Ringvorlesung Sensorische Materialien

Funktionskonforme Sensorintegration mit magnetostriktiven Partikeln

Steffen Opitz, Peter Wierach, Marcus Kubicka, Thorsten Mahrholz, Alexandra Kühn, Michael Sinapius

DLR

Zu meiner Person

Steffen Opitz:

- Studium der Mechatronik an der Otto-von-Guericke Universität Magdeburg
- Promotion mit dem Thema: Funktionskonforme Sensorintegration in hoch belasteten, adaptiven, umströmten Strukturen

- Mitarbeiter am Institut für Faserverbundleichtbau und Adaptronik des Deutschen Zentrums für Luft- und Raumfahrt
- Stellvertretender Abteilungsleiter der Abteilung Multifunktionswerkstoffe
- Mitarbeit in der Forschungsgruppe 3022: Ultraschallüberwachung von Faser-Metall-Laminaten mit integrierten Sensoren

Institute of Composite Structures and Adaptive Systems

Director: Prof. Dr.-Ing. Martin Wiedemann
Vice Director: Prof. Dr.-Ing. Peter Wierach

DLR

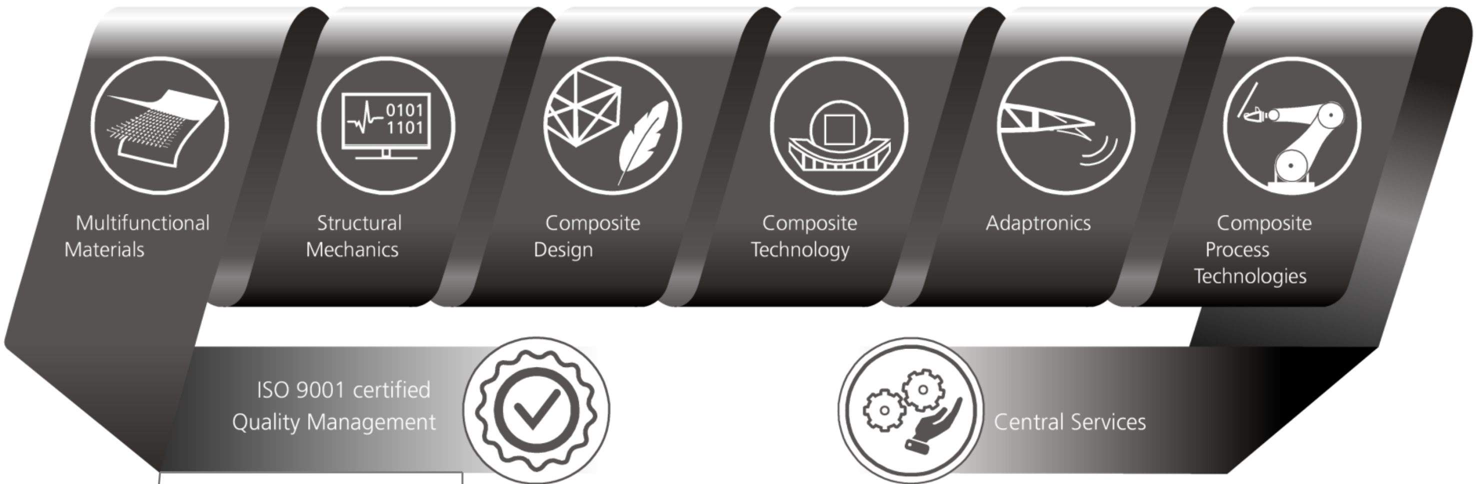
Our Mission

Design and realize adaptable, efficiently manufactured and tolerant lightweight systems. We do research on:

- proper lightweight design
- cost efficiency
- improved functionality
- higher degree of comfort
- environmental protection

DLR

The institute in detail – six scientific departments, certified laboratories



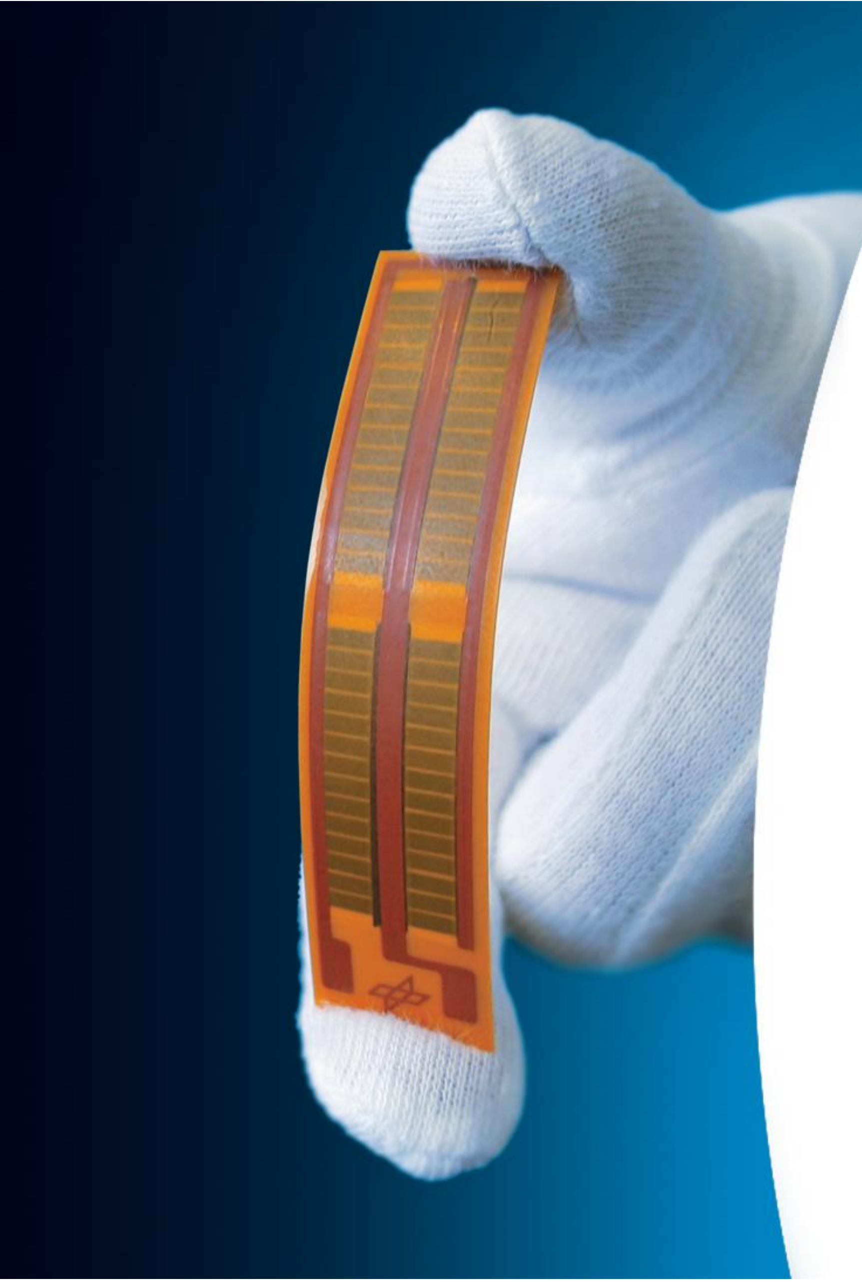
Accredited Nadcap™

LLOYD'S REGISTER • LRQA
ISO 9001

DAkkS
Deutsche
Akkreditierungsstelle

Testing Lab DIN ISO 17025 accredited

DLR



More functionalities in the materials

Our research focusses at:

- Composite materials & Nano composites
- Smart Materials
- Structural Health Monitoring (SHM)
- Characterization of materials

We are concentrating on the development, characterization and qualification of composite materials with superior properties and new functionalities

DLR

Wollen Sie mehr über uns und unsere Forschung erfahren?

Dann schauen Sie rein unter:

- www.leichtbau.dlr.de/
- www.DLR.de/FA

Ringvorlesung Sensorische Materialien

Funktionskonforme Sensorintegration mit magnetostriktiven Partikeln

Steffen Opitz, Peter Wierach, Marcus Kubicka, Thorsten Mahrholz, Alexandra Kühn, Michael Sinapius

DLR

Outline

- Introduction and motivation
- Idea and potential
- Challenges and approach
- Material processing and manufacturing of specimen
- Optical assessment of specimen
- Test setup and experimental results
- Conclusions and future work

Introduction
The ultimate Goal

Ultimate smart material properties:

- Sensor capabilities
- Actuator abilities
- Other functions

  (conductivity, good FST properties,…)
- High strength / robustness
- High stiffness
- Lightweight

Introduction

The ultimate Goal

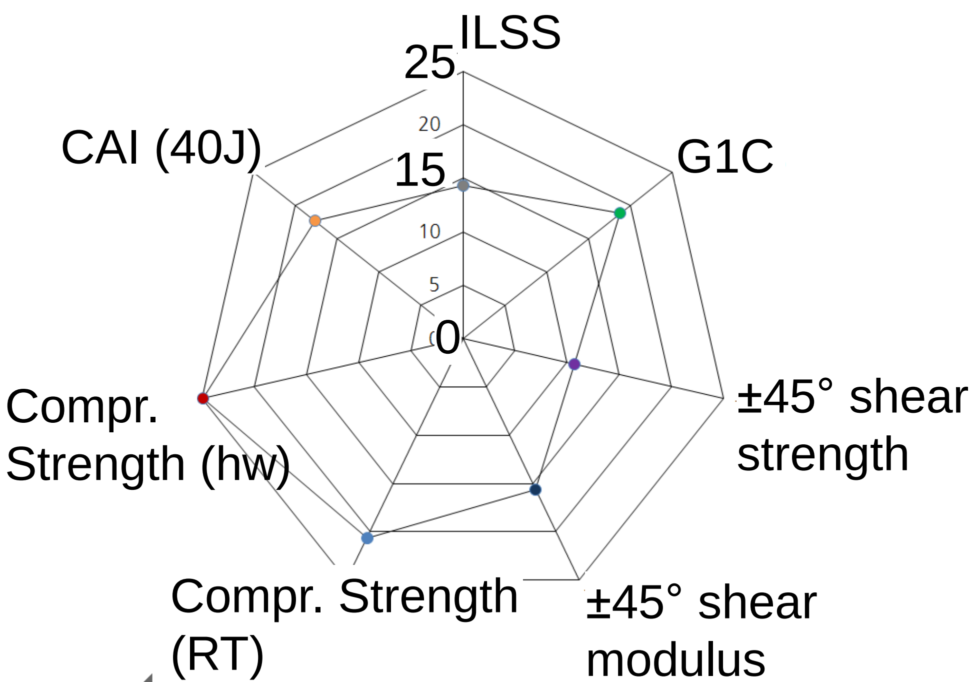
Ultimate smart material properties:	Carbon fiber reinforced polymers
• Sensor capabilities	
• Actuator abilities	
• Other functions (conductivity, good FST properties,…)	?
• High strength / robustness	?
• High stiffness	✓
• Lightweight	✓

