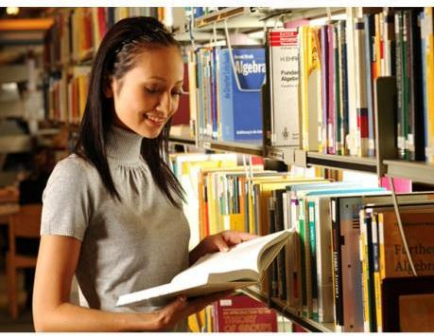
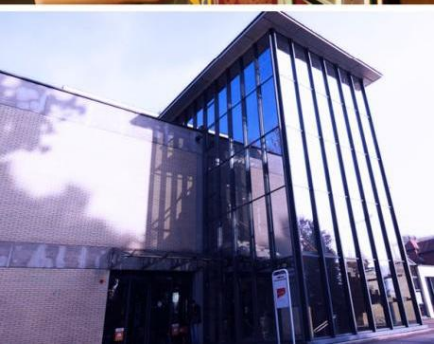


Competition of Polymeric Materials for Light Weight Design and Manufacturing – or Complementary Options

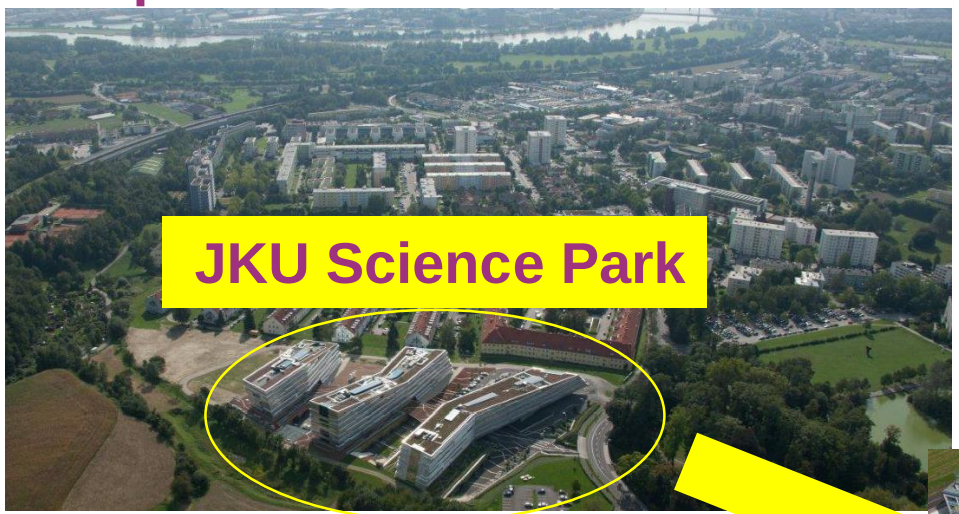
Zoltán Major

Institute of Polymer Product Engineering

27. February 2013, 4a Tagung

Content

Competition - The Home of the Team



ipim Institute of Polymer Injection Moulding and Process Automation

ipeb Institute of Polymer Extrusion and Building Physics

ippe Institute of Polymer Product Engineering

ipmt Institute of Polymeric Materials and Testing

Introduction

- **Metals vs. Polymers**
  - Comparison of plasticity both from practical and from material modeling point of view
- **Thermoplastic (uncrosslinked) vs thermoset (cross-linked) polymers for composites**
  - Development continuous fiber reinforced thermoplastic matrix composites (Engel, ipim)
  - **Discontinuous, injection molded composites**
- **Thermoplastic vs. crosslinked elastomers and composites**
  - For **Hydrogen** applications
  - For controlled damping applications

Hydrogenius, Kyushu University, Fukuoka, Japan

Betankung mit lH_2 (12-20 min)

700 bar

-40 ° C !!

Bericht 2014 ?

