High-Resolution X-Ray CT for 3D Failure Analysis and Metrology

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Area Sales Manager
GE phoenix|x-ray, Wunstorf/D
Outline

• GE phoenix|x-ray product line
• Principles of high-resolution X-ray CT
• CT for material science and failure analysis
• CT for 3D dimensional measurements
• Recent advances of high-resolution CT
GE Measurement & Control Solutions

Radiography Product Line

phoenix|x-ray
GE: A company with global reach

- 125+ years
- >300,000+ employees
- 2009 $157B Rev
- In >100 countries

Measurement & Control Solutions (MCS)
- 7,000 employees
- 60 countries
- 2010 $2B Rev
MCS Product Lines

**Inspection Technologies**
- Radiography, Film, CT, CR/DR,
- Ultrasonic, Eddy current
- Remote Visual
- Software

**Bently Nevada**
- Monitors
- Field devices
- Tech support
- System 1® software
- Machinery diagnostics

**Measurement Solutions**
- Flow
- Gas and Moisture
- Pressure

**Control Solutions**
- Retrofits and parts
- EX2100
- Mark IV, V, VI, Vle
- OC 4000 DCS
- Software upgrades

**Advanced Sensors**
- Temperature
- Pressure (MEMS)
- Infrared
- Validation

**Reuter Stokes**
- Nuclear instrumentation
- Flame detectors
- He-3 detectors
- Scintillations sensors
- Mechanical assemblies
The MCS Radiography Product Range

Film & Equipment
- Complete range of Agfa X-ray films
- State-of-the-art processing equipment
- Film Scanning

Digital Radiography
- Computed Radiography
- Reusable Phosphor plates
- Digital Detector Arrays
- Image processing and storage software

X-ray Sources
- Portable and mobile X-ray systems
- Stationary systems
- Micro- and nanofocus tubes and generators

2D Systems
- Stationary manual and automated digital X-ray inspection systems
- Fully automated defect recognition software

3D CT
- 3D industrial failure analysis with CT
- 3D CT systems for materials research, bio- and geosciences

3D Metrology
- Reproducible 3D coordinate measurement with X-ray CT
- Fully automated CT data acquisition and volume processing

Electronics Inspection
- 2D micro- and nano-focus X-ray
- Software for high resolution electronics inspection
- CAD-based programming

X-ray Diffraction
- Quantitative and qualitative phase analysis, structure and tension measurement
- Single crystal materials orientation analysis

phoenix|x-ray
Product line phoenix|x-ray

- A leading manufacturer of high-resolution 2D X-ray inspection and 3D computed tomography systems for non-destructive testing and 3D metrology

- Founded 1999 in Wunstorf / Germany

- 2007 acquired by GE Sensing & Inspection Technologies

- More than 1800 installations

- Development and production in Germany
X-ray Electronics Inspection

- Leading edge 180 kV micro- and nanofocus X-ray tube technology
- Live imaging with GE’s unique DXR digital detector technology
- Efficient CAD programming with minimized setup time
- Easy and fully automated X-ray inspection of PCB assemblies
- Live 3D CAD data and inspection result overlay in the X-ray live image
- Extremely high defect coverage with high magnification and repeatability

- phoenix inspector
- phoenix xaminer
- phoenix microme|x
- phoenix nanome|x
High resolution Computed Tomography

• Non destructive 3D defect analysis for quality assurance and production control
  – Precise quantitative analysis of position, size and frequency of defects
  – Multi-positional 2D cross-section planes or 3D volume view

• Wide range of nanoCT® materials sciences applications
  – Leading 180 kV high power nanofocus X-ray technology
  – Closest to synchrotron CT in many application fields

• phoenix v|tome|x s / m / L

• phoenix nanotom s / m
3D Metrology with CT

• **CT precision** comparable to tactile Coordinate Measurement Machines (CMMs)
  - Reverse Engineering
  - Nominal/actual comparison
  - Dimensional measurement (e.g. internal wall thickness, distances, holes, radiuses, angles etc.)

• **Click & measure|CT with phoenix datos 2.0**
  - Automated execution of CT scan, reconstruction, analysis process and generation of first article inspection reports within one hour
Principles of high-resolution X-ray computed tomography
Principle of operation

V.E. Cosslett
W.C. Nixon
Cambridge 1951
“X-ray Shadow Microscope”
Nature 10 (1951) S.24 ff.