DLR

Introduction
Potentials of matrix modification

Mechanical properties

- Boehmite nano particles
- Nano-composite with 15 wt.-%



Integrated fire protection

- Epoxy resin modification with ATH (Aluminumtrihydroxid) nano particles

5% ATH
Nano particles

10% ATH
Nano particles

20% ATH
Nano particles

Introduction
The ultimate Goal

Ultimate smart material properties:	Carbon fiber reinforced polymers
• Sensor capabilities	?
• Actuator abilities	?
• Other functions (conductivity, good FST properties,…)	✓
• High strength / robustness	✓
• High stiffness	✓
• Lightweight	✓

Composite materials offer:

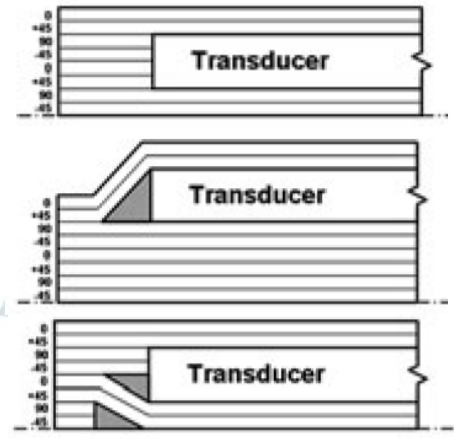
- Excellent strength to density ratio
- Possibility for the integration of additional functionalities by
  - Modification of the different material phases
  - Integration of new material phases in the material system

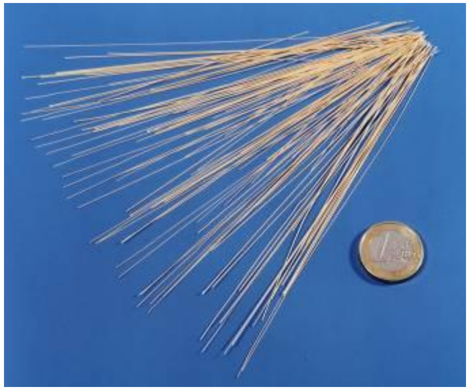
Introduction
Integration of smart / active materials

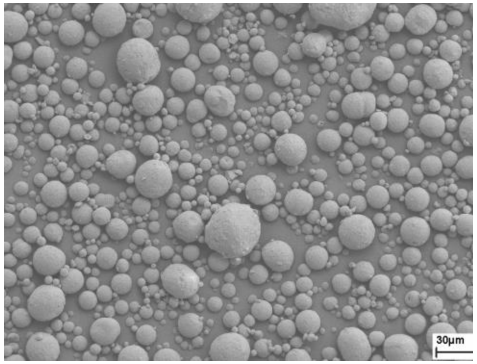
- Integration / Application of smart materials as foils/plates
  - Discontinuity in stiffness
  - Weakening of the structure?

- Integration of fibers
  - Complex manufacturing
  - Issues of contacting
  - Limited interfacial surface with the resin

- Integration of micro- or nano-scaled particles
  - Knowledge from previous works
  - Structural conformable
  - Functional conformable?
  - Filtering during injection?







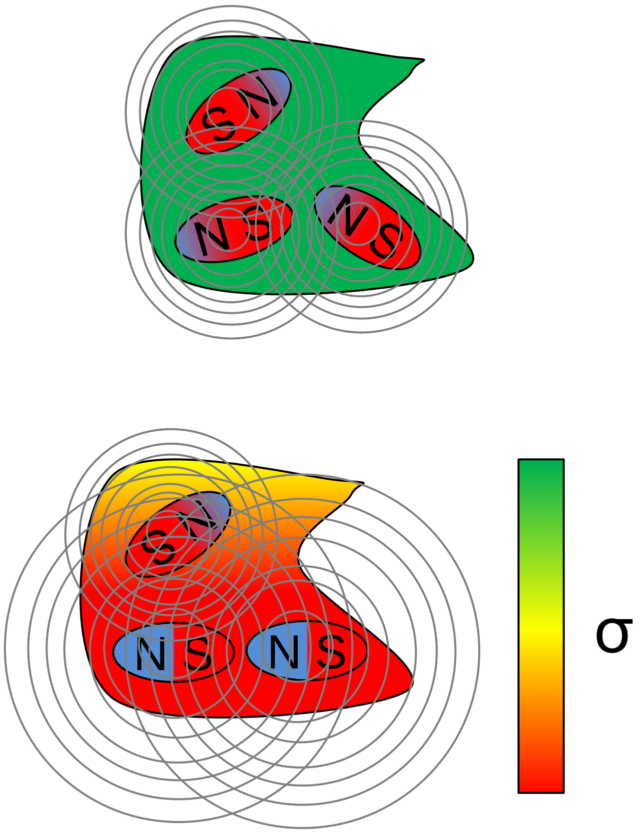
DLR

Idea and potential
Basic idea

- Integration of sensor capability to detect stresses in the material

- Modification of the resin with:
    - Piezoelectric particles
    - Magnetostrictive particles

    → Distributed sensor

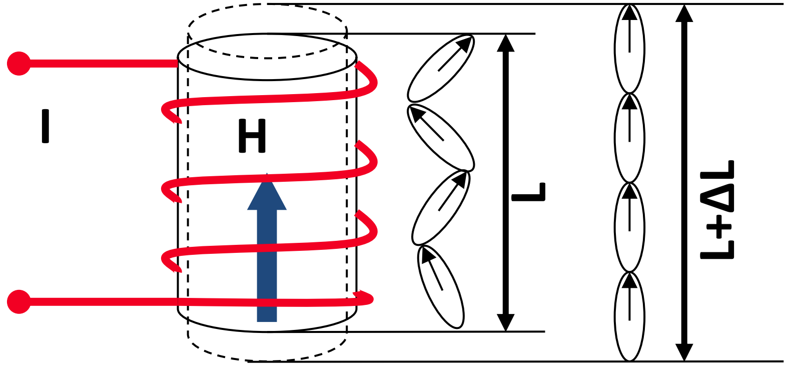


Idea and potential
Basic idea

- Embedding of micro- or nano-scaled magnetostrictive particles into the resin
  - Small size particles → large surface Area to introduce the loads into the particle
  - Focus on Terfenol-D

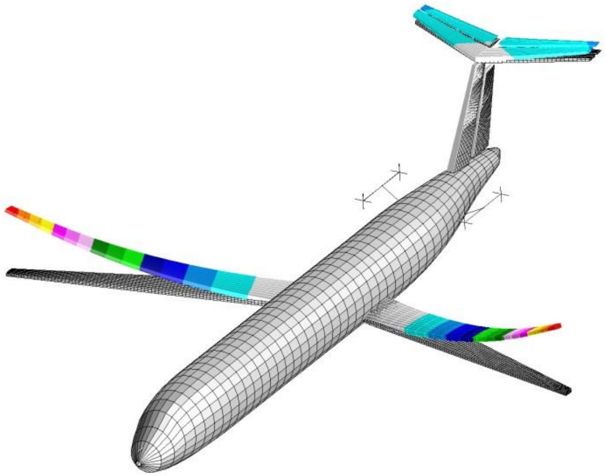
- Change of magnetic flux density due to strain

  →Villary effect (inverse magnetostriction)

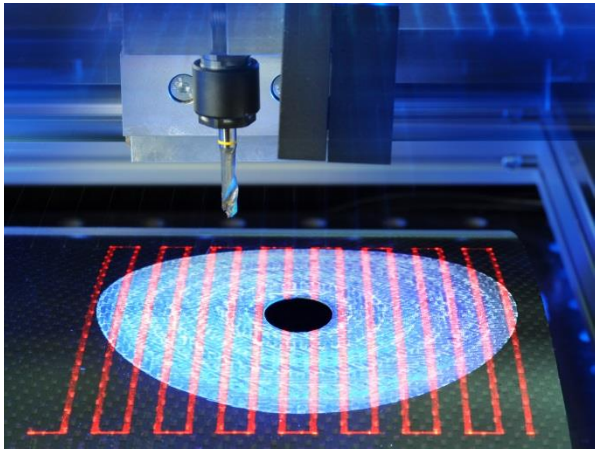


DLR

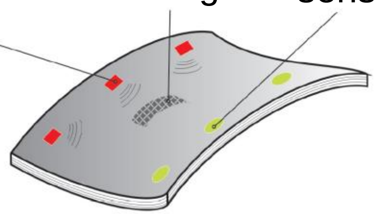
Idea and potential
… for transport and mobility



- Assessment of:
  - Structural loads
    - Loads during operation
    - Condition based maintenance
  - Residual stresses
    - Design optimization
    - Process optimization
  - Quality of bonds
    - Repair
    - Detection of kissing bonds
- Improvement of health monitoring systems



- Distributed over the whole structure
- Without any negative impact on the structural performance



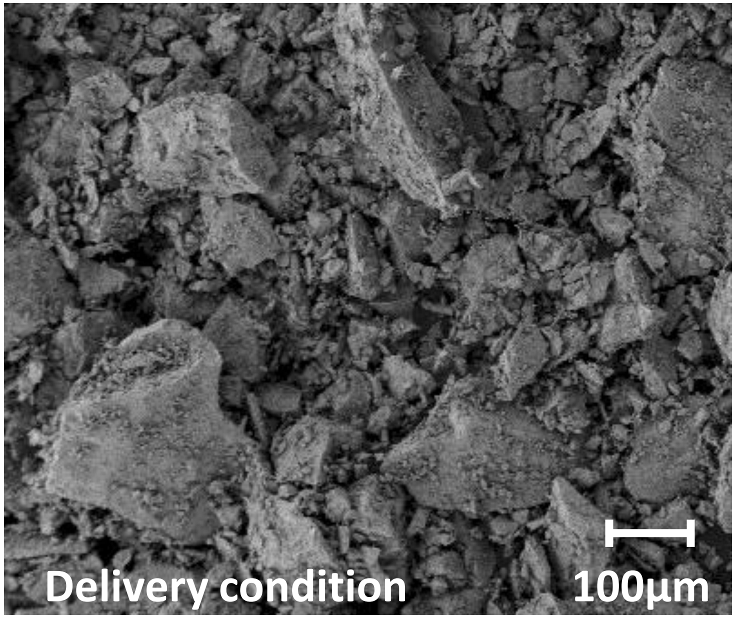
Main questions & challenges

- Is it possible to measure stresses with embedded magnetostrictive particles?
  - How to manufacture homogeneous specimen?
  - What is the effect of particle size?
  - How does the particle concentration change the sensitivity?
  - …
  - How can the effect be used in a composite structure?