Honda FCX Clarity

Discontinuous Short Fiber Reinforced Polymer Composites

Matrix Materials

- PP
- PA
- PEEK

Fillers and Fibers

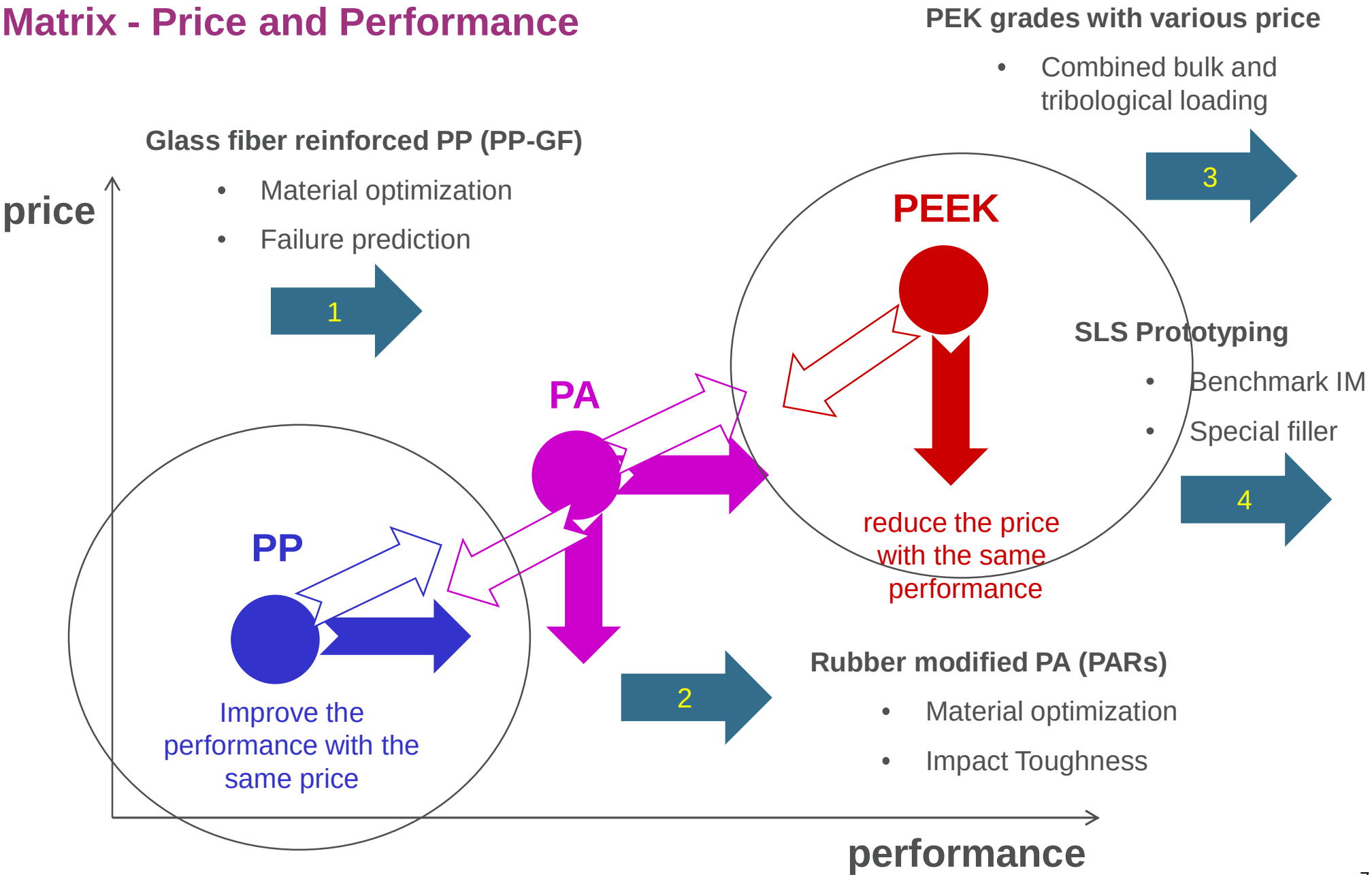
- Glass fibers
- Carbon fibers
- other Fibers
- Reinforcing fillers
- Toughening
- Functional fillers

Cheap matrix with expensive fiber ?

expensive matrix with cheap filler ?
To degrade the properties ??

Not only **competition** of **matrix materials** but **fillers/interfaces**

Matrix - Price and Performance



Filler Materials

Hard (mineral, glass, C)

$E_f > E_m$

Mechanical properties ≠ f(t, T)!

Glass Beads

Spherical Particles

Mica, Talc, Kaolin

Platelet

Glass fiber
Wollastonite,
C fiber

Needle

Soft (elastomers)

$E_f < E_m$

Mechanical properties = f(t, T)!