The X-ray shadow microscope
X-ray tubes

Microfocus vs. nanofocus®
X-ray tubes
Directional - Transmission

Transmission Target

Directional Target

Magnetic Lens
Target

higher magnification

higher power

Electron Beam
X-rays
Resolution

Focal Spot size influence:

Ø 2.5 µm

Ø 1.5 µm

Ø 0.8 µm

2 µm bars

2 µm bars

0.6 µm bars
Principle of computed tomography

Acquisition: cone beam

of 2D projections under step-by-step rotation

steps < 1°
Principle of computed tomography

Acquisition: fan beam

of line projections under step-by-step Rotation and shift steps< 1°
Principle of CT: Reconstruction Method

Example: spark plug

- Projection
- Inversion
- Log + filter
- Line profile
- Back-projection

Acquisition of 600 projections

600 back projections

3D visualisation
Principle of Operation: CT resolution

Three contributions from apparatus:

- voxel size $V = \frac{P}{M}$
- focal spot size $F$
- mechanics

The focal spot size $F$ is the ultimate limit of resolution.
Benefits of Computed Tomography
Example: Al Casting

Microfocus 2D X-ray image

Microfocus 3D CT dataset
X-ray CT systems
CT for material science and failure analysis
Glas fibre reinforced material

2D X-ray image

- 2D: Only the average density is visible
- 2D: Voids would be visible
Glass fibres with particles

- Orientation and distribution of the 10 µm thin fibers
- Accumulations of the mineral filling material
Carbon fibre composites

CT results

- Impacted carbon fibre composite plates
- Impacted carbon fibre composite plates
Detection of imperfections, such as shrinkage, cracks, inclusions
• Classification of void size in colours
Cylinder head

3 Cylinder-motor

450 kV Multiline Scan

0.14 mm voxel size (isotrop!)

Typical tasks
• Void detection, wall thickness analysis, metrology
• Defect analysis (voids).
BGA/CSP solder joints

3D movie

- 3D: wetting conditions and void positions are visible, lead phases are visible
- Solder joints with 400 µm diameter
Slice through the 3D volume of a shell limestone with microfossils (Ø 0.7 mm)

Courtesy of O. Rozenbaum, ISTO France

$V_x = 1.2 \mu m$

- Zoom into a tomographic slice to measure the wall thickness (~3µm) of a small ammonite
Virtual flight through the 3D volume of a shell limestone with microfossils (Ø 1.8 mm)

Courtesy of O. Rozenbaum, ISTO France

\[ V_x = 1.25 \mu \text{m} \]

- Movie: Flying around the sample, slicing and fading out
Hoverfly

35 kV
Molybdenum target

• 3 µm voxelsize
• even eye facet structures are clearly visible
GE Measurement & Control Solutions

3D Metrology with CT
Metrology

Process flow

1. CT Volume data
2. Surface
3. CAD Data
4. Alignment
5. Comparison / Measurements
Metrology

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Process flow

1. CT Volume data
2. Surface
3. CAD Data
4. Alignment
5. Comparison, Measurements

+300µm above CAD

-300µm below CAD

10.045 mm
Al casting: CT vs. CMM

CT system:
phoenix v\textcompwordmark{tome}\textcompwordmark{x} m 300
in air conditioned environment

Al Cylinderhead model by
ACTech GmbH, Germany

Reference system:
Hexagon Metrology/Leitz PMM 12106
in certified measurement room class 1

Comparison of ~20 features
distances, diameters
## Al Casting: distances comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>tactile DKD value</th>
<th>CT value</th>
<th>Dev CT-tactile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Z09A-Z09B-A</td>
<td>64.9993</td>
<td>65.0041</td>
<td>0.004</td>
</tr>
<tr>
<td>2. Z09A-Z10A-A</td>
<td>20.0094</td>
<td>20.0056</td>
<td>-0.004</td>
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<tr>
<td>3. Z09B-Z10A-A</td>
<td>68.0055</td>
<td>68.0088</td>
<td>0.003</td>
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<tr>
<td>4. Z13A-Z13B-A</td>
<td>88.4336</td>
<td>88.4332</td>
<td>0.000</td>
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<tr>
<td>5. Z10A-Z13B-A</td>
<td>100.6552</td>
<td>100.6476</td>
<td>-0.007</td>
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</tbody>
</table>
## Al Casting: diameter comparison