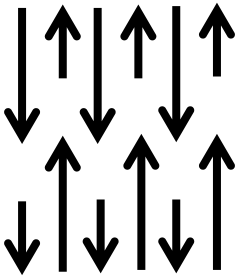
Approach

- Particle fractionation / characterization
- Particle dispersion
- Manufacturing of specimen
- Assessment of specimen
- Testing of specimen

Particles



- Terfenol-D ($Tb_{0,3}Dy_{0,7}Fe_{1,92}$)
  - Terbium (42,3 wt%)
  - Dysprosium (40,0 wt%)
  - Iron (17,7 wt%)
- Selected properties:
  - Density: 9,25 g/cm³
  - Young modulus: 25 - 35 GPa
  - Tensile strength: 28 MPa
  - Free strain: 800 - 1200 µm/m
  - Ferrimagnetic

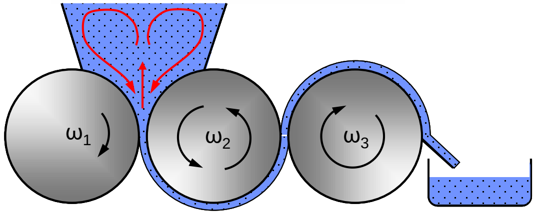


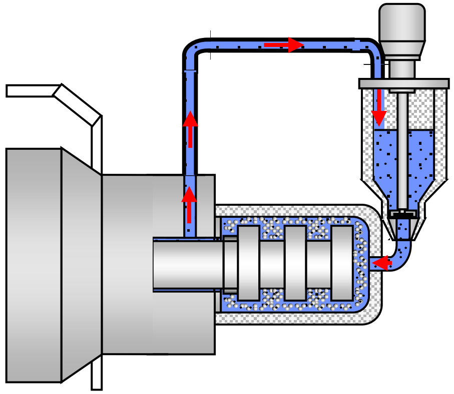
- Delivered as Powder (ETREMA USA):
  - particle size: 0-300µm
  - particle shape: irregular stochastic
    broken fragments (grinding process)

DLR

Particle fractionation

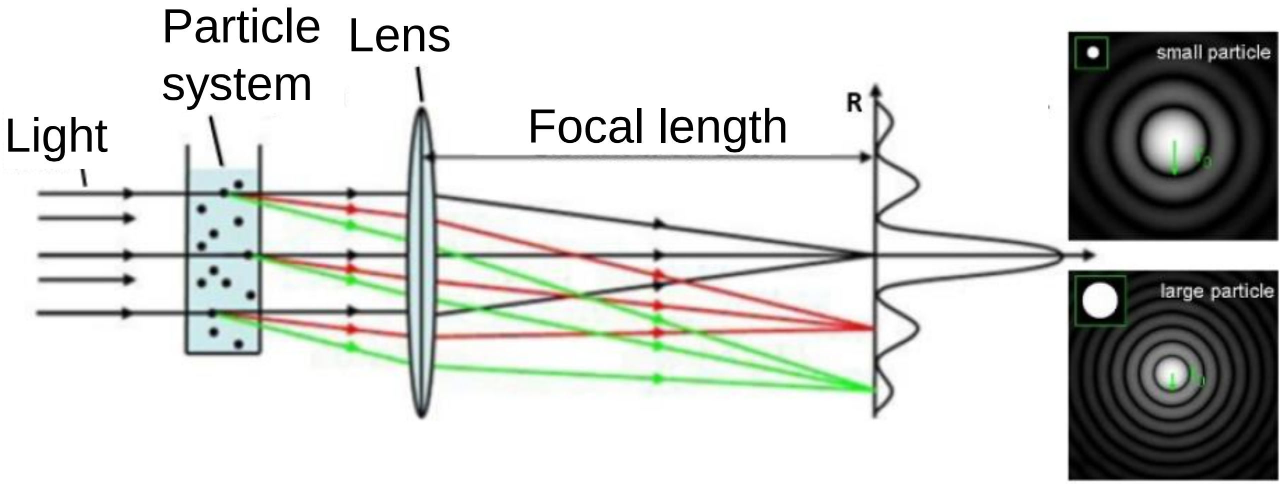
- Characterization and manipulation of particle sizes and particle size distributions
- Prerequisite to investigate the influence of the particle size
- Sieving of bulk particle powder:
  - Sieving tower: 0-300µm → 0-100µm; 100-300µm
  - Air jet sieve: 0-100µm → 0-20µm; 20-100µm
- Further processing of particle resin mixture:
  - Resin + 0-300µm → master batch (32.25wt%)
  - Roll mill:
    - Gap mode → ~15µm
    - Force mode → 0-15µm
  - Bead mill → 0-10µm





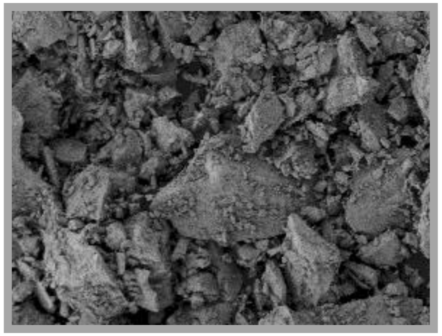
Particle fractionation

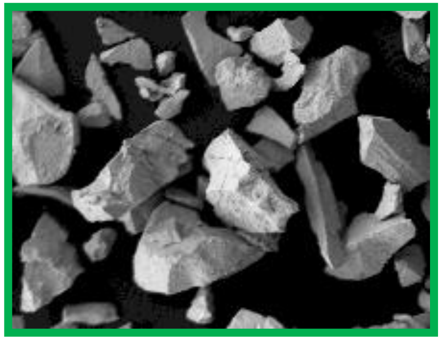
- Assessment via laser diffraction method (Laserspectrometer: Helios, Sympatec)
  - 100nm – 875µm

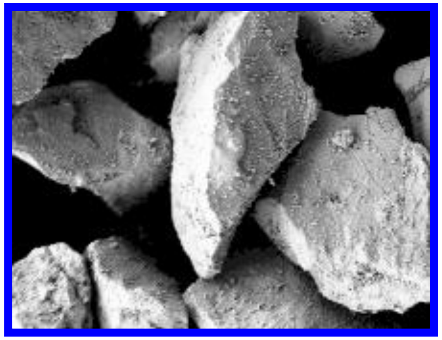


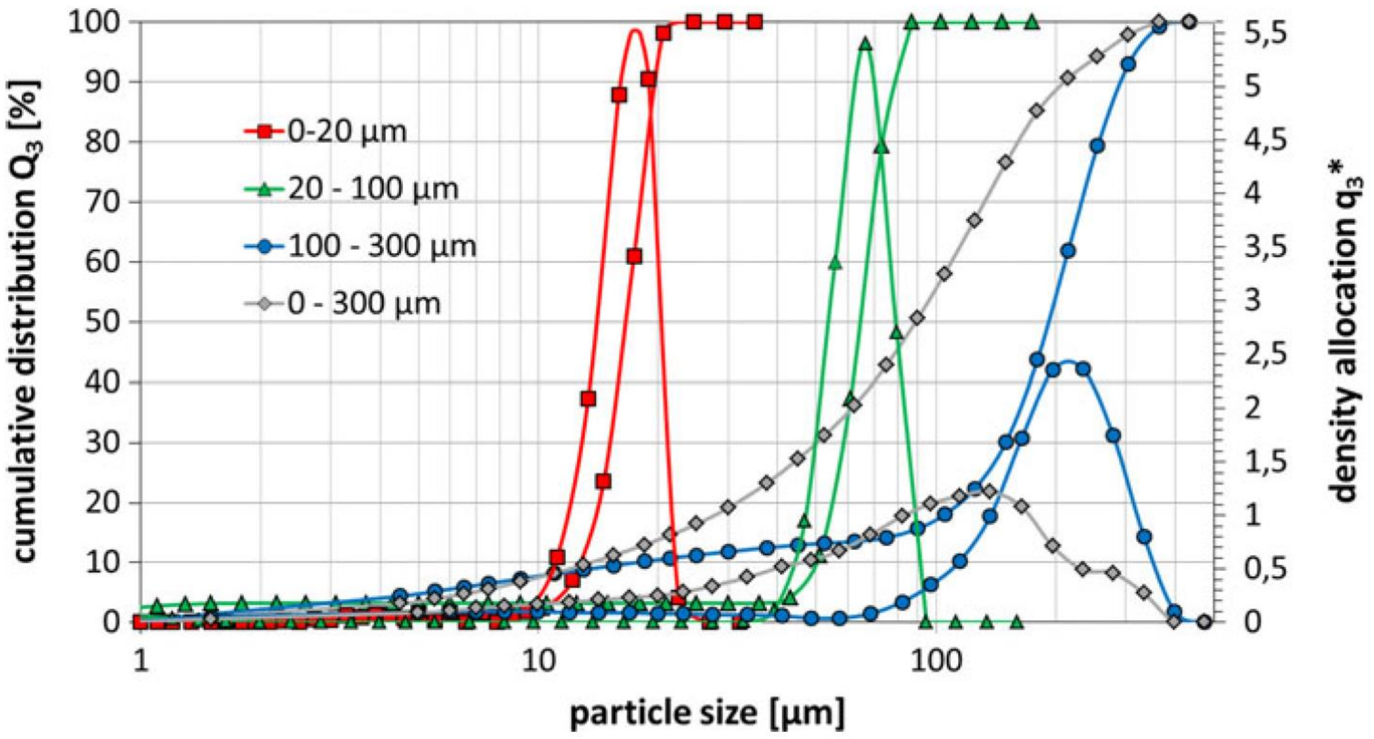
- Optical assessment using SEM
  - Directly possible after sieving
  - Separation of particles out of the processed master batch with acetone