Prolate Rotational Ellipsoid

Needle

AR=1

Aspect Ratio

1<AR<100

Polymer fibers, self reinforcement

Interface compatibilization

Alignment, orientation of the particles

Spatial and material design of multiphase systems

PP's vs PAs

Short glass fiber reinforced PP-GF for interior and exterior automotive applications – how far is PA-GF ?

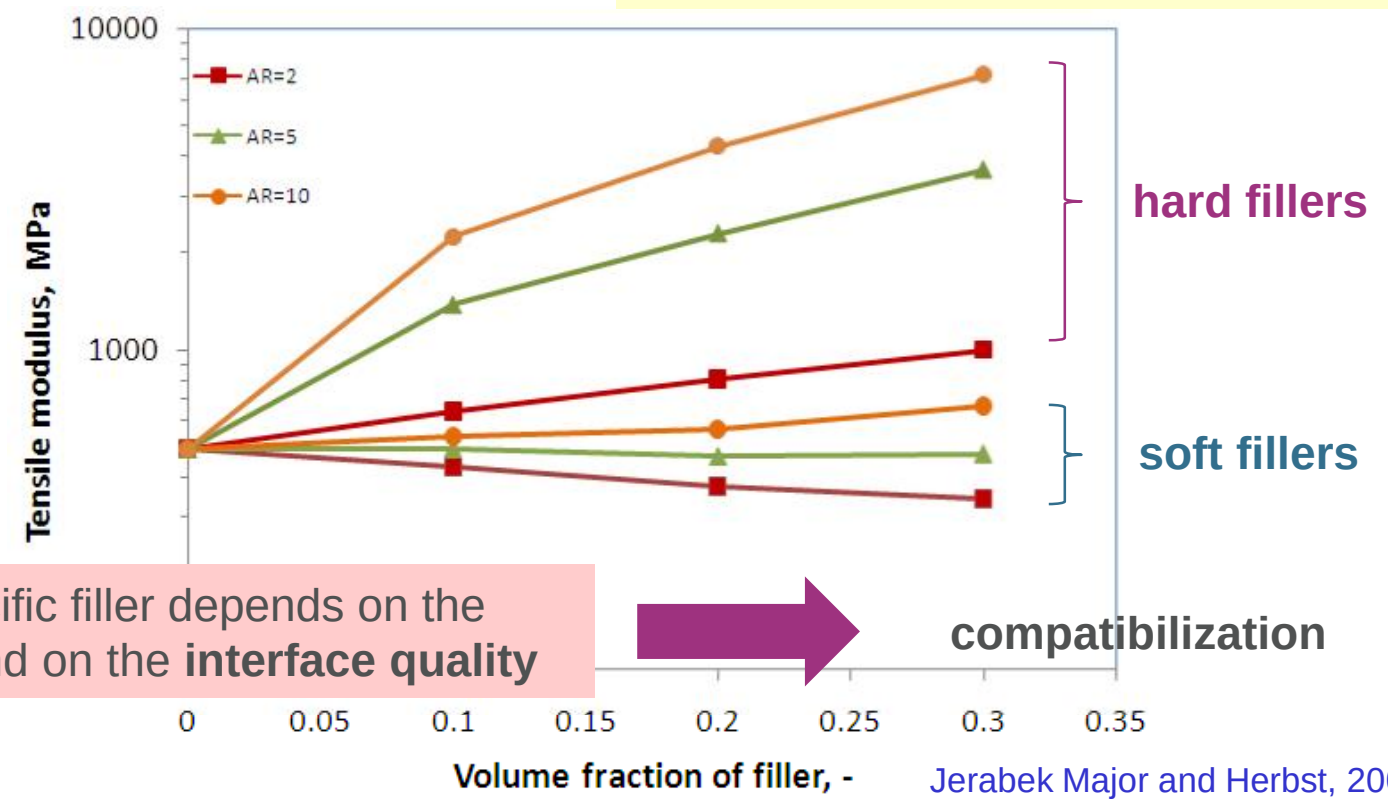
Rubber Modified PP and PA grades

E_{PP}=1200 - 2000 MPa < E_{PA} = 2000 – 3400 MPa

Stiffness for a specific filler depends only on the **matrix properties**

Toughness for a specific filler depends on the matrix and particle properties on the interface quality

