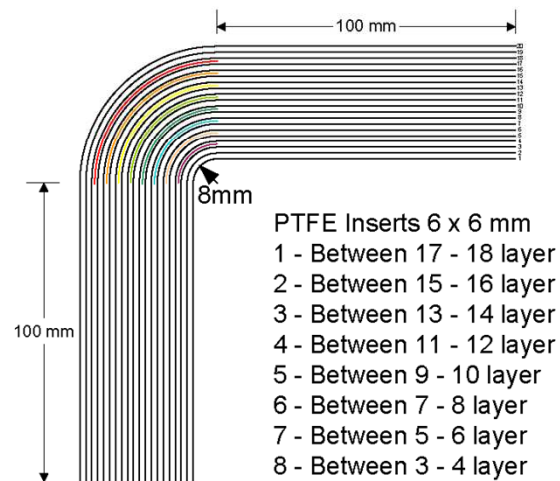
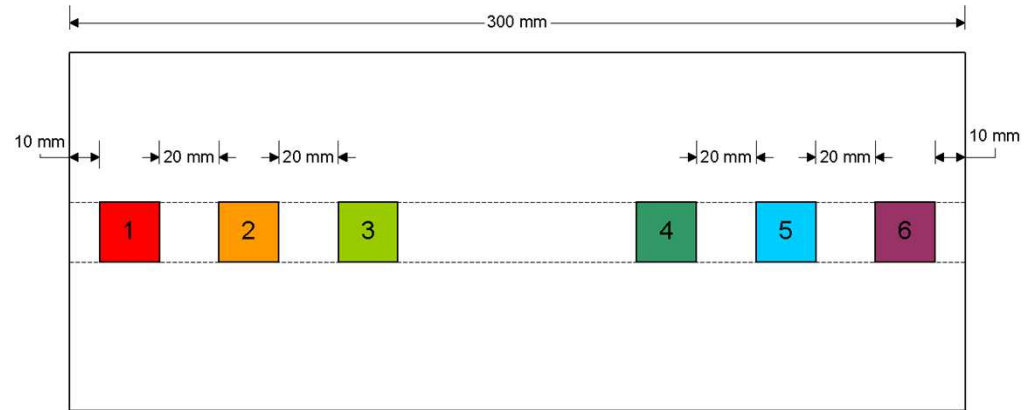
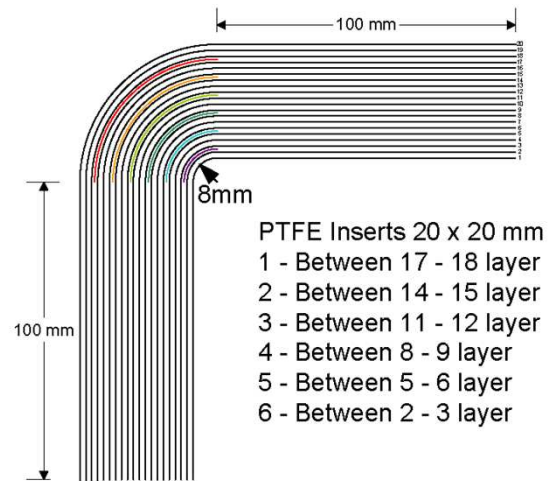


Semi-infinite Lösung: $0 < x < \infty$

$$T(x, t, d) = \frac{1}{2d} \cdot \left[\operatorname{erfc} \left(\frac{a-x}{2\sqrt{\alpha_{x,y}t}} \right) + \operatorname{erfc} \left(\frac{a+x}{2\sqrt{\alpha_{x,y}t}} \right) \right] \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left(-\frac{n^2\pi^2}{d^2} \alpha_z t \right) \right] \quad (1)$$

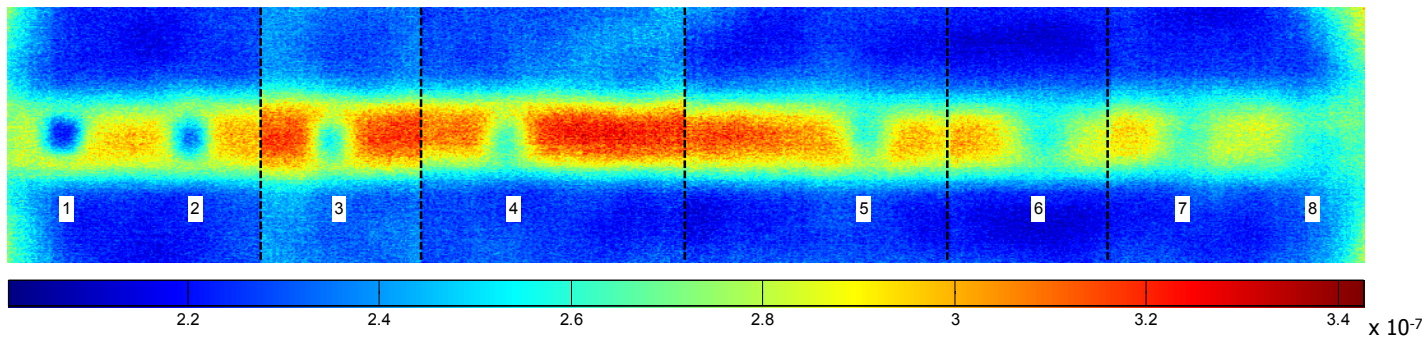


CFRP - test specimens



Qualitative Correction Method for Flaw Detection

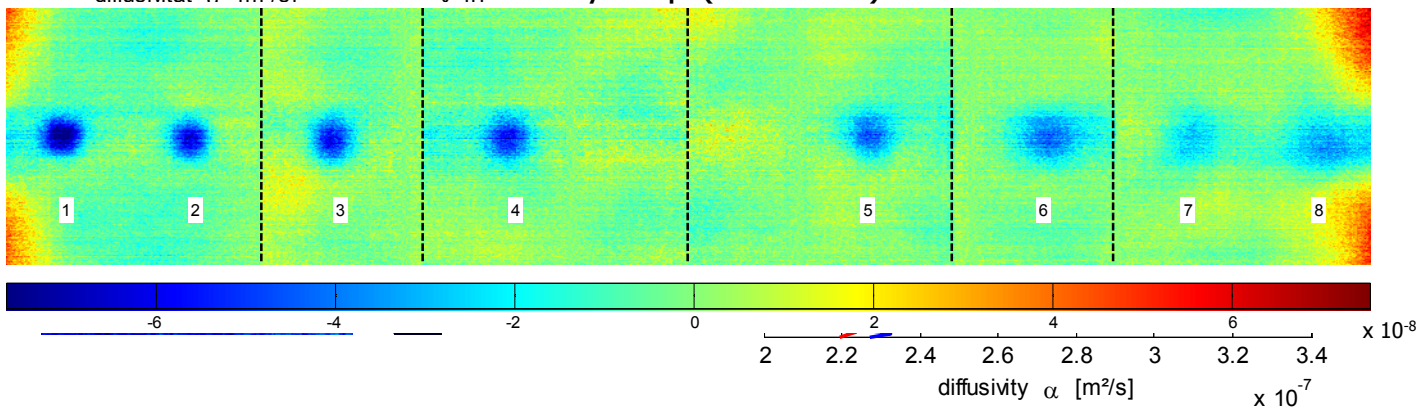
diffusivity map based on the assumption of a constant wall thickness (4 mm)



$$d = a - b = \Delta\alpha$$

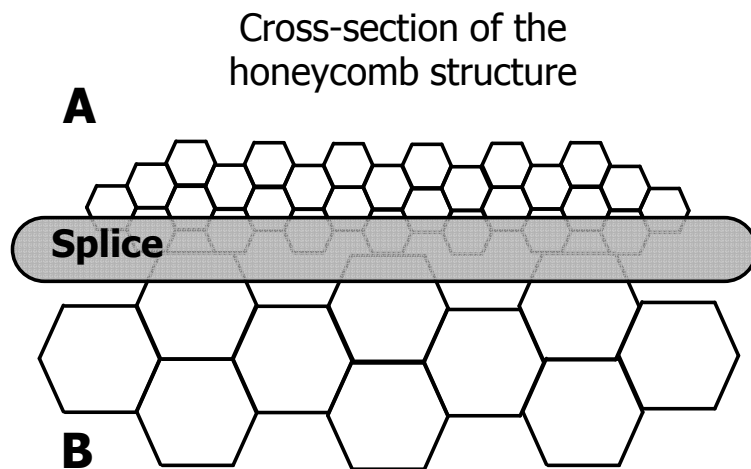
diffusivität α [m²/s]

diffusivity map (corrected)



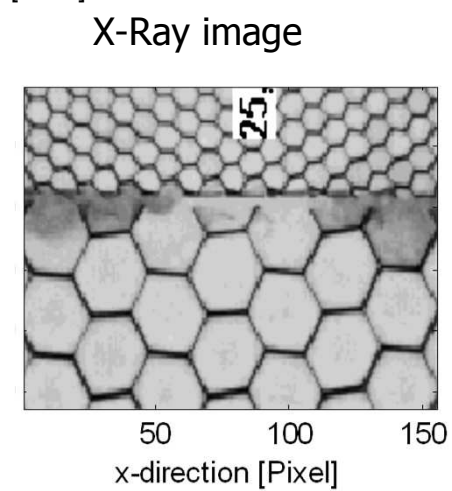
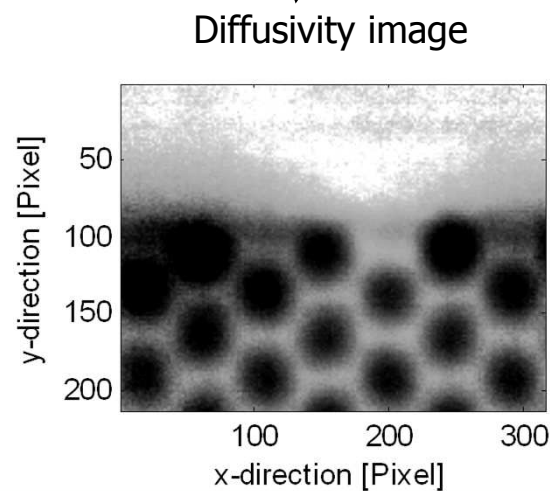
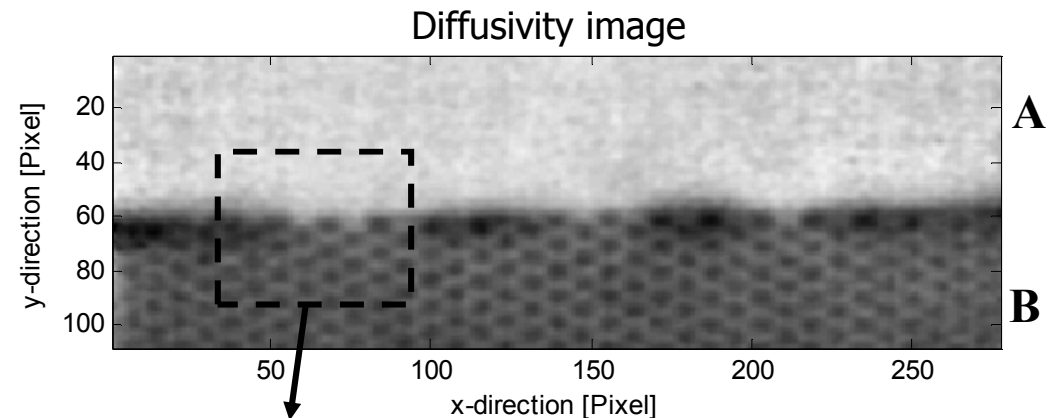
Bestimmung der Temperaturleitfähigkeit zum Nachweis von Verklebungsfehler

Splice defects in honeycomb structures Comparison: Diffusivity Imaging and X-Ray Tomography



Bonding of honeycomb structures with different cell size

Plate thickness: 25 mm !