Particle fractionation







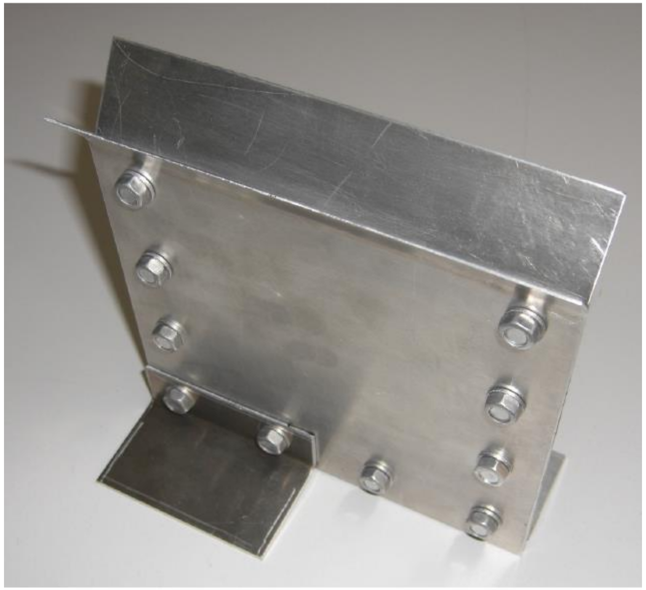


Particle dispersion

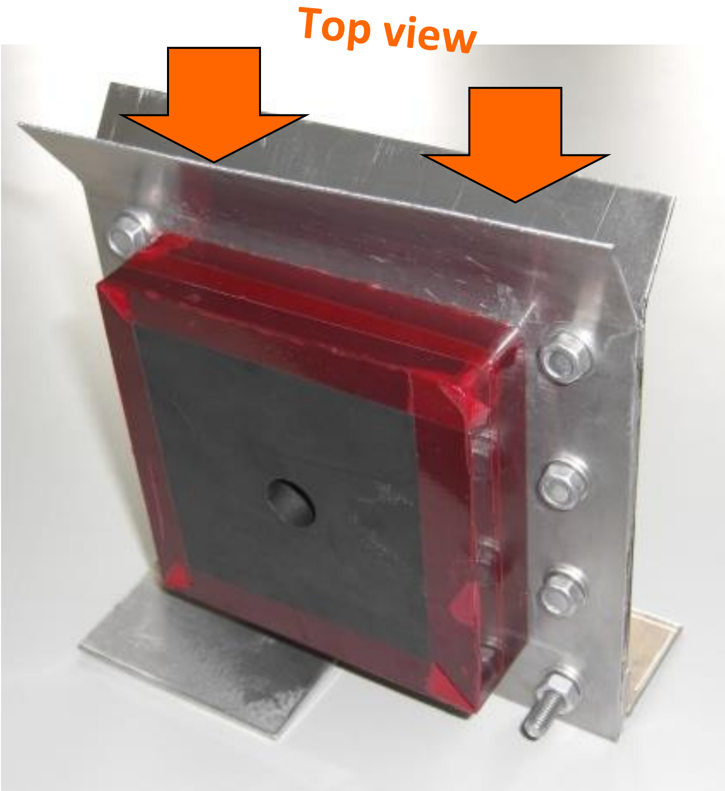
- 3 component Matrix (100/90/1; all by Huntsman):
  - Resin: Araldite LY 556
  - Hardener: Aradur HY 917
  - Accelerator: DY 070

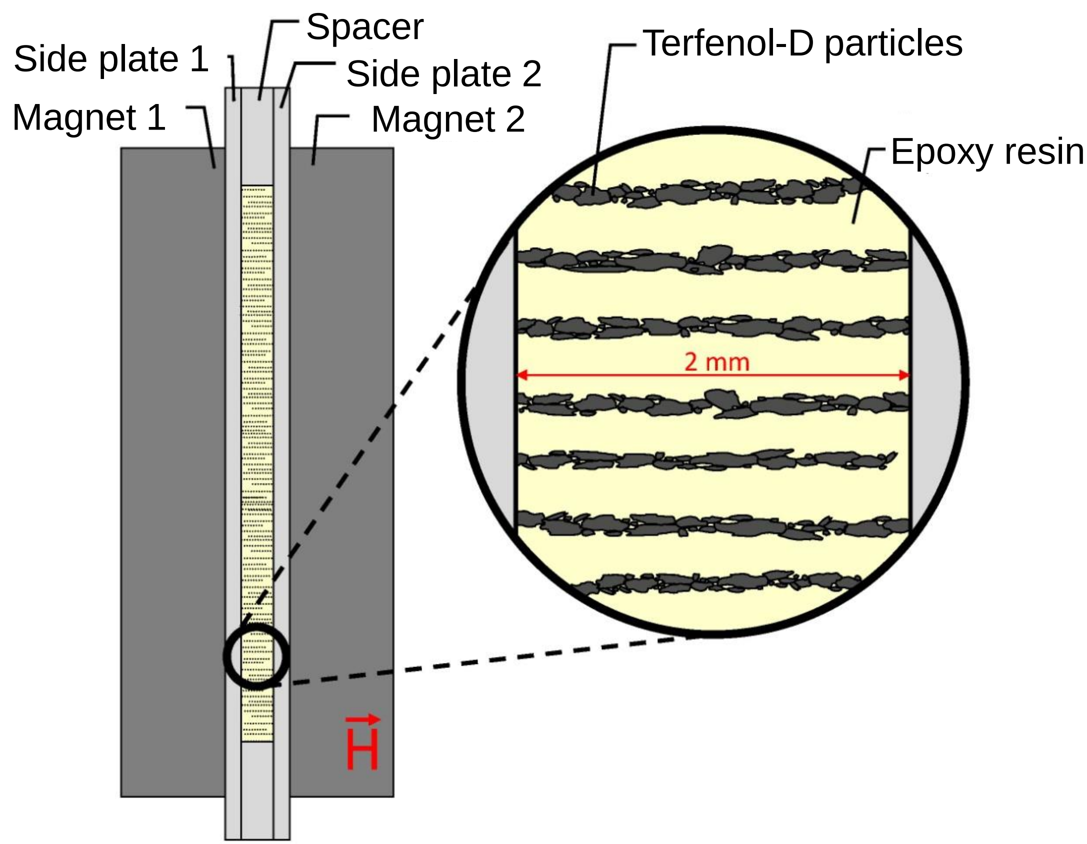
- Particle sedimentation due to huge difference in density: 9.25g/cm³ vs. 1.2g/cm³

- Idea: combination of orientation and stabilization of the particles within a magnetic field



Manufacturing of Specimen

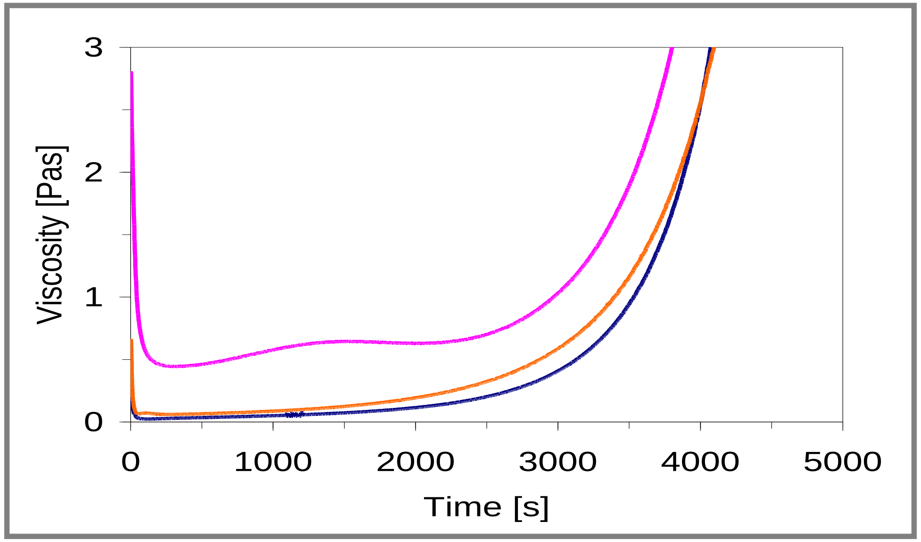




- Formation of particle chains
- Orientation of particles in the magnetic field
- Stabilization of the particles

Manufacturing of Specimen

- Field strength is crucial
- Too strong magnetic field leads to separation of the particles to both magnets
- Viscosity of the resin changes with time
  → Application of field at the right time
  → Electromagnet favorable

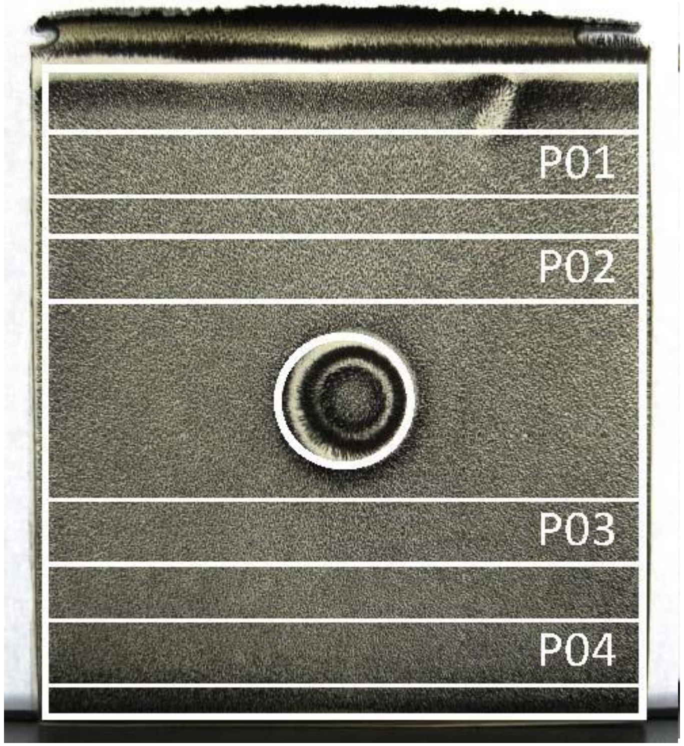


Specimen overview

	20wt%	5wt%
0-10µm	tbd.	tbd.
0-15µm	tbd.	tbd.
15µm	Optical	Optical
0-20µm	Optical / Mechanical	Optical / Mechanical
20-100µm	Optical / Mechanical	Optical / Mechanical
100-300µm	Optical	Optical
0-300µm	Optical / Mechanical	Optical

Optical assessment of specimen

- Specimen with different particle sizes (20 wt%)