EPP ⇒ 3000 MPa

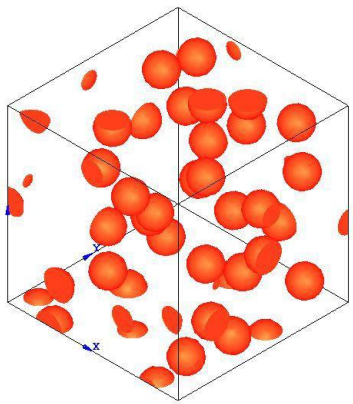


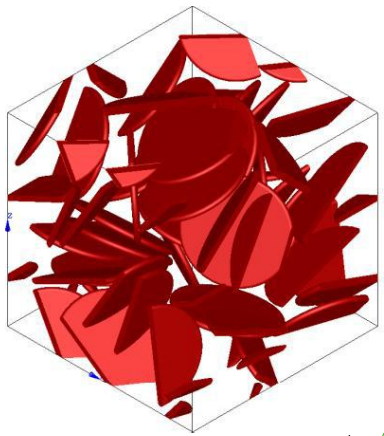
Strength for a specific filler depends on the matrix properties and on the **interface quality**

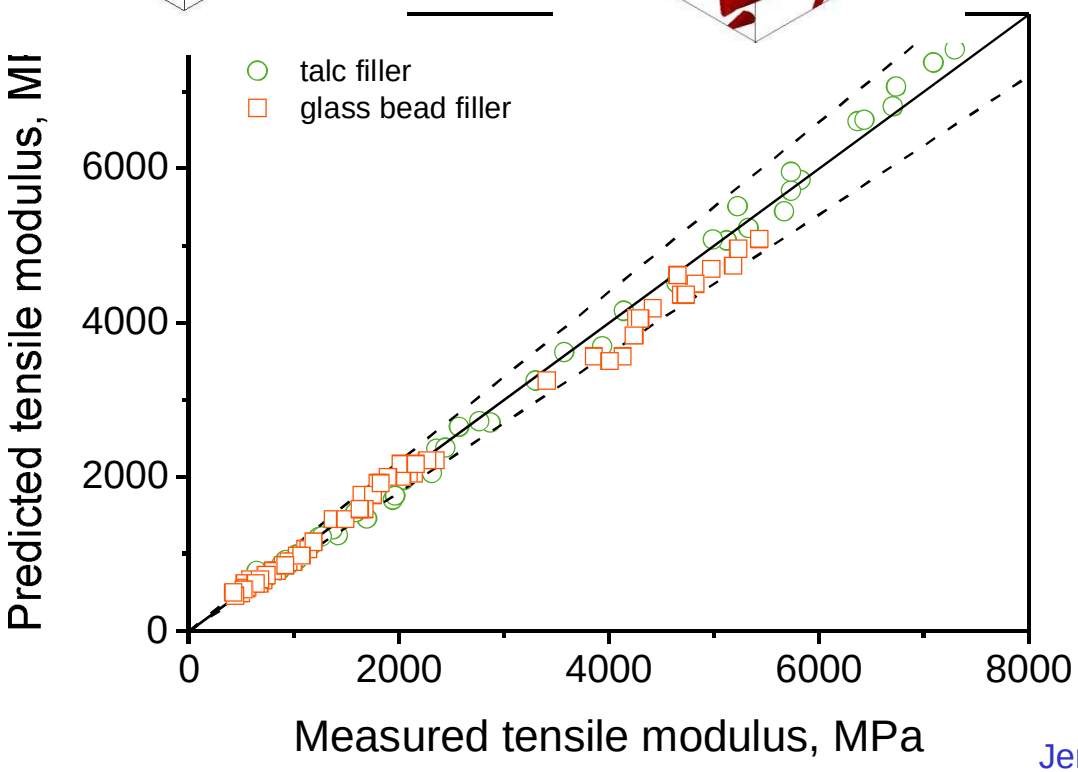
compatibilization

Jerabek Major and Herbst, 2007, Borealis

Deformation and Fracture Behavior of (Hard) Particle Filled Thermoplastics (Polypropylene (PP))