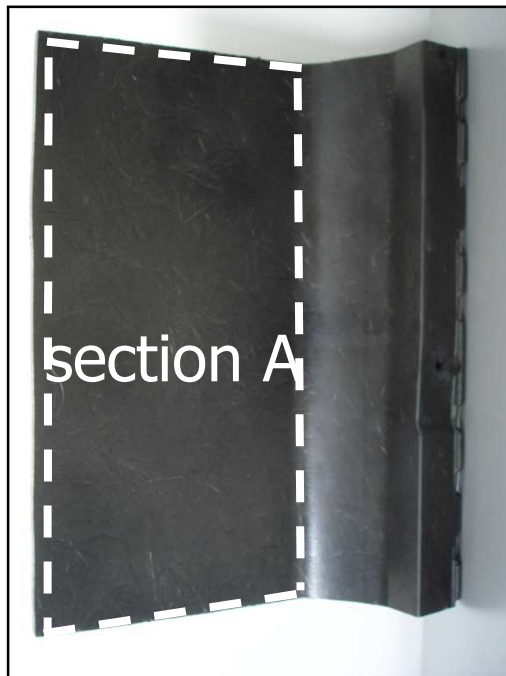


Bestimmung der Temperaturleitfähigkeit zur Bestimmung einer Glasfaserverteilung

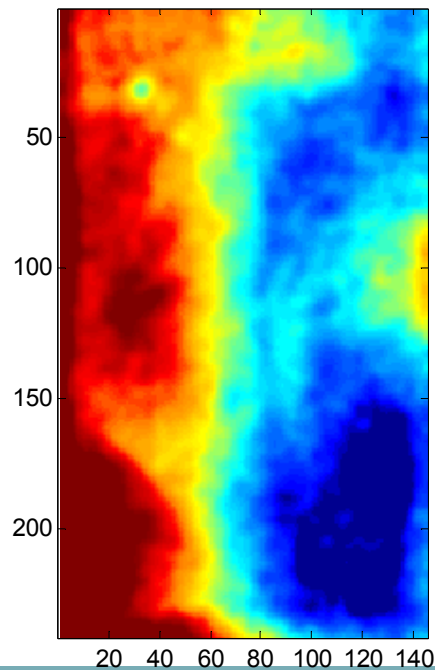
Glass fiber distribution of a car roof

Comparison: Diffusivity Imaging and 3D-Computed Tomography

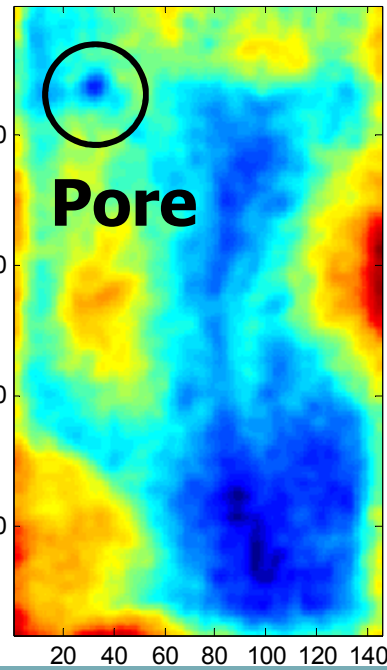
GFRP - Glass Fiber Reinforced Plastic



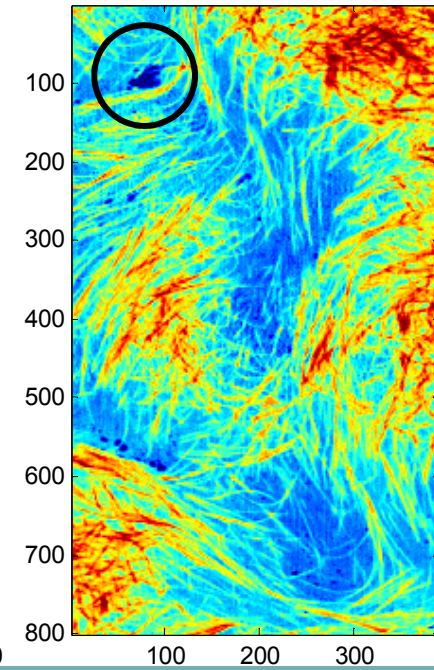
Diffusivity Image
UNCORRECTED



Diffusivity Image
CORRECTED

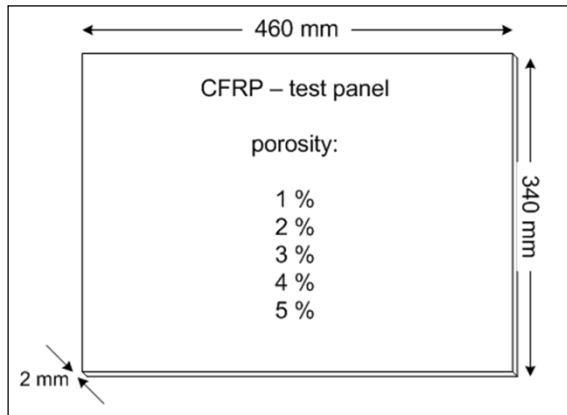


3D-Computed
Tomography
IMAGE

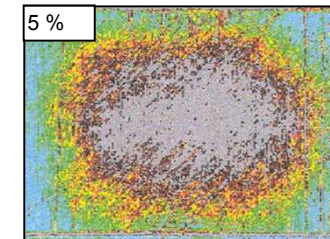
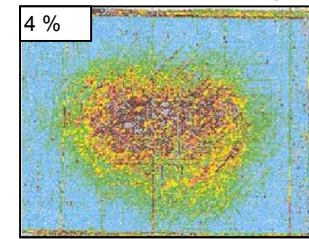
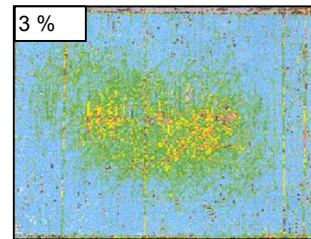
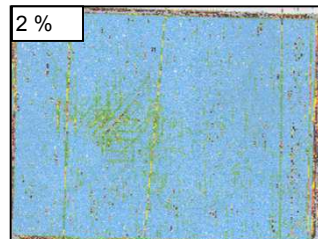
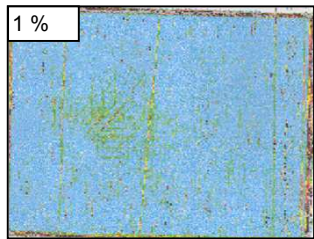
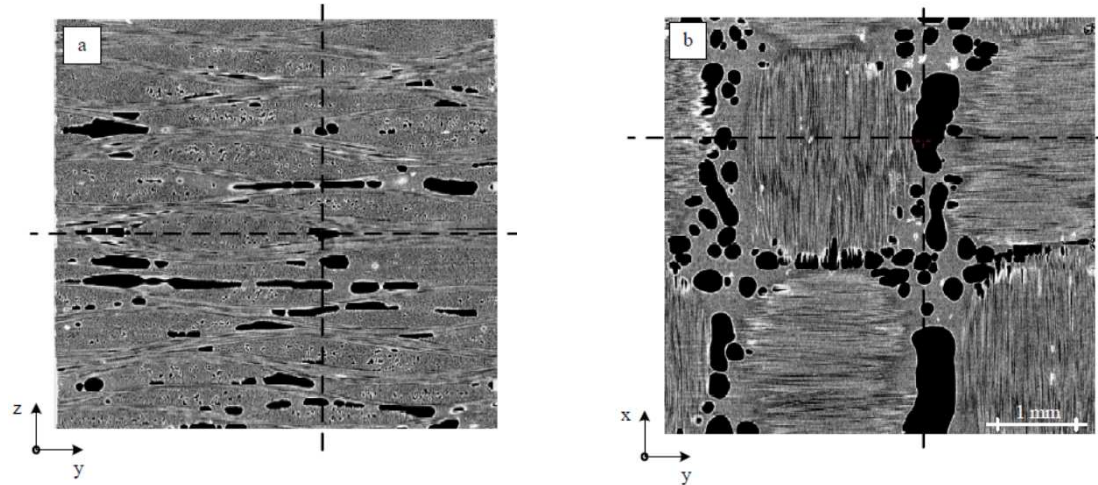