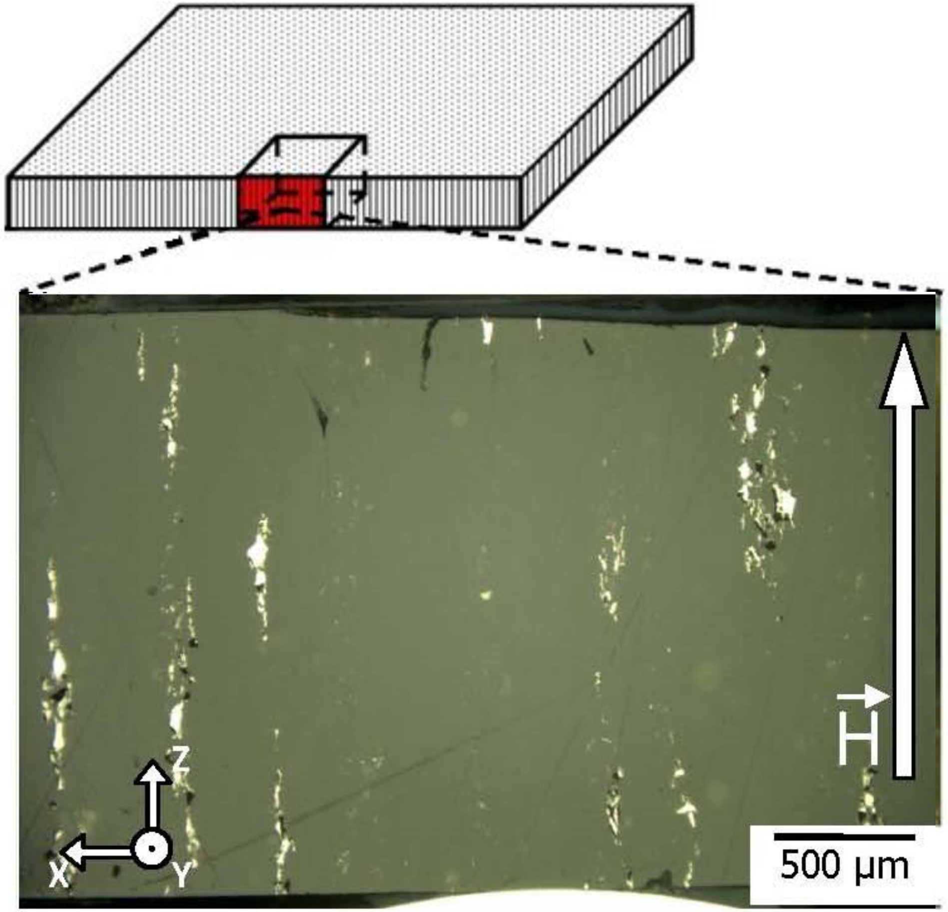


Particle size: 0 - 20 µm,
homogeneous, dense particle distribution

Particle size: 100 - 300 µm,
inhomogeneous particle distribution

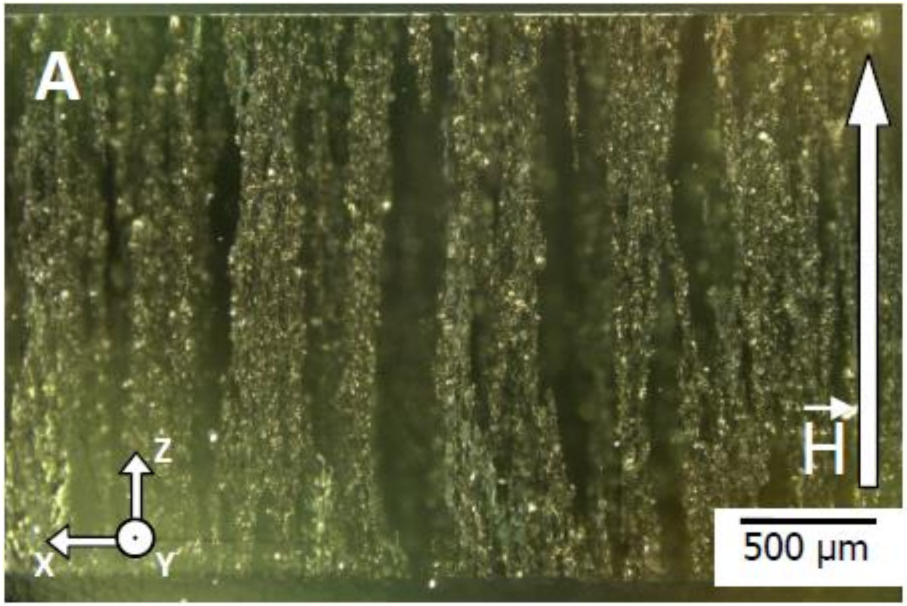
Optical assessment of specimen

- Optical Characterization of the particle distribution
- Light microscopy of a sample with 20 wt% particles of a size between 0-300µm
- Benificial use of polarization filter