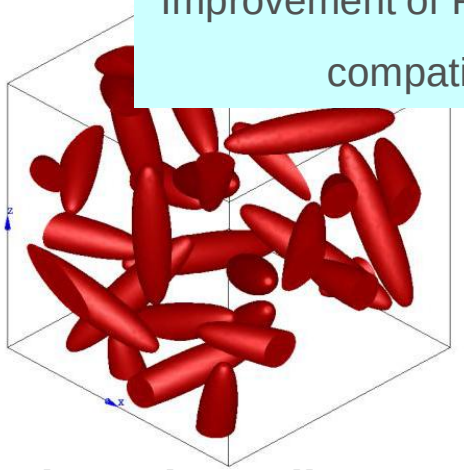




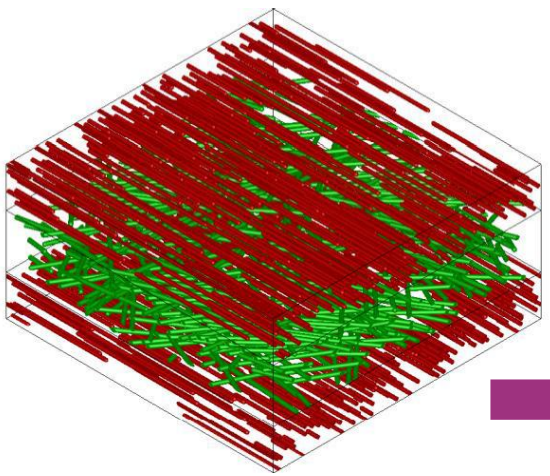


Aspect Ratio 10 to 50

Improvement of PP matrix compatibilization



Orientation, Alignment