Anwendungen

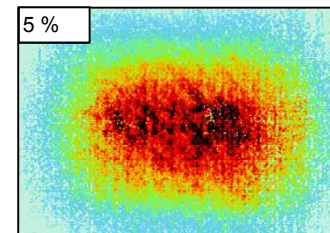
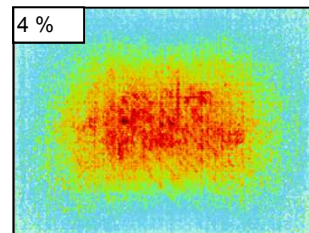
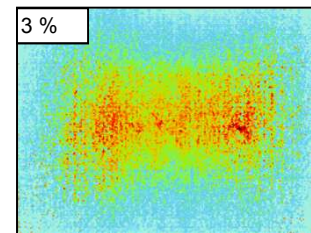
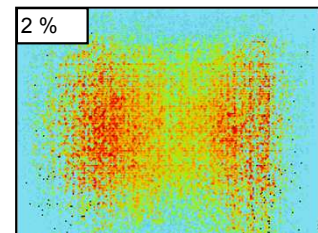
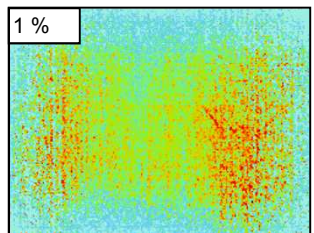
- Porositätsbestimmung in CFK - Bauteilen



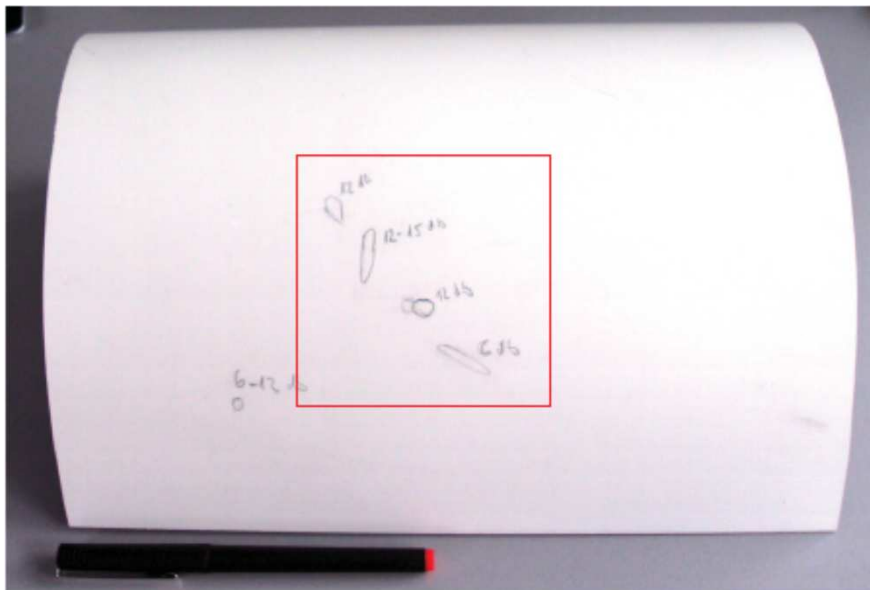
Ultrasonic C-scan images



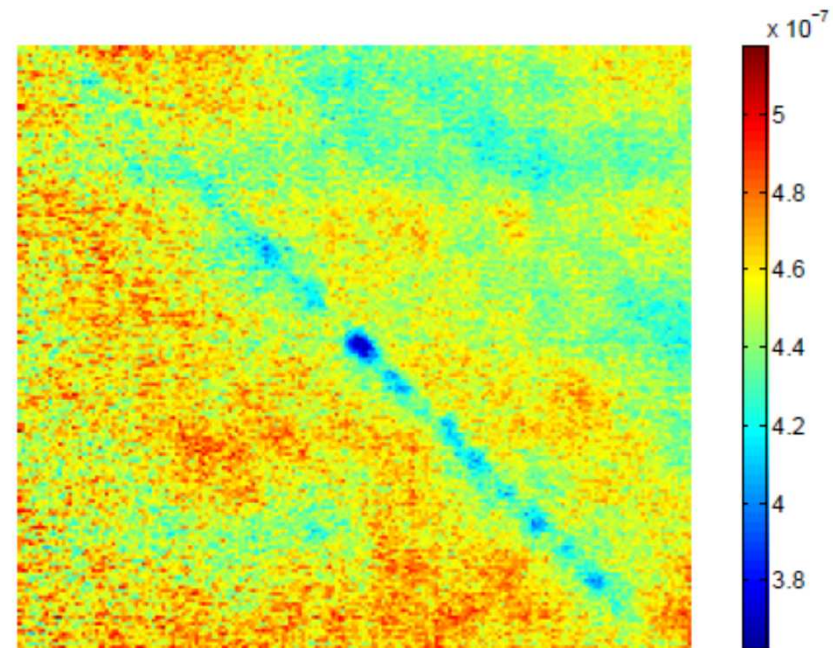
Active Thermography – Diffusivity images



Bestimmung von Porositäten in gekrümmten Bauteilen



(a) Curved CFRP specimen



(b) Thermal diffusivity image

3D – Computer Tomographie Messungen zur Bestimmung der Volumsporosität



phoenix|x-ray
Part of GE's Sensing &
Inspection Technologies business



Röhre:

180kV nanofocus Röhre

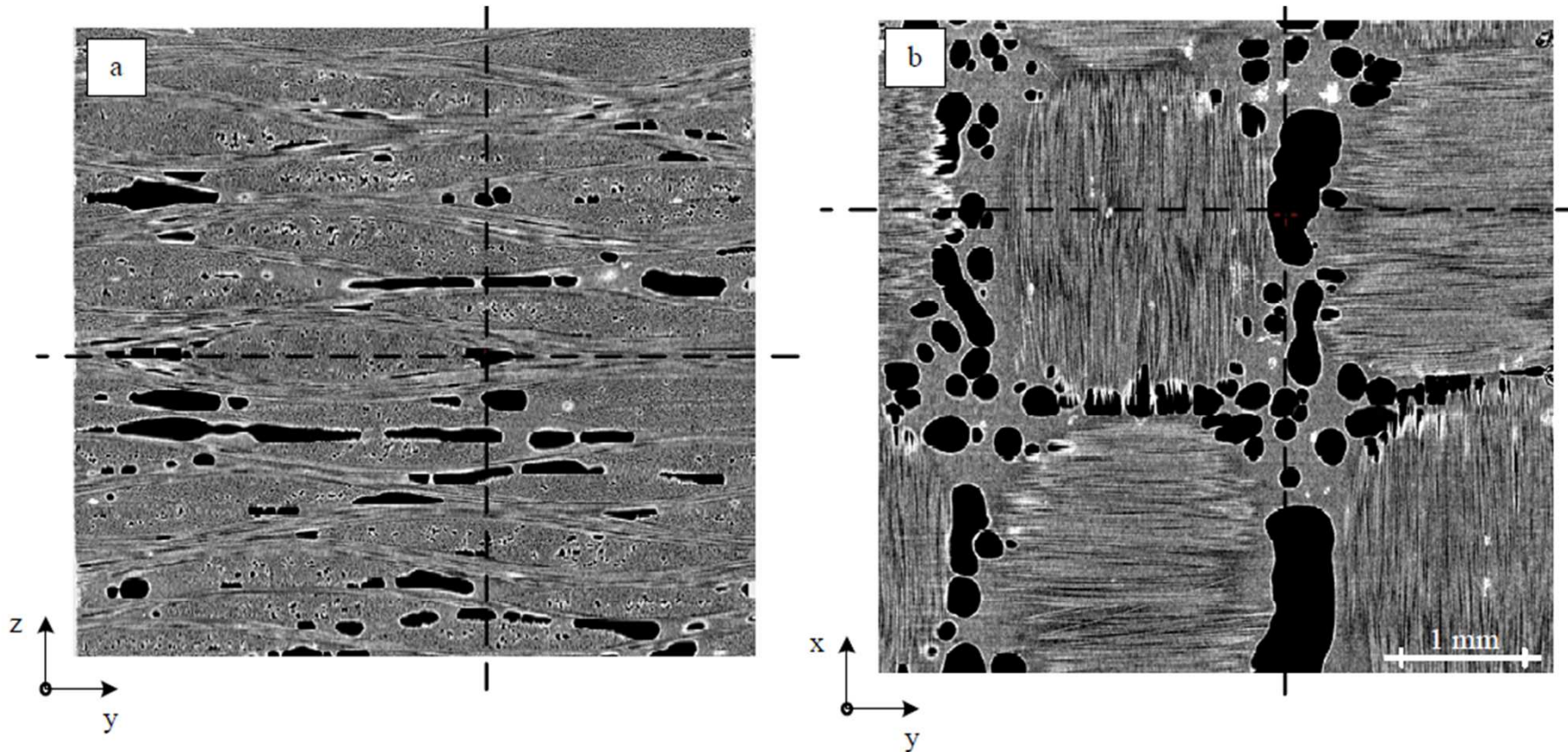
Max. Messauflösung:

Voxelgröße <0,5 μm

→ Auflösung [μm] ~ D [mm] / 2000

Anwendungen

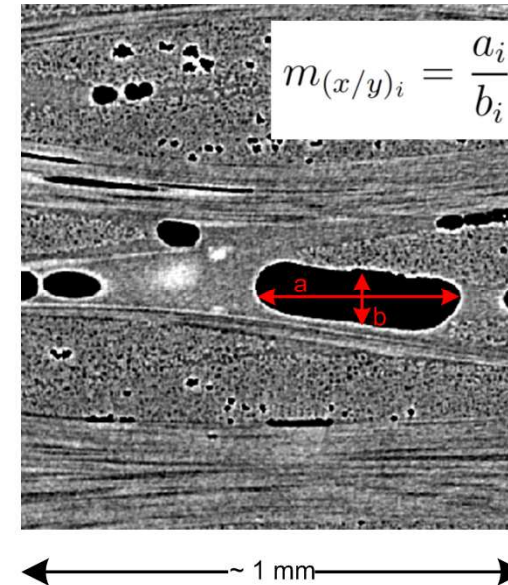
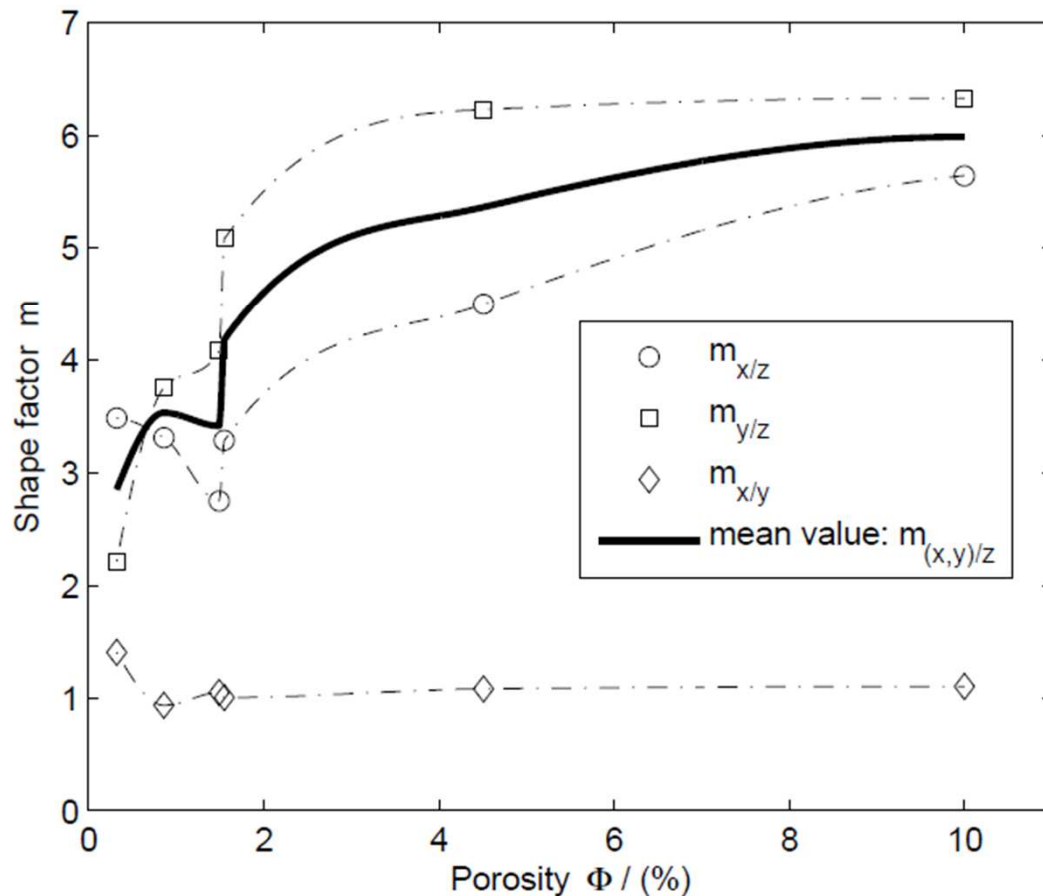
- CT Schnittbilder



The interlaminar shear strength decreases by about 7 % per 1 % porosity, up to a total porosity of 4 % ¹.

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Porenformen in PREPREG in Abhängigkeit der Volumsporosität

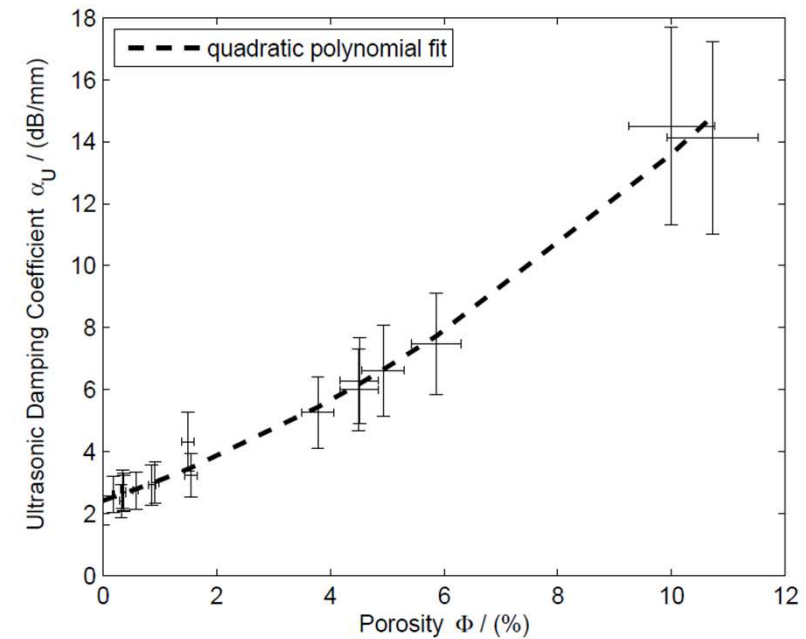
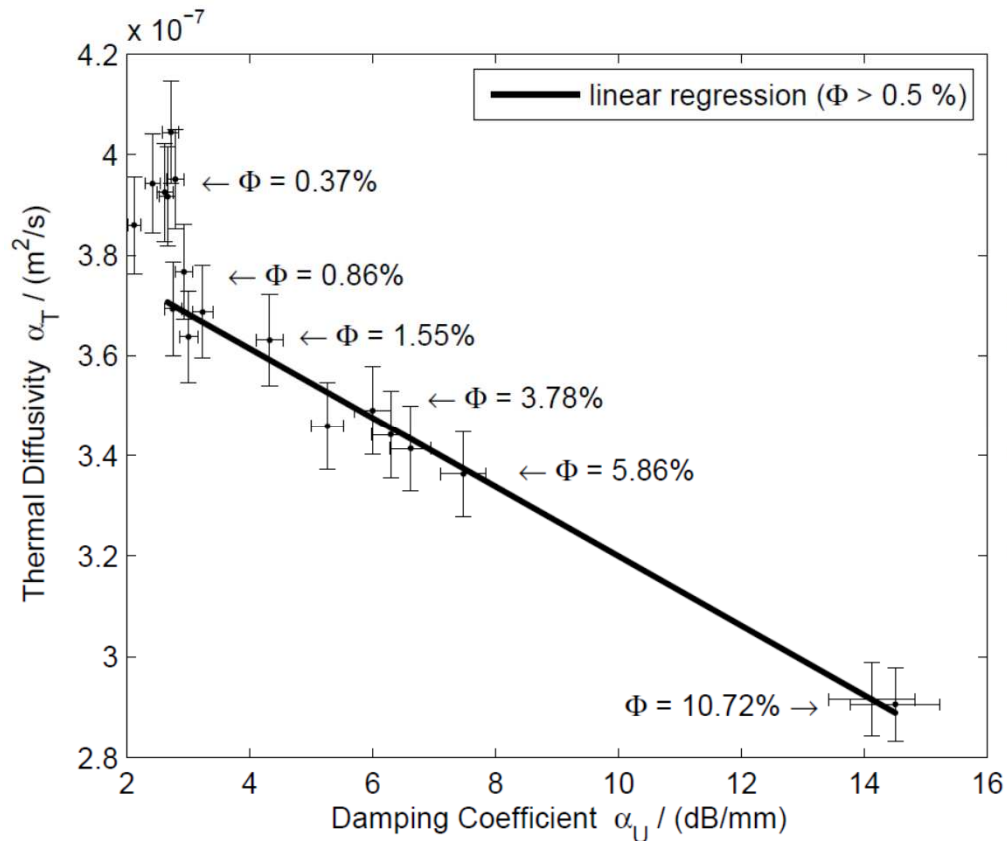


$$m = \sum_{i=1}^N \frac{V_i}{V_P} m_i$$

N ... numbers of pores
V ... volume of a pore

G. Mayr et al., Porosity determination in CFRP specimens by means of pulsed thermography combined with effective thermal diffusivity models, AIP Conference Proc. 2009; 29B: 1103 – 1110.

Vergleich Aktive Thermographie zu Ultraschall

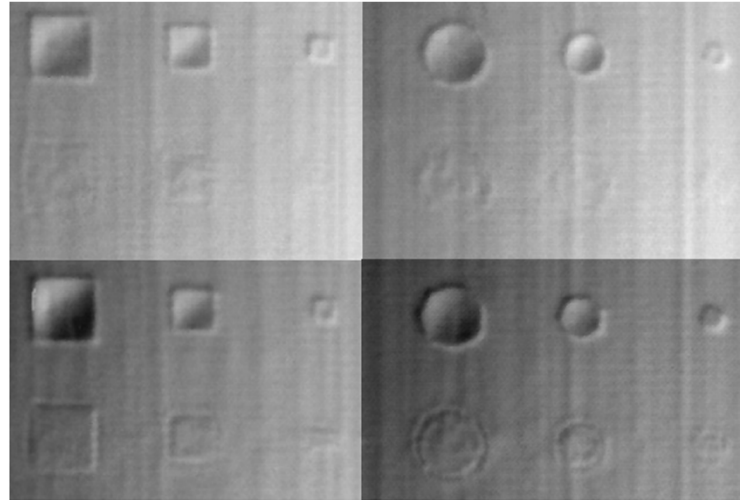
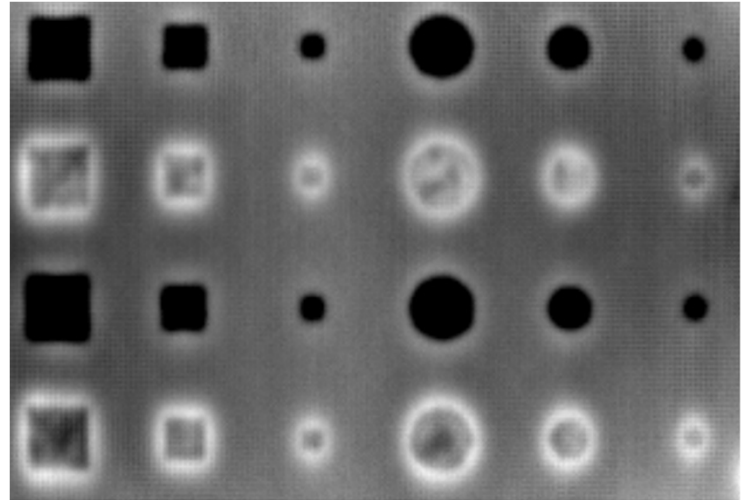


Pulsed Thermography: FLIR Thermacam PM695 ($\Delta T = 80$ mK, FPS = 25, 8 - 12 μm)
 Ultrasonic C-SCAN: (inspection frequency $f = 5$ MHz, probe diameter = 0.75"')