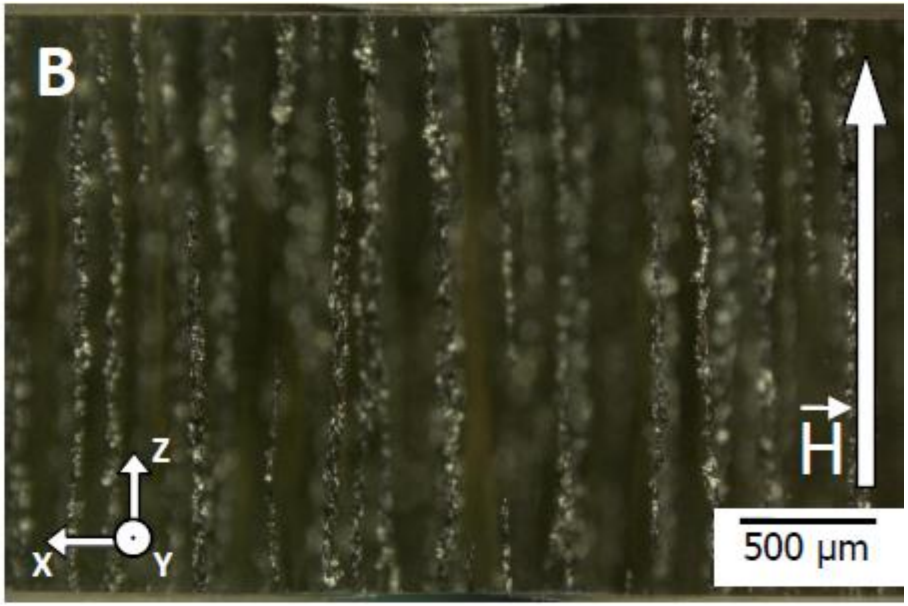


Optical assessment of specimen

15µm, 20 wt%

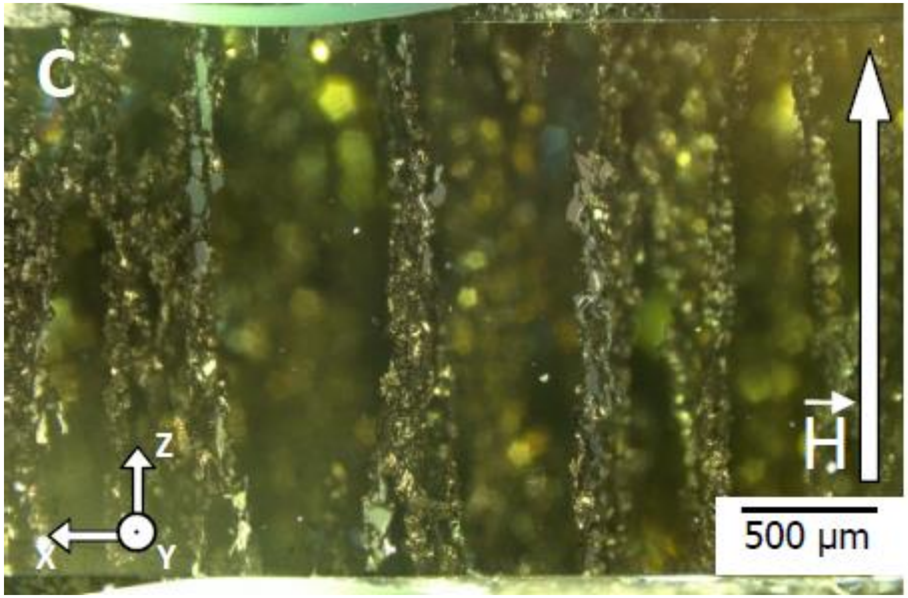


15µm, 5 wt%

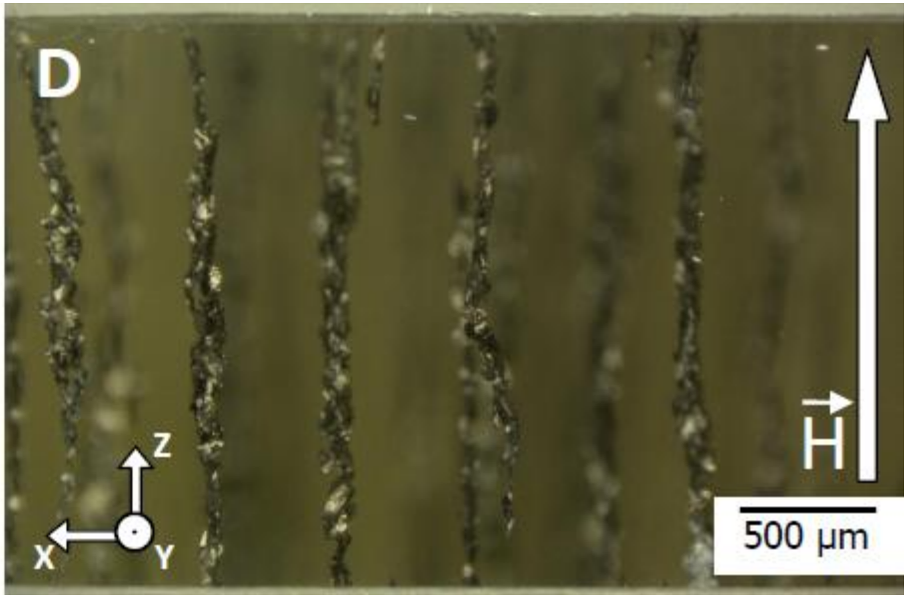


Optical assessment of specimen

0-20µm, 20 wt%

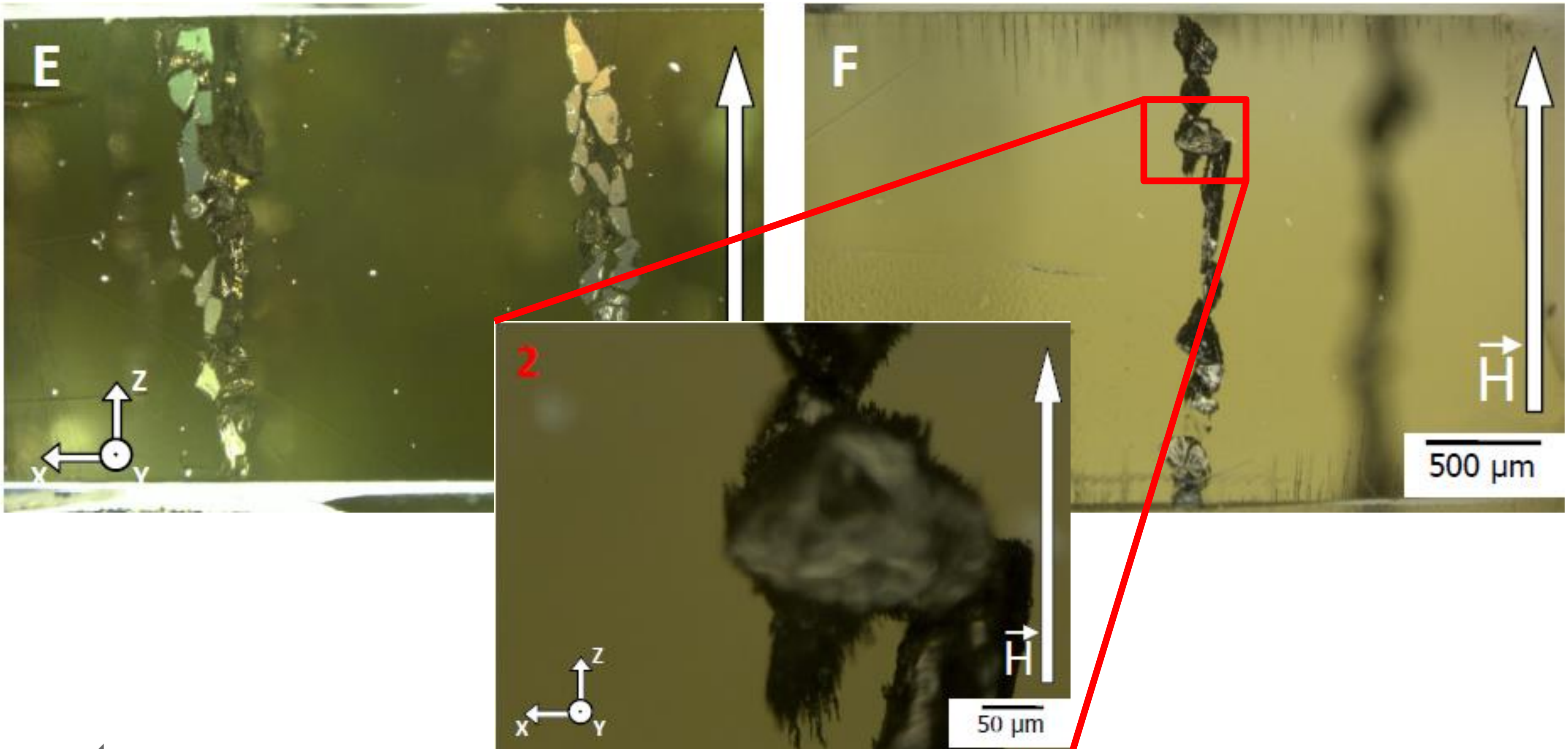


0-20µm, 5 wt%



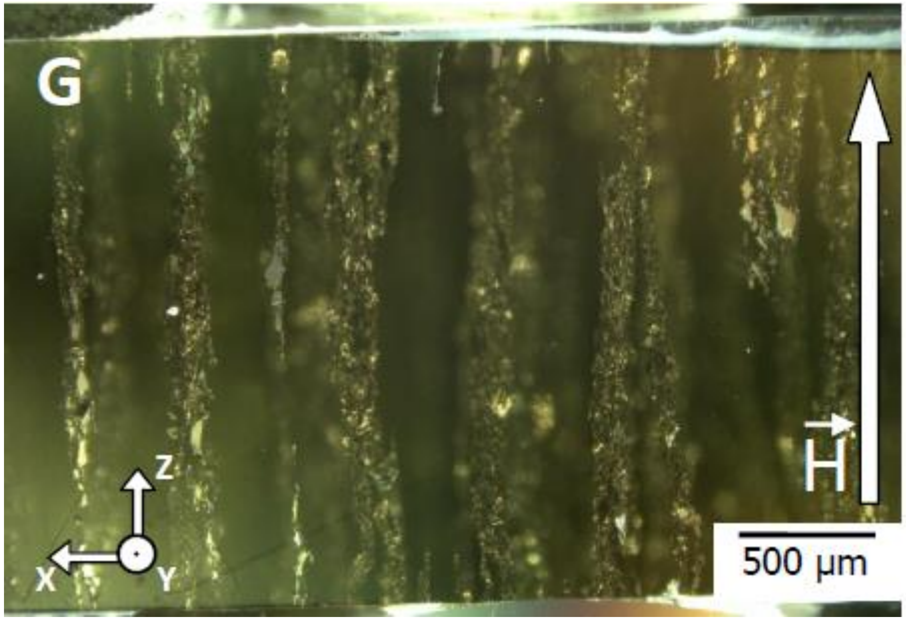
Optical assessment of specimen

100-300µm, 20 wt% **100-300µm, 5 wt%**

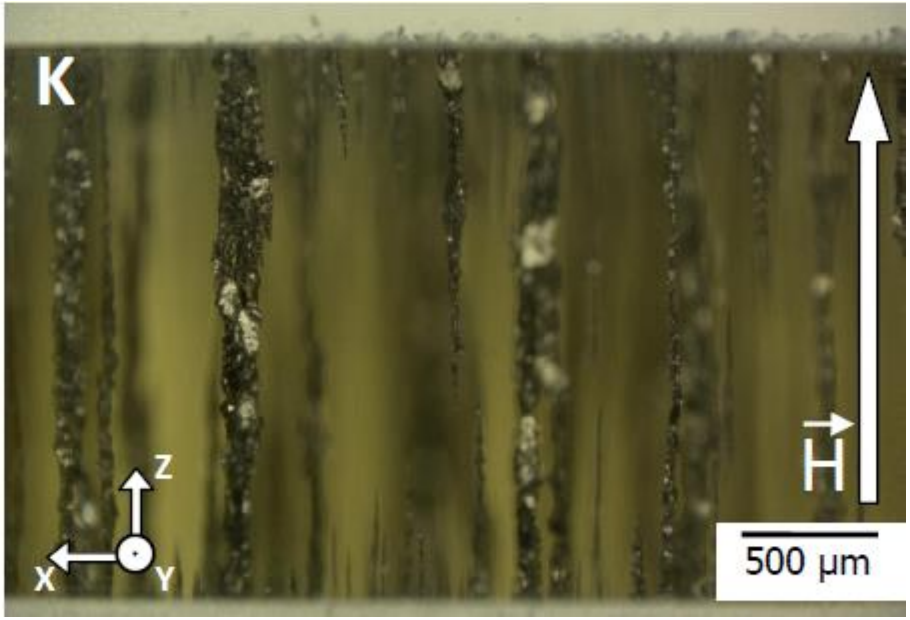


Optical assessment of specimen

0-300µm, 20 wt%



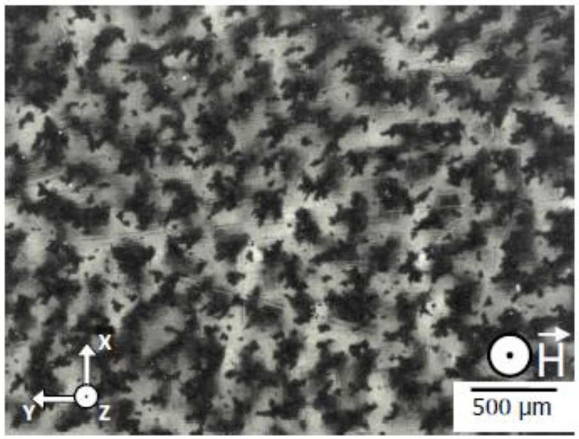
0-300µm, 5 wt%

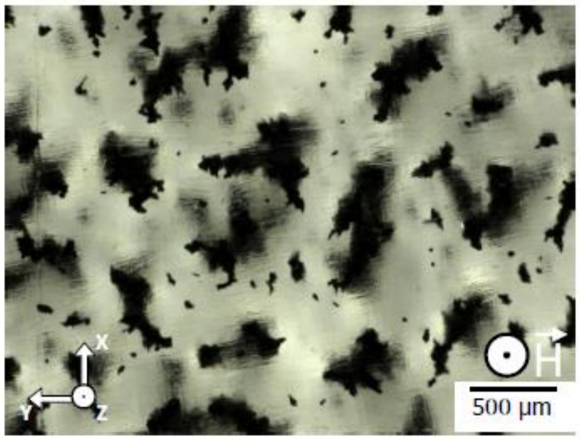


Optical assessment of specimen

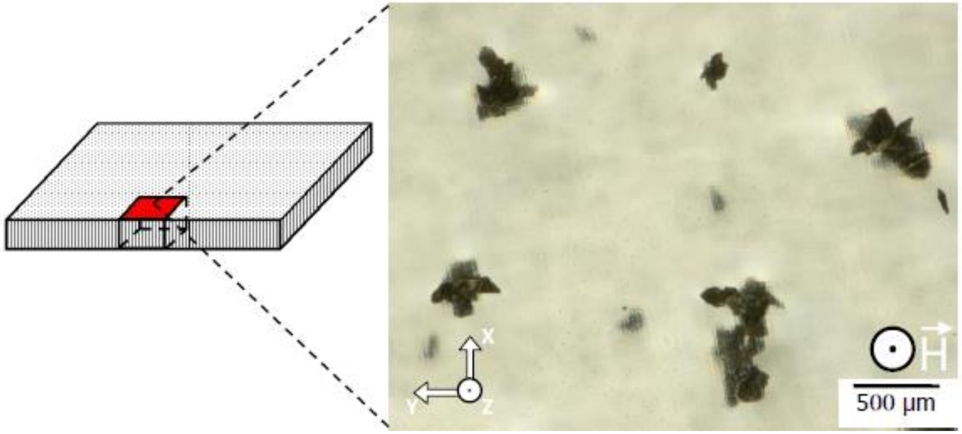
20 wt%

0-20µm





20-100µm



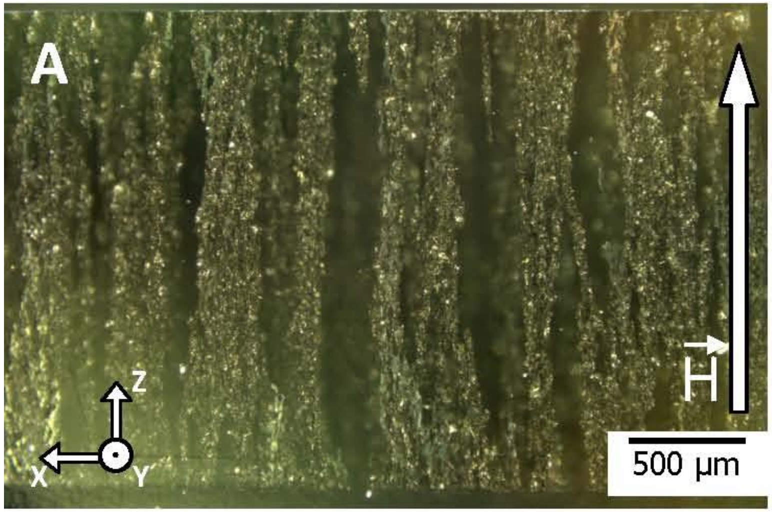
100-300µm

DLR

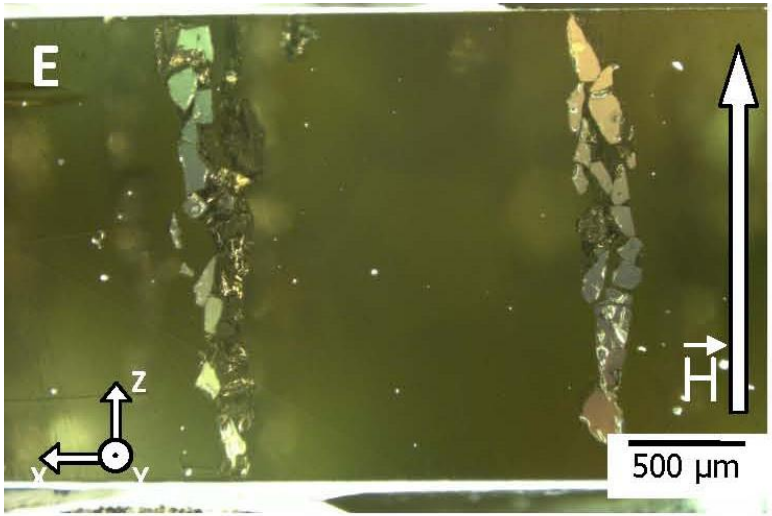
Conclusions of optical specimen assessment