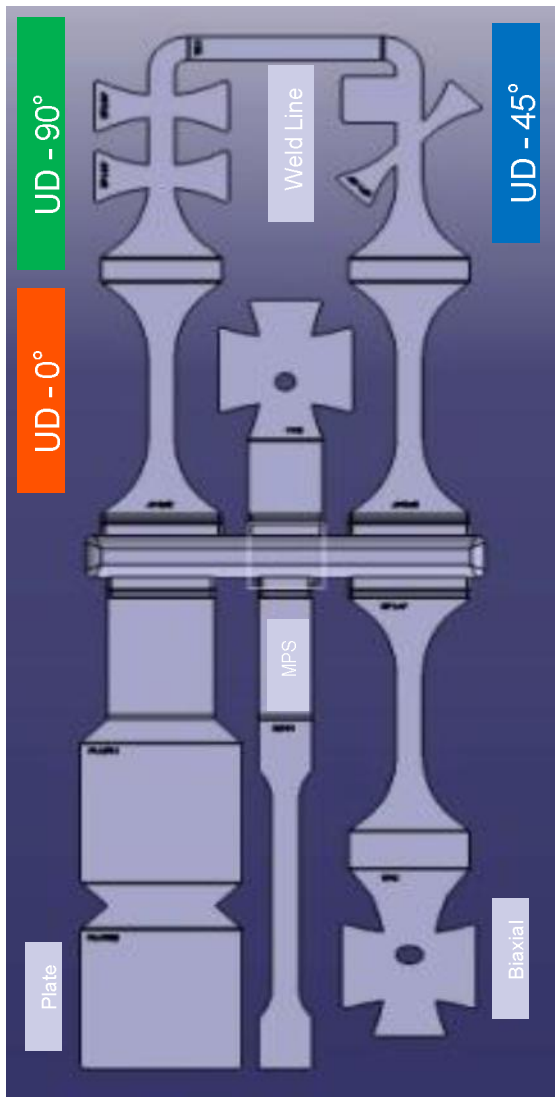


Discontinuous fibers, realized FOD/FLD

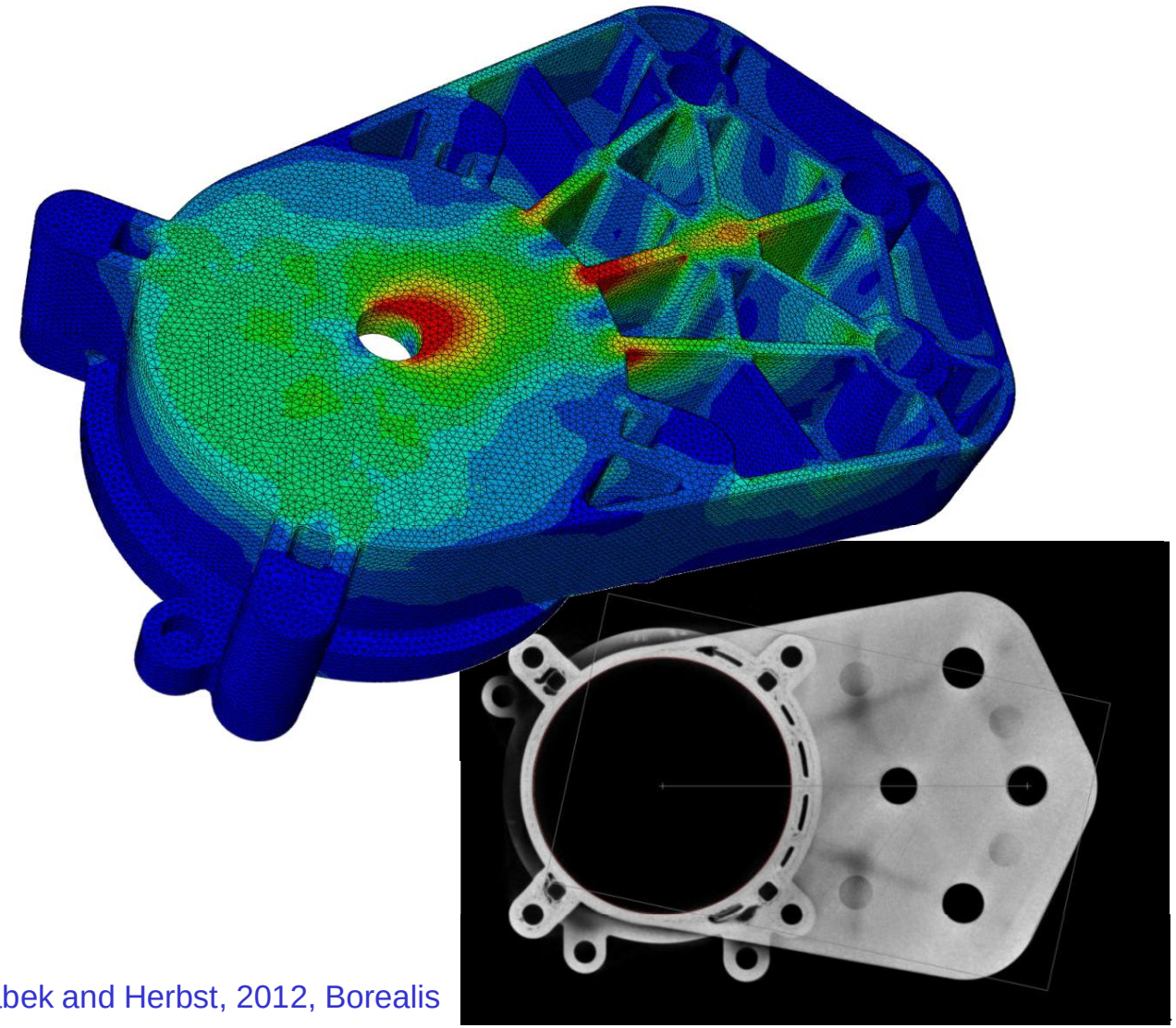
Jerabek Major and Herbst, 2007, Borealis