Vergleichsstudie

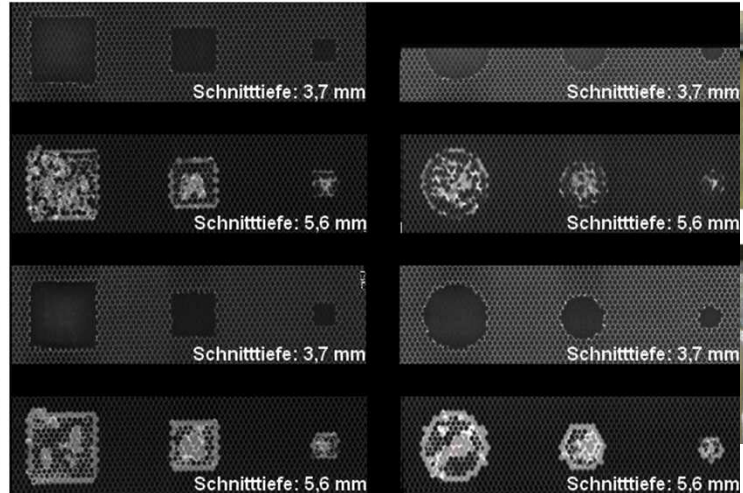
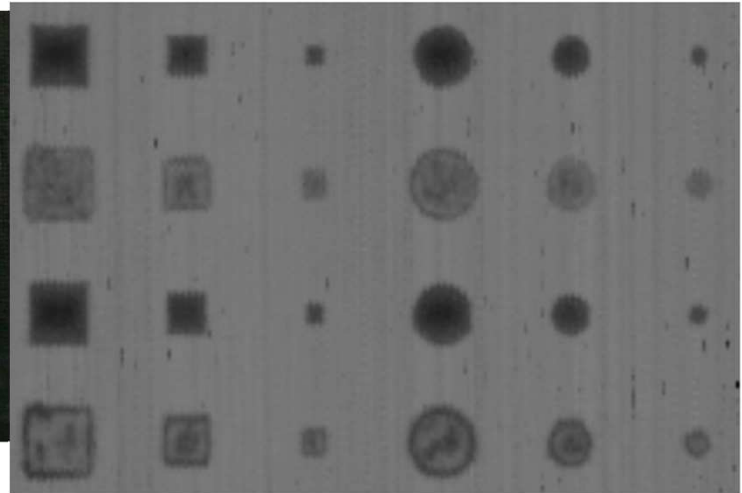
Sandwich-Bauteil (Alu - CFK)

Aktive Thermographie

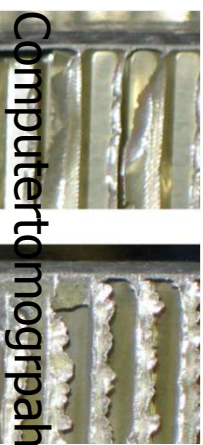


Digitale Shearographie

Ultraschall



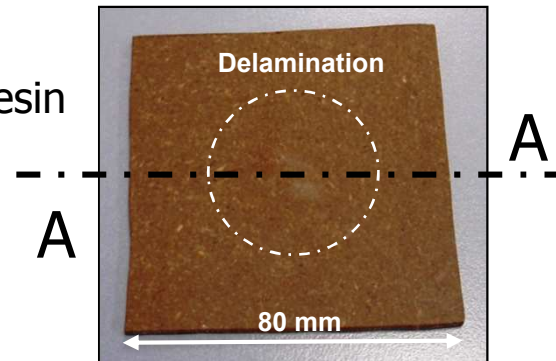
Computertomographie



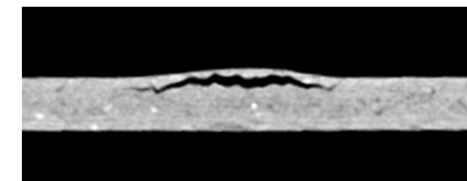
Delamination in a wood-plastic composite (WPC) panel

Components:
wood flour + melamine resin

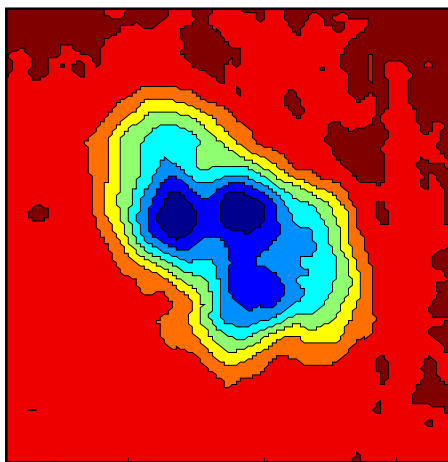
Applications:
automobile industry
furniture industry



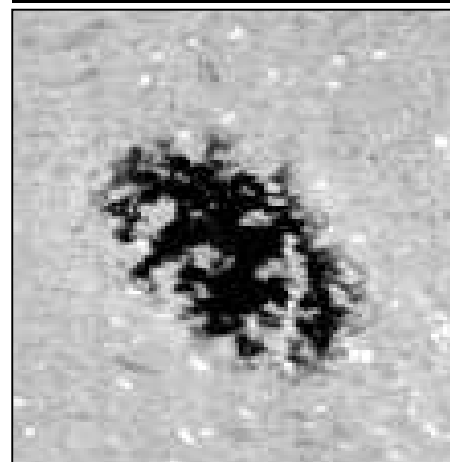
Section A-A



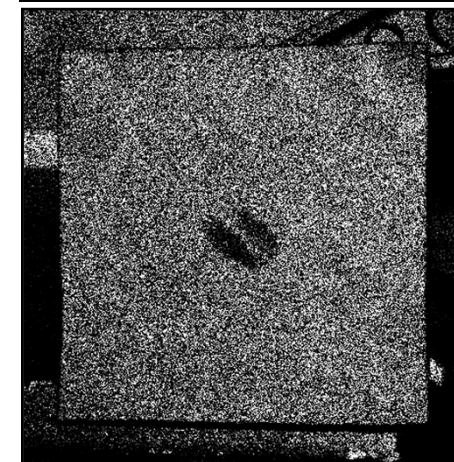
Active Thermography



Computed Tomography



Digital Shearography



Badewanne

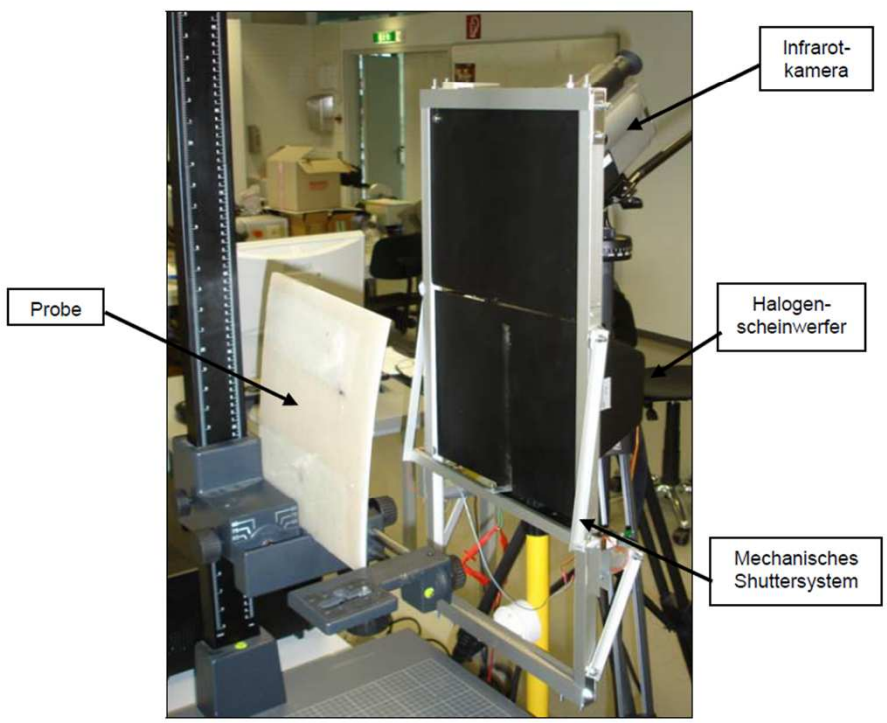
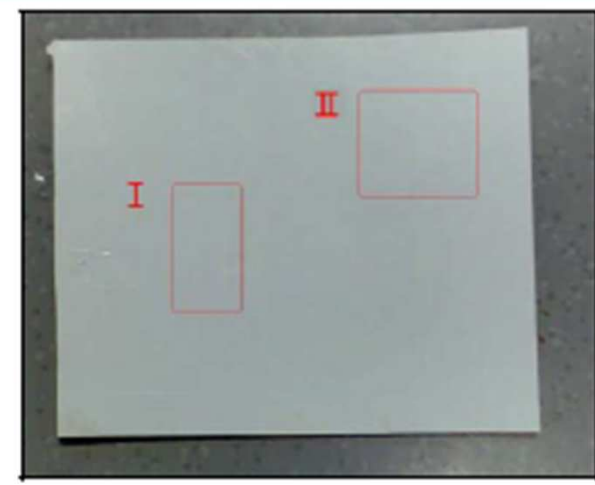


Abbildung 1- Aktive Thermographie Messaufbau

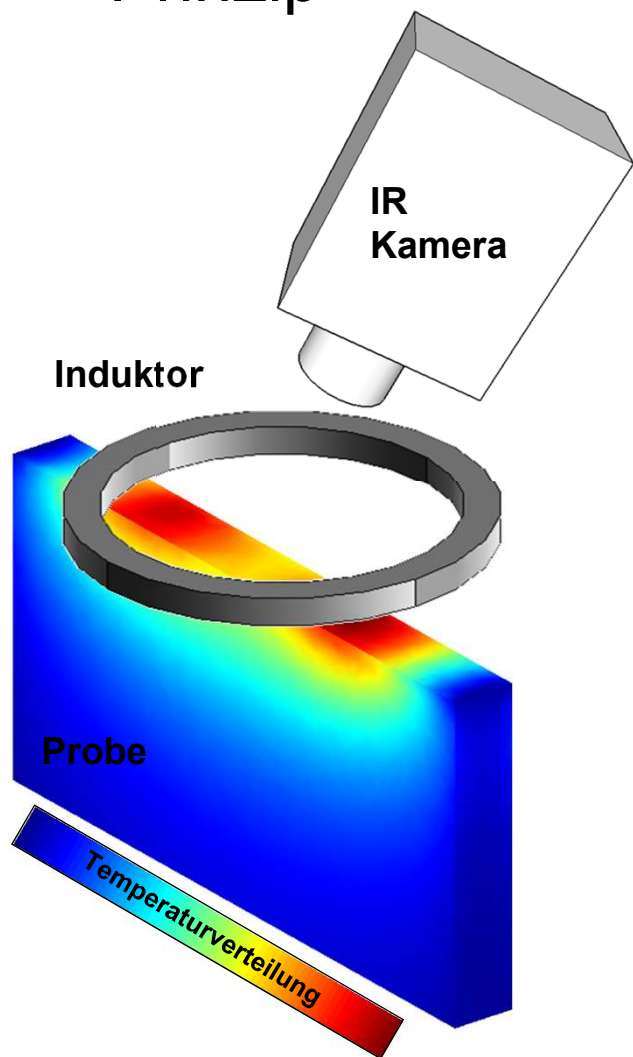


Aktive Thermographie	Sherographie
<p>Probe 1 - Fehlstelle I</p>	<p>Probe 1 - Fehlstelle I</p>
<p>Probe 1 - Fehlstelle II</p>	<p>Probe 1 - Fehlstelle II</p>