- Small particles (<20µm):
  - Many particles / particle chain
  - High density of particles / particles chains
  - Fine structures
  - Chain to chain distance in the µm range
  - →Homogeneous distribution

- Big particles(>100µm):
  - Few particles /particle chain
  - Low density of particles / particles chains
  - Coarse structures
  - Chain to chain distance in the mm range
  - →Inhomogeneous distribution



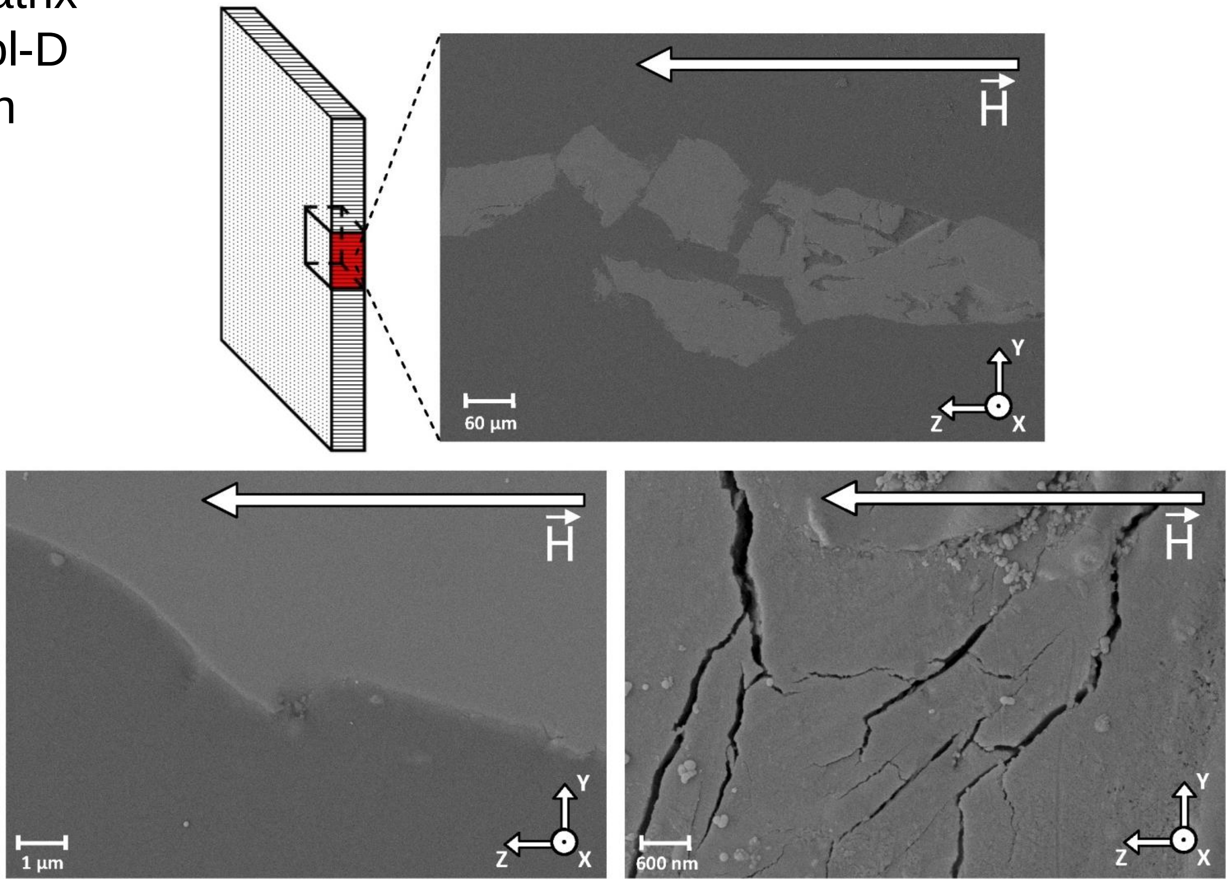
20 wt%, approx. 15 µm



20 wt%, 100-300 µm

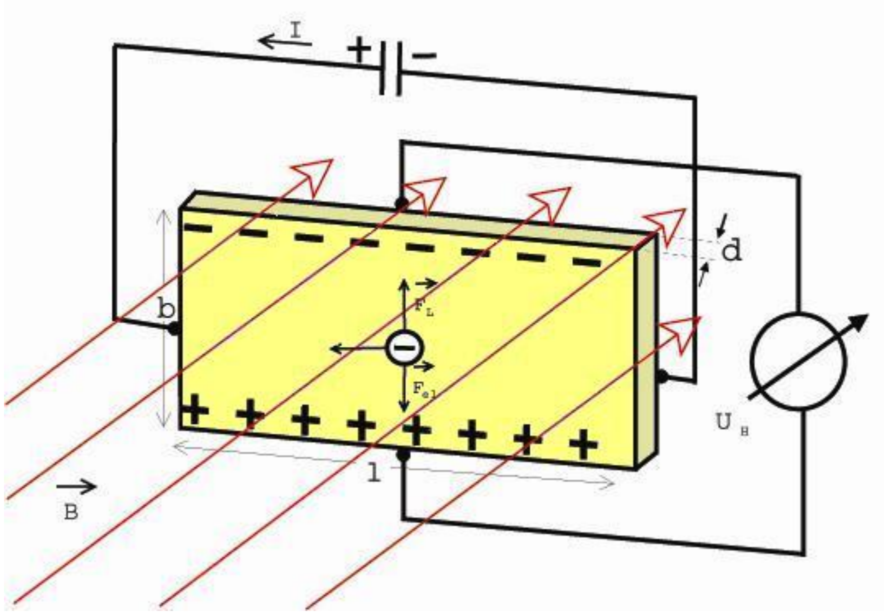
Particle-matrix adhesion

- SEM investigation of a specimen after loading (100-300µm, 20 wt%):
  - Good adhesion to matrix
  - Cracks in the Terfenol-D
  - No cracks in the resin



Test setup

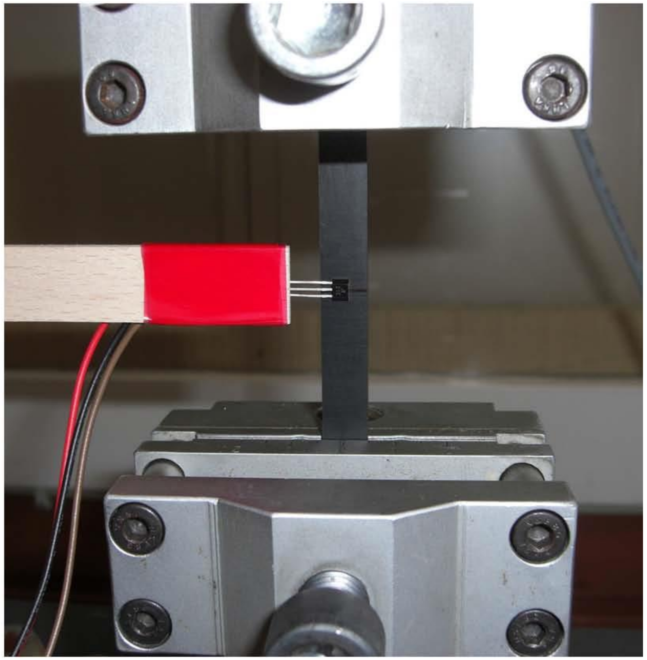
- Equipment:
  - Universal testing machine
    - Measurement of traverse position
    - Measurement of force
  - Measurement of magnetic flux density via Hall-Sensor
    - Free moveable
    - Only relative measurements
    - Measurement range ~ ±2mT