Short glass fiber reinforced, PP-GF

Laboratory Specimens



Model Components

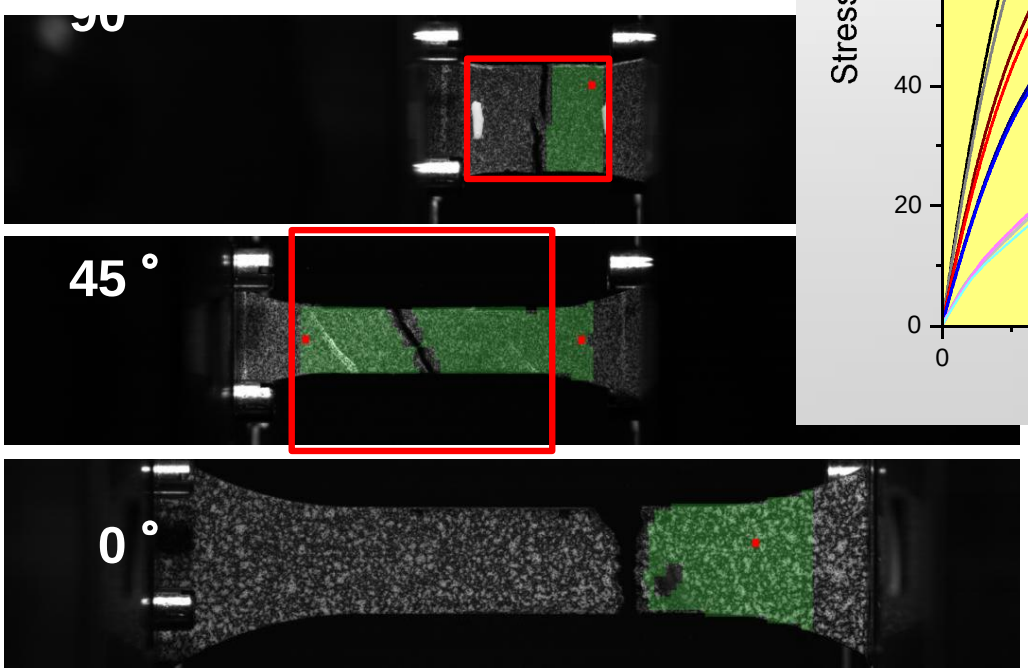


Jerabek and Herbst, 2012, Borealis

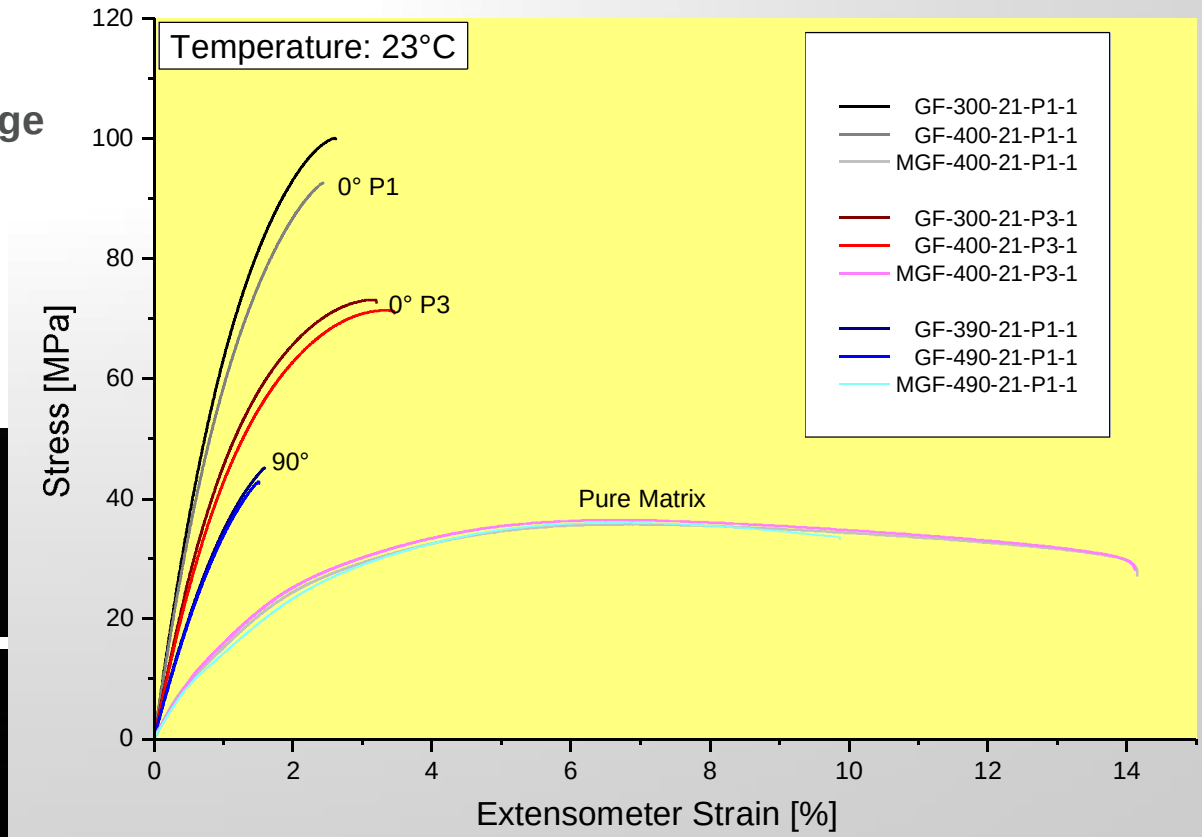
Short glass fiber reinforced, PP-GF – Experiments & Simulation

Strain Measurement

High resolution (12 Mpixel) digital image correlation (Aramis, GOM)