Abbildung 4 – Ergebnisbilder bei Probe 1

Induktionsthermographie

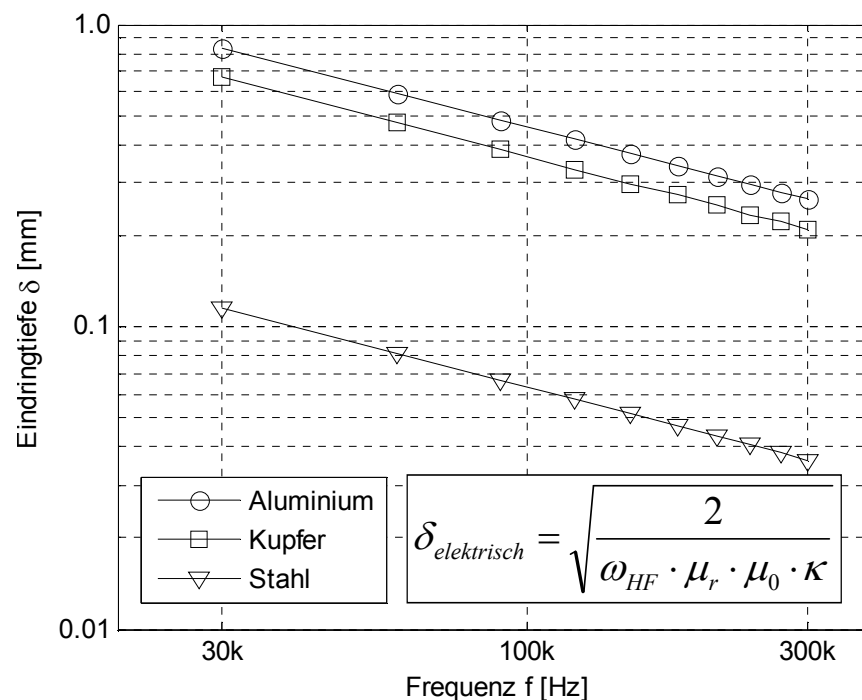
Prinzip



Entscheidende Faktoren:

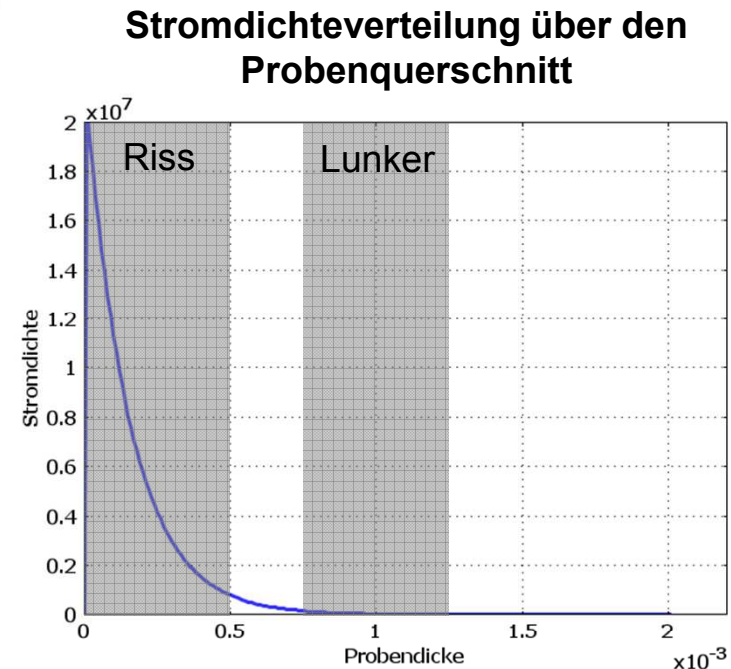
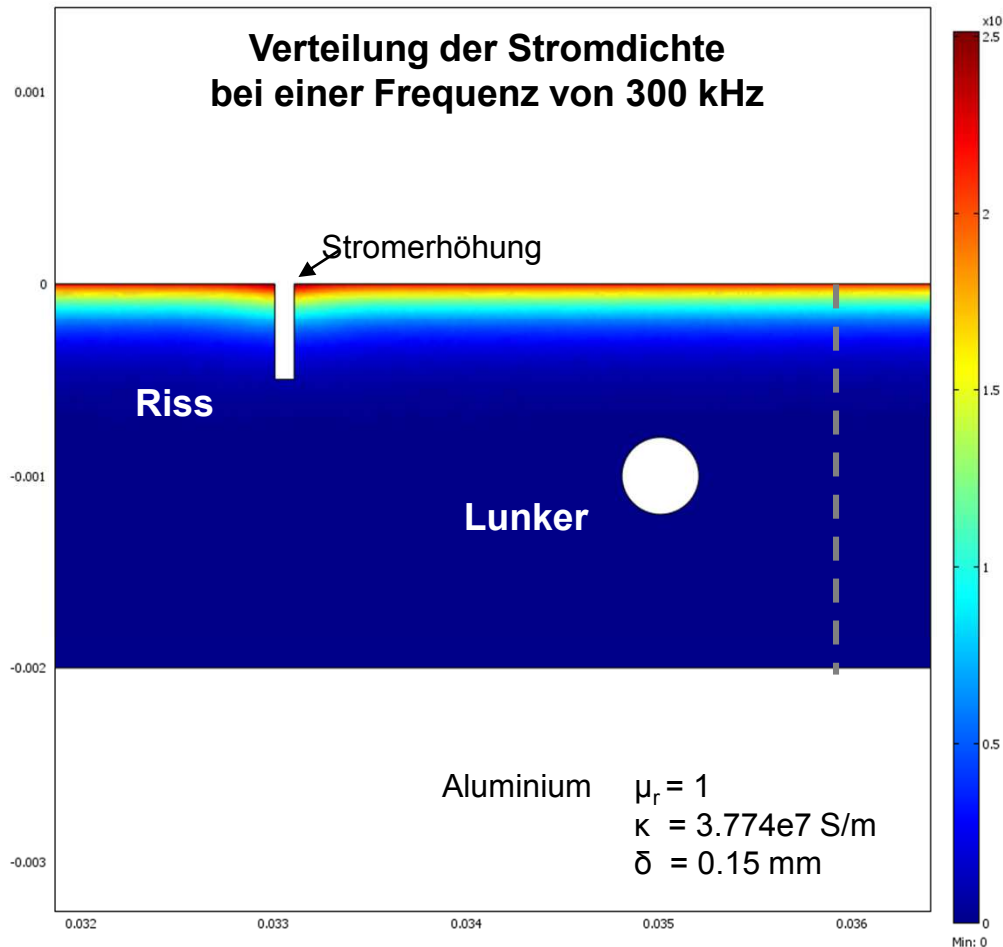
- Frequenz des magn. Wechselfeldes (30-300 kHz)
- Dauer und Form des Anregungspulses (Puls - Sinus)
- Abstand zwischen Induktor und Probe

Skineffekt:



Methoden

Unterscheidung aufgrund Fehlertiefe



- Direkte Fehlstellenanregung**
- Fehlertiefe < Skineindringtiefe
- Erzeugung von Wärmewellen**
- Fehlertiefe > Skineindringtiefe

Finite Element Methode FEM

Elektrische – thermische Wechselwirkung

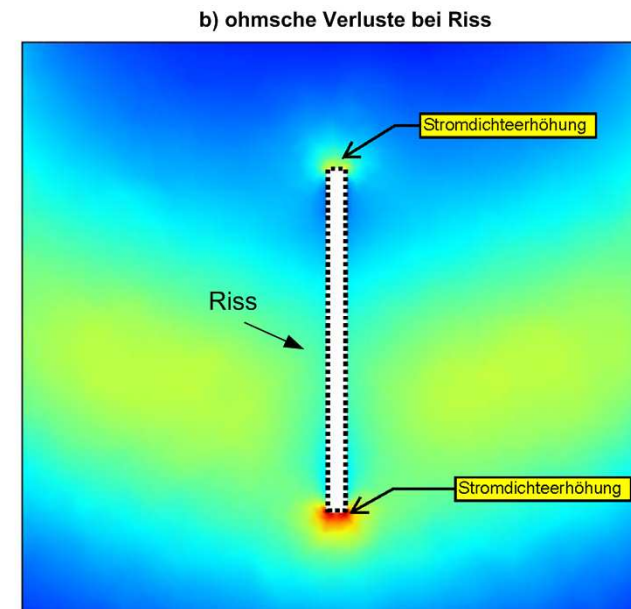
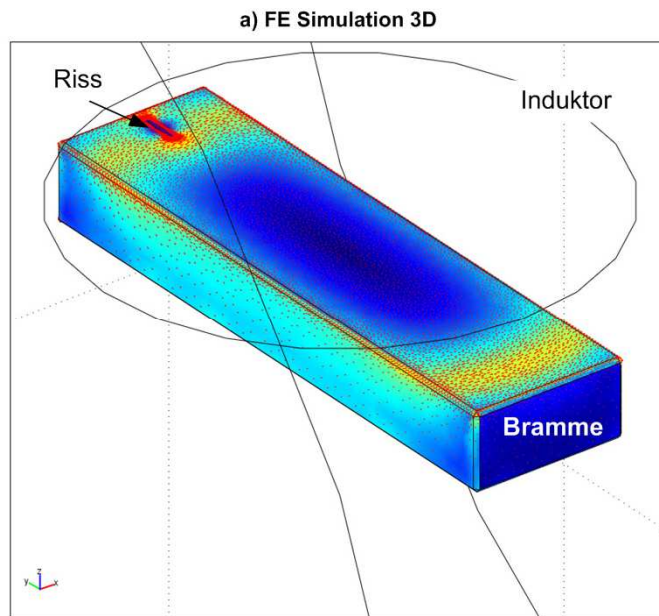
1. Elektrisch