DLR

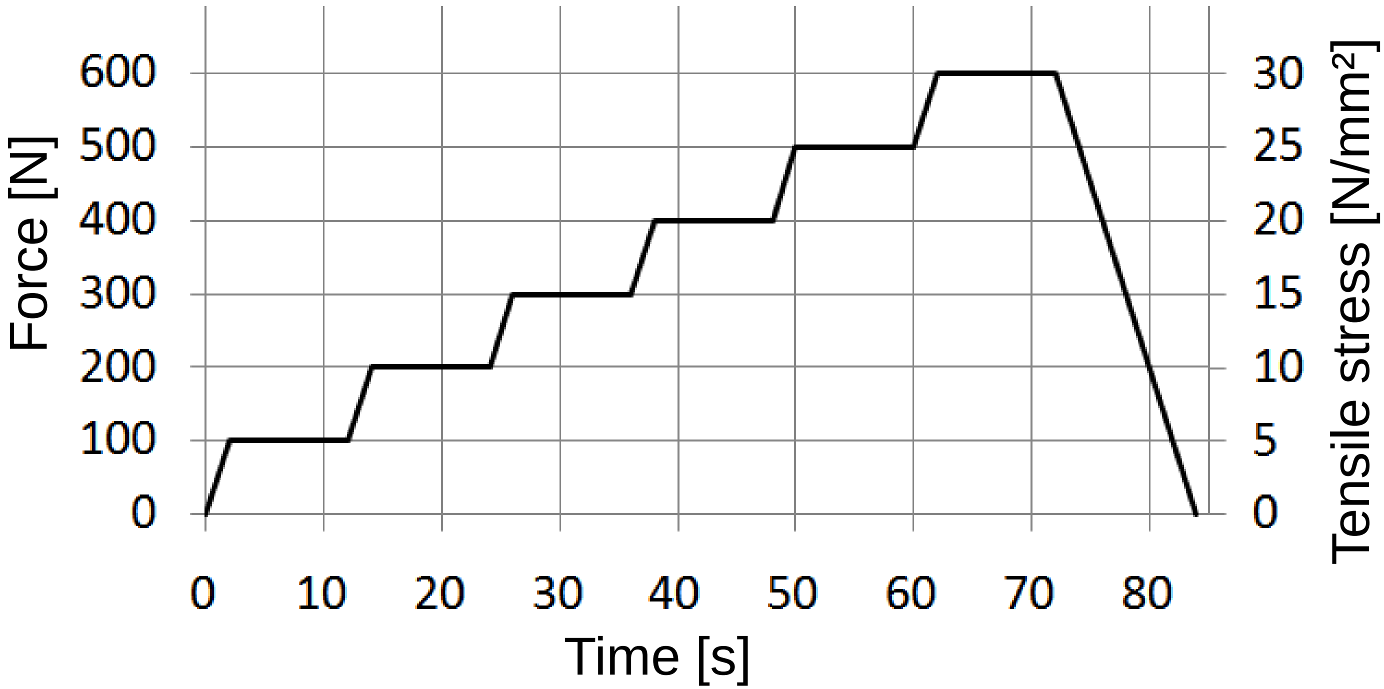
Test setup

- Measurement setup



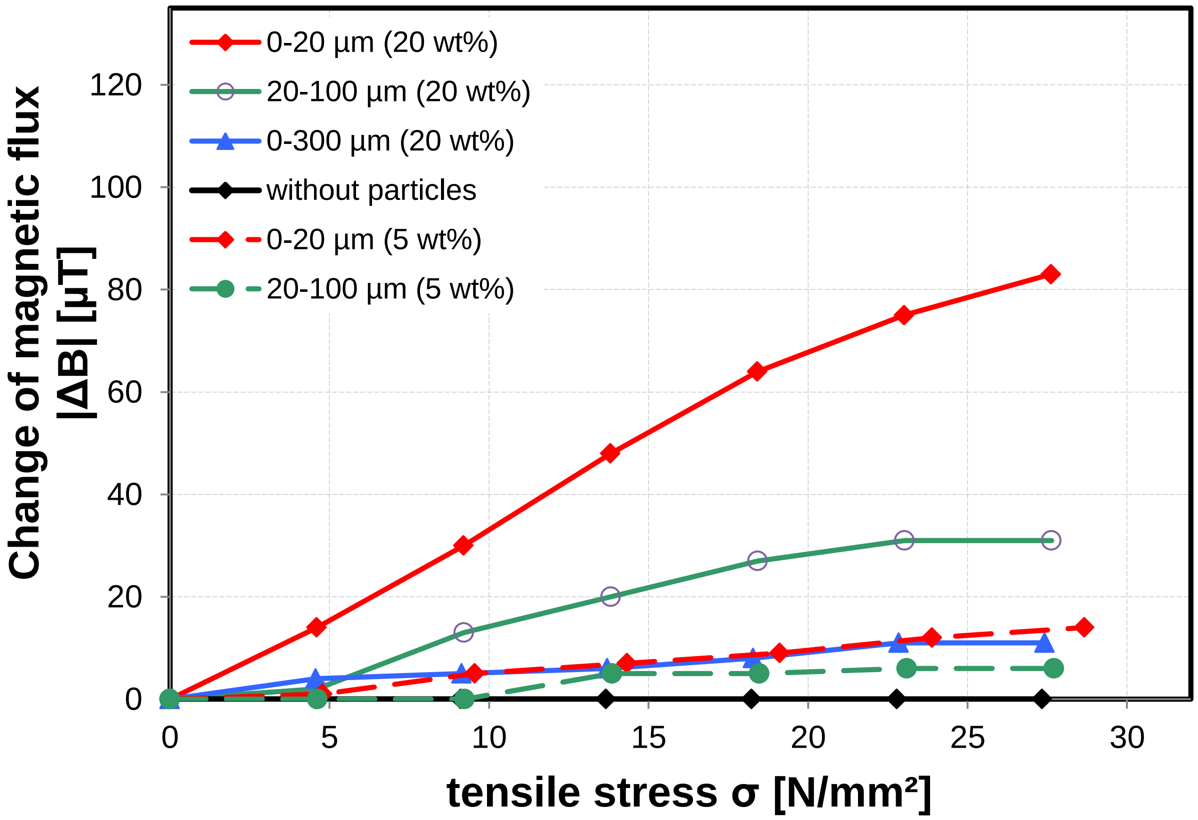
Test setup

- 6 force steps 100N each
- Loading speed: 2mm/min
- Stage dwell: 10s
- manual measurement of |ΔB| after 5s



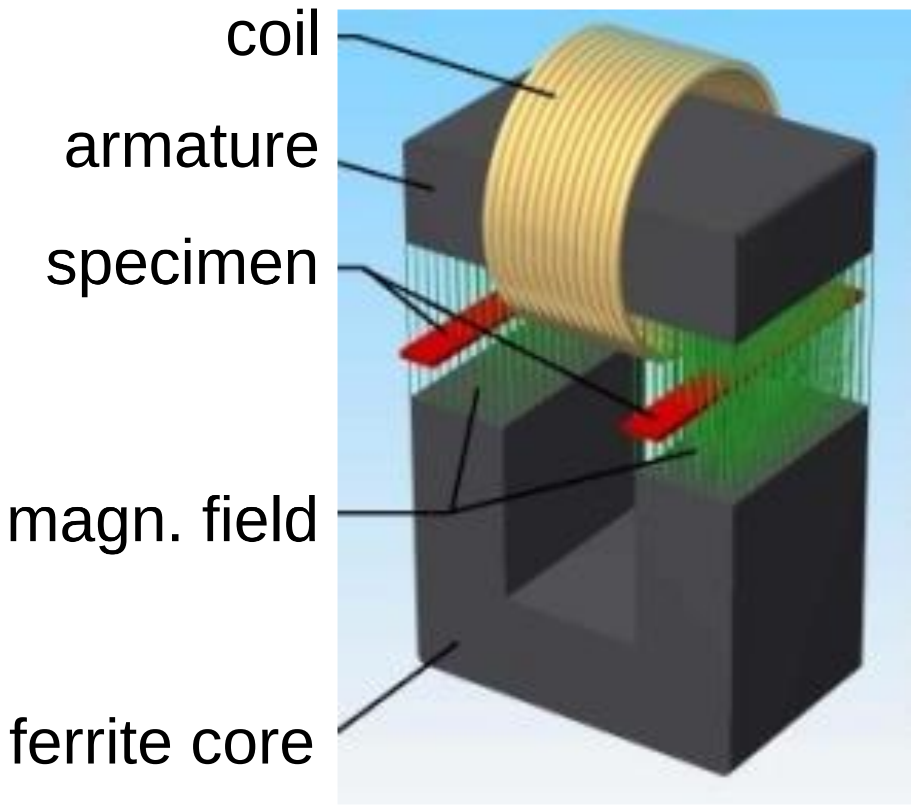
Experimental results

- Fairly small changes in flux density
- Clear dependency of stress
- Smaller particles show bigger effect
- Higher concentrations lead to higher sensitivity
- Stress almost reaches the tensile strength of Terfenol-D



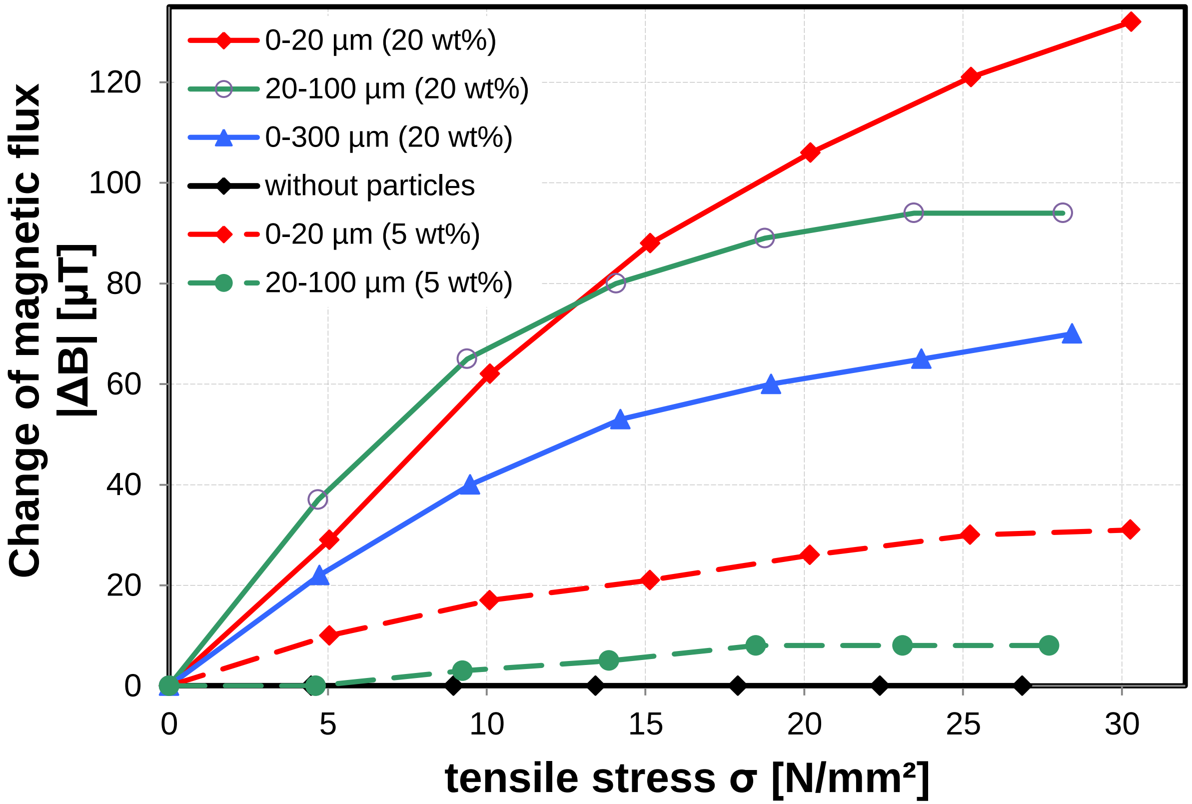
Experimental results

- 2nd magnetization
    - Duration: 30s
    - Magnetic flux density: 1.5T



Experimental results

- Magnetic response to external loading after 2nd magnetization:
  - Significant increase in sensitivity



Conclusions

- Change in flux density depends on:
  - Mechanical strain
  - Particle size
  - Particle content
  - Particle distribution

  → Strong mutual influence
- Specimen with lower particle content showed lower changes in magnetic flux density
- Smaller particles seem to be favorable
  - Bigger signal
  - More uniform distribution
- Post magnetization leads to enhanced sensitivity

Future work

- Statistical confirmation
- analytical / numerical modeling
- Further reduction of particle size → nano?
- Impact of mechanical and rheological properties (e.g. resin viscosity)
- Tuning of process parameters
- Manufacturing of composite specimens
  - Challenge: orientation and stabilization of particles in big or complex parts, definition of zero state → residual stresses
  - Impact on mechanical properties of the laminate
- Improvement of test and manufacturing equipment
- Other sensor materials (lower density, better availability)

Thanks for your attention.

Contact:

Dr.-Ing. Steffen Opitz
steffen.opitz@dlr.de

more information:

www.leichtbau.dlr.de/
www.DLR.de/FA