### Diameters

<table>
<thead>
<tr>
<th>Feature</th>
<th>tactile DKD value</th>
<th>CT value</th>
<th>Dev CT-tactile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Z09A-DM</td>
<td>3,5963</td>
<td>3,5956</td>
<td>-0,001</td>
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<tr>
<td>2. Z09B-DM</td>
<td>3,5974</td>
<td>3,5952</td>
<td>-0,002</td>
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<tr>
<td>3. Z10A-DM</td>
<td>3,5962</td>
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<td>4. Z10B-DM</td>
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<tr>
<td>6. Z13B-DM</td>
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<td>6,0197</td>
<td>0,003</td>
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<td>7. Z14-DM</td>
<td>7,0033</td>
<td>7,0083</td>
<td>0,004</td>
</tr>
</tbody>
</table>
Recent advances of high-resolution CT
CT for turbine blade inspection
UNIPOLAR 300 kV microfocus X-ray tube

- max. voltage: 300 kV
- unipolar design, FOD < 5 mm
- max. power: 500 W
- focal spot size: 3 – 200 µm
>>> Reduced artifacts: increased global gray value homogeneity allows higher measurement accuracy
Example for wall thickness measurements on a jet engine turbine blade with vtomezlx m 300
CT for materials science

State of the art

V = 15 µm, 100kV, 470µA, Mode 0, 1h

nanotom m

V = 15 µm, 100kV, 470µA, Mode 0, 1h

Improved sharpness (+80%) & increased CNR (+100%) due to diamond window and low noise detector.
GE Gantry based CT for fast 3D industrial part inspection
GE AtlineCT overview

Inspection volume:
400mm width x 300mm height x 800mm length
Up to 50kg sample weight

Scan- and inspection times:
5-10mm/s
-> 10-60s for typical castings

Spatial resolution:
≥ 300µm
-> min. detectable defect size: >0.5 mm

Penetration length:
up to 300mm Al

GE 3D automatic defect analysis and -classification

Designed for operation in harsh environments (foundries)

Belt conveying system
GE 3D Automatic Defect Detection

Result on a die casting, 5 s defect detection time
Automated 3D inspection with CT

Usage of CAD-models

Detection of part deviations and defects in 3D

- Actual-Nominal-Comparison (part deviations)
- Comparison to admissible tolerances
- Compare with CAD-Data of machined part
- Defect unearthing after machining
- Wall thicknesses after machining
GE InlineCT Setup

- X-ray cabinet
- X-ray sliding gates
- Roller conveyor with lift
- Roller conveyor customer
- Gantry
- Dust protection cover
- Belt conveyor
- Inspection part
- Shock absorber

3D-ADR Image Processing
Automatic workflow for unmanned operation
END

Mila esker! Grazie mille! ¡Muchas gracias!
Merci beaucoup! 谢谢! Muito obrigado!
Mange tak! 谢谢! Muito obrigado!
Vielen Dank!

谢谢! 谢谢! 谢谢!

तोड़ह रवा! मन्ने वाद मन्ने वाद!

धन्यवाद धन्यवाद!

شكرا جزيلًا!

Vielen Dank!

Большое спасибо! Tack så mycket!

どうもありがとうございます!
High-resolution X-ray computed tomography
# Sites and contacts

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wunstorf, Germany</td>
<td>Headquarters + central laboratory world-wide</td>
<td><a href="mailto:phoenix-info@ge.com">phoenix-info@ge.com</a></td>
</tr>
<tr>
<td>Stuttgart, Germany</td>
<td>Branch laboratory Germany/Switzerland</td>
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<tr>
<td>Quezon City, PH</td>
<td>Service + Support Asia</td>
<td><a href="mailto:phoenix-asia@ge.com">phoenix-asia@ge.com</a></td>
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</table>
Contact and further information:

Visit:

www.phoenix-xray.com
or
www.ge-mcs.com/phoenix
“I find out what the world needs. Then I go ahead and try to invent it.”

Thomas A. Edison
Founder, GE