2. Induktive Erwärmung

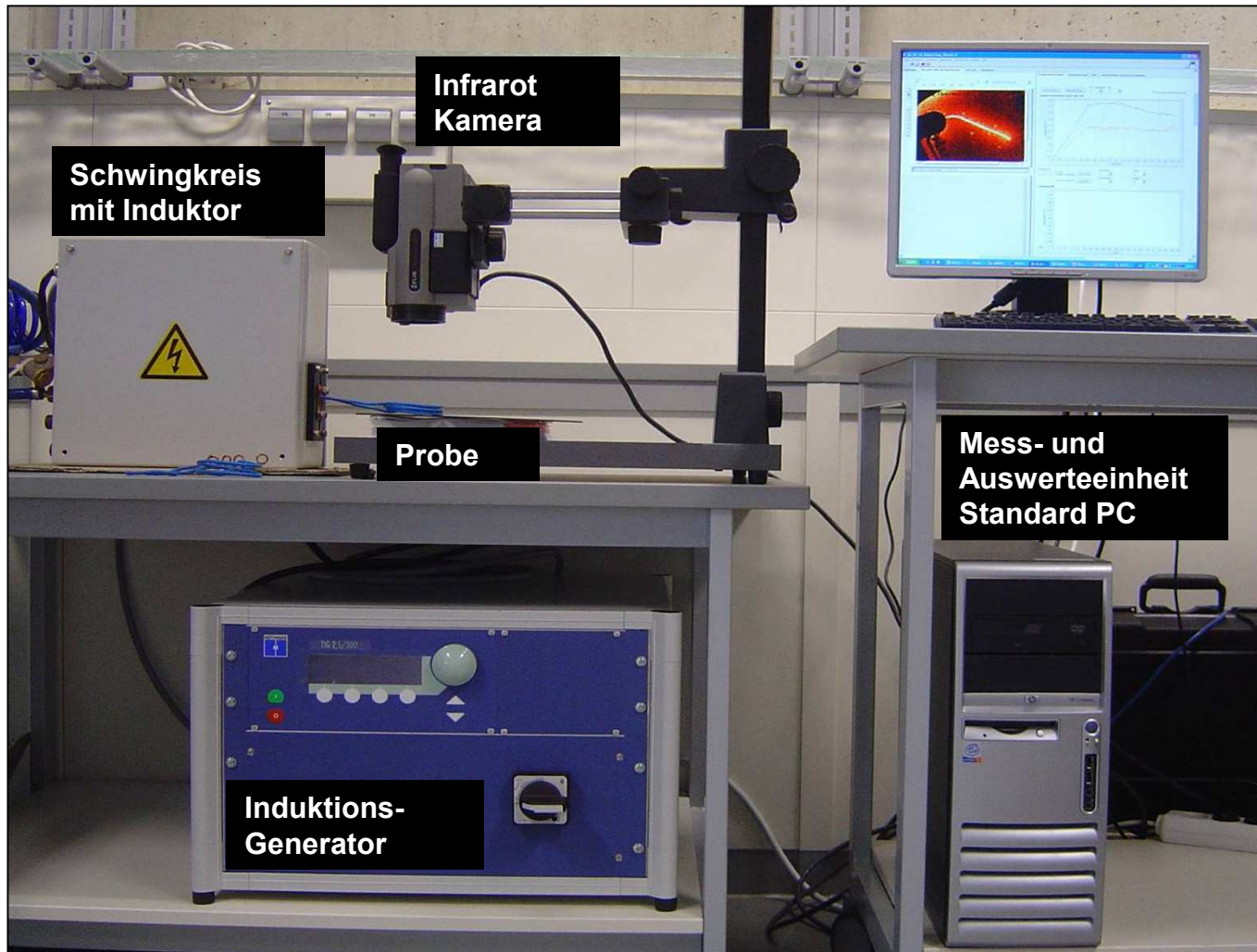
3. Thermisch

$$j\omega\sigma A + \nabla \times (\mu^{-1} \nabla \times A) = 0 \quad \rightarrow \quad Q = \frac{1}{2} \sigma |E|^2 \quad \rightarrow \quad \rho C \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = Q(T, A)$$

Anwendung: Riss in Stahlbramme



Messaufbau Induktionsthermographie



Ergebnisse Risserkennung bei Metallen

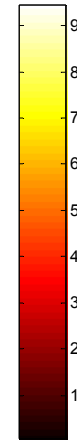
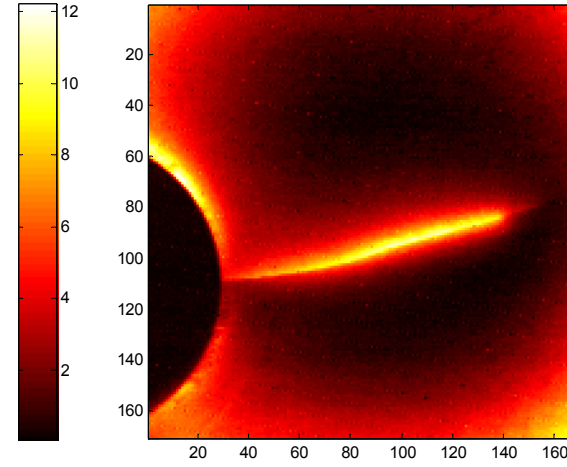
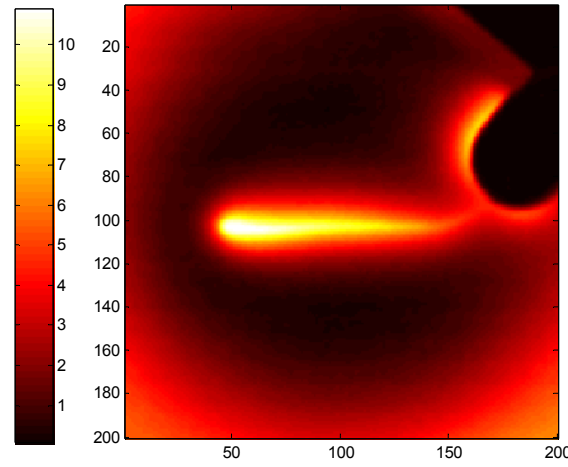
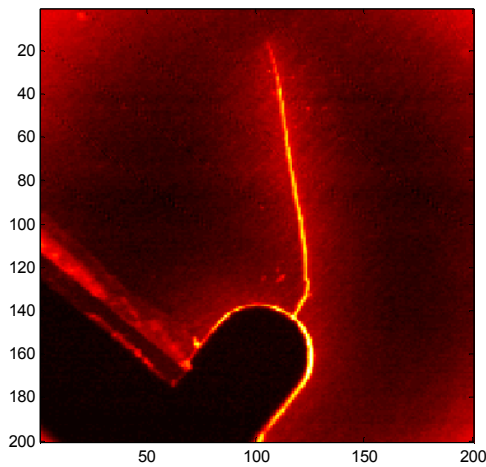
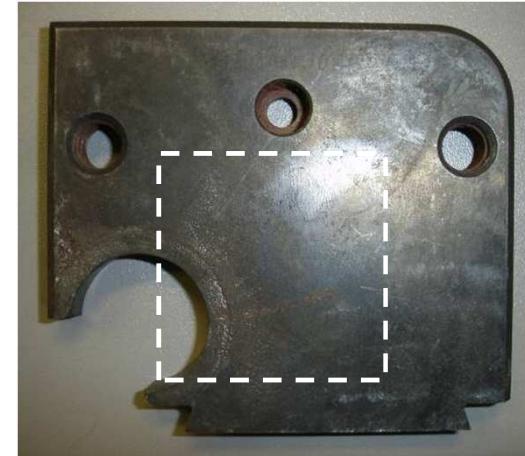
offener Riss - unlackiert



offener Riss - lackiert

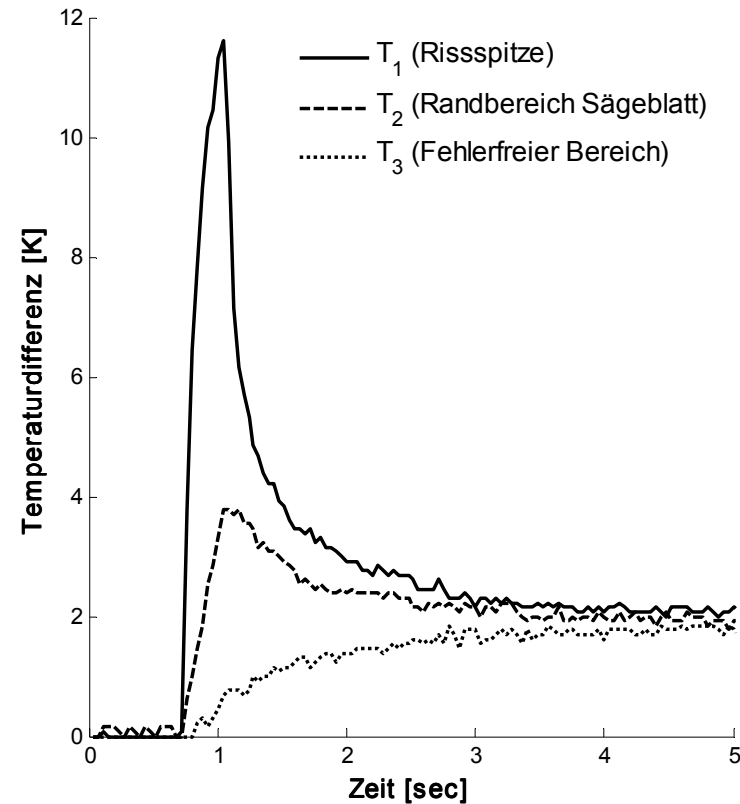
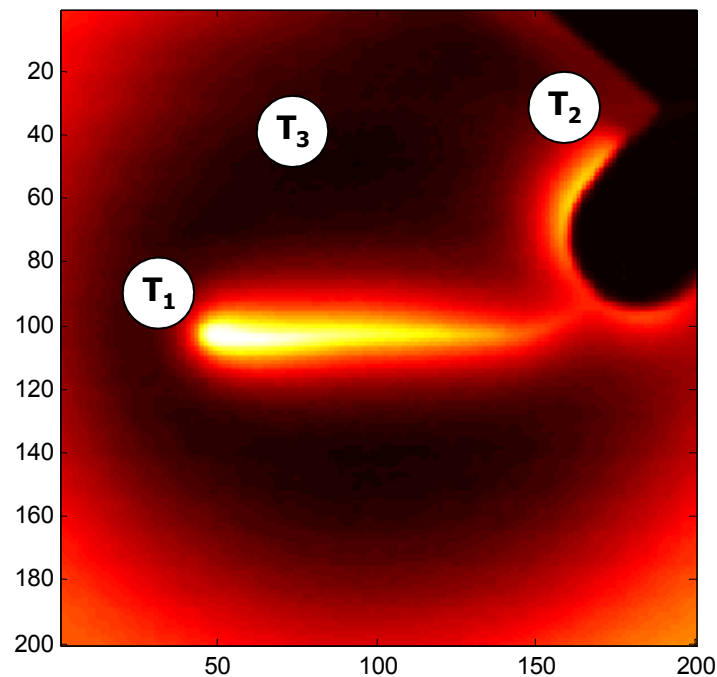


offener Riss - unlackiert



Risserkennung bei Metallen

Temperaturentwicklung an Probenoberfläche



Auswertung der Temperaturverläufe:

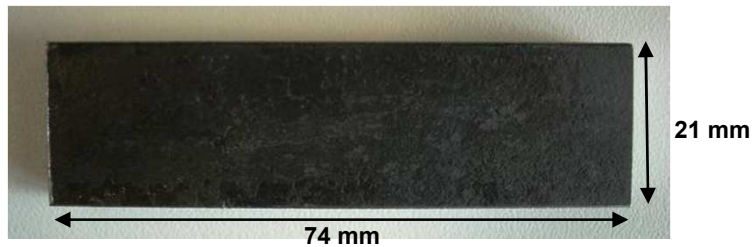
- Temperaturbild bei höchsten Kontrast (nach thermischer Anregung)
- Phasenbild: Fourier-Transformation der gemessenen Temperaturverläufe (Unterdrückung von Artefakten)

Randeffekte: Erwärmung im Randbereich der Probe → ist Unterscheidung möglich?

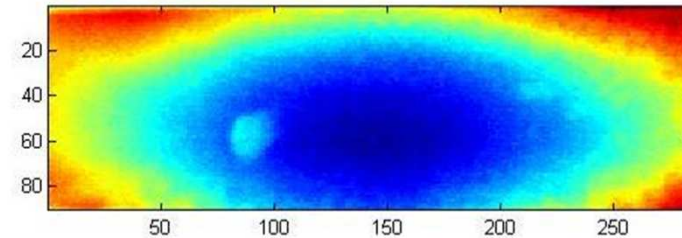
Bramme mit Walzfehler

Direkte Fehlstellenanregung mit Bildverarbeitung

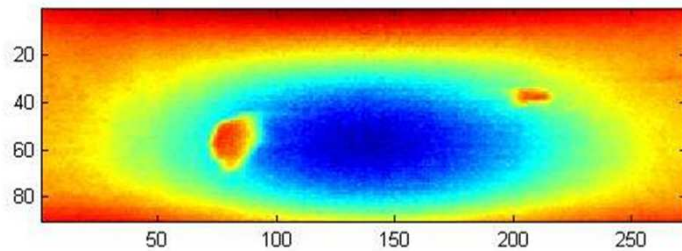
Teilstück der Bramme mit Walzfehler



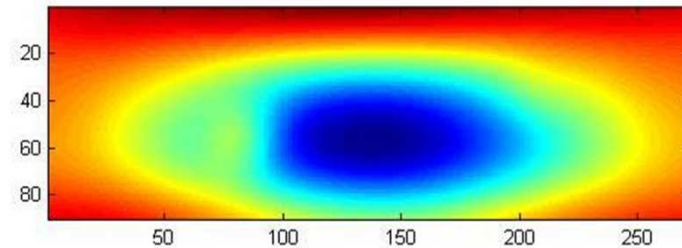
1. Thermogram nach Anregung (Puls mit 2 kW)



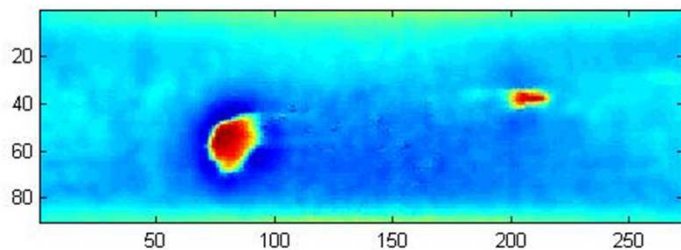
2. Berechnung des Phasenbildes



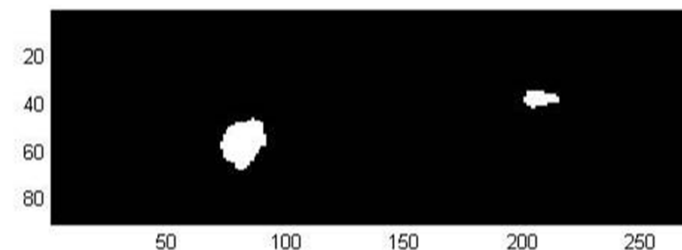
3. Berechnung des Hintergrundes



4. Differenzbild – Unterdrückung Störeffekte



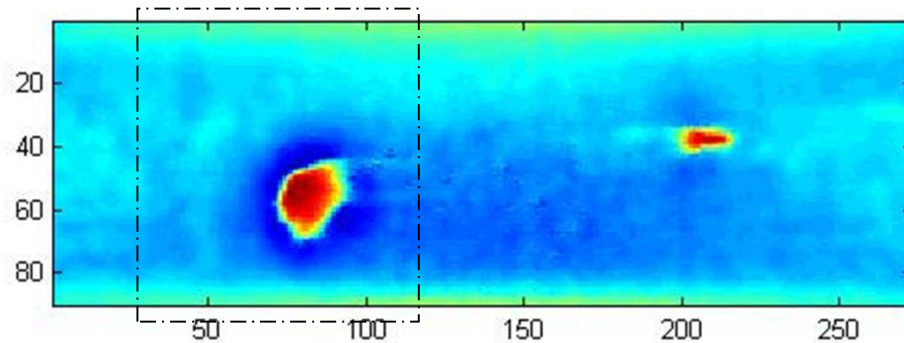
5. Binärbild → Automatisierung



Bramme mit Walzfehler

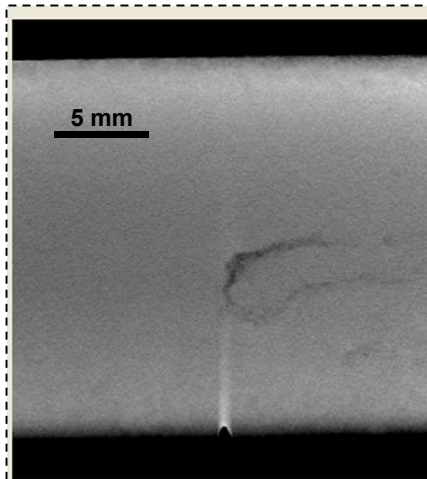
Vergleich mit 3D Computer Tomographie (3D CT)

Ergebnisbild der Induktionsthermographie

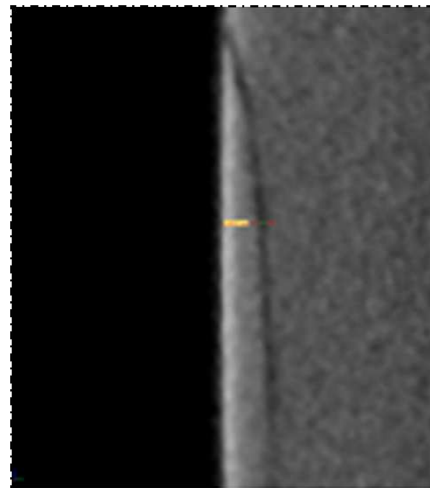


Vergleichsmessungen mit 3D CT

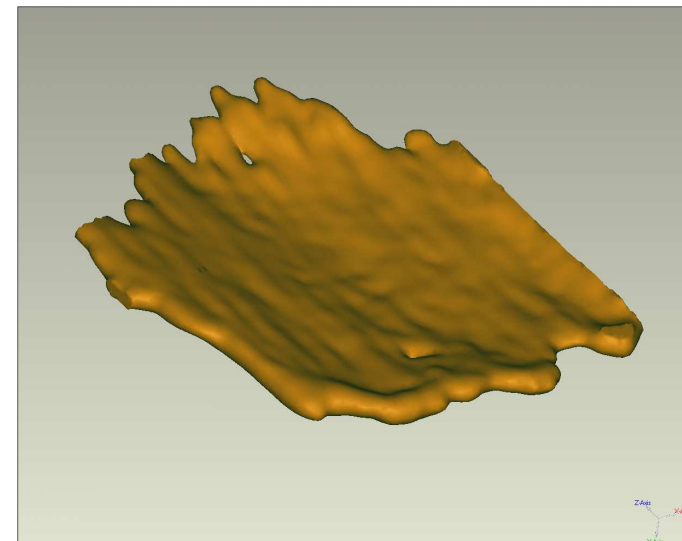
Draufsicht



Schnitt durch Probe



3D Darstellung der Fehlstelle



Schlussfolgerung:

Durch pfannenförmigen Ausbildung der Fehlstelle kann Wärme nicht abfließen → Großflächige Erwärmung der Fehlstelle

	OTvis	PTvis	UTvis	ITvis
Fügeverbindungen				
Klebverbindungen	o	o	+	+
Schraubverbindungen	+	o	o	o
Nietverbindungen	o	o	+	o
Punkt-/Laserschweißungen	o	o	+	o
Clinchverbindungen	o	o	+	o
Schichten				
Lackdicke	o	+		
Haftung	o	+		
Faserverbundwerkstoffe				
Trennfolien	+	+		o
Schlagschäden	+	+	+	o
Delaminationen	o	o	+	o
Porosität	o	o		o
Faserkeramik				
Delaminationen	+	+	o	o
Risse			+	o
Inhomogenitäten	+	+		
Porosität	+	+		
Metalle				
Risse				o
Lunker			+	
Passungen			o	
			+	
Faser-Metall-Lamine				
Schlagschäden	o	o	+	o
Delaminationen	o	o	+	o

+ gut geeignet
o bedingt geeignet

Danksagung

Dieses Projekt wurde vom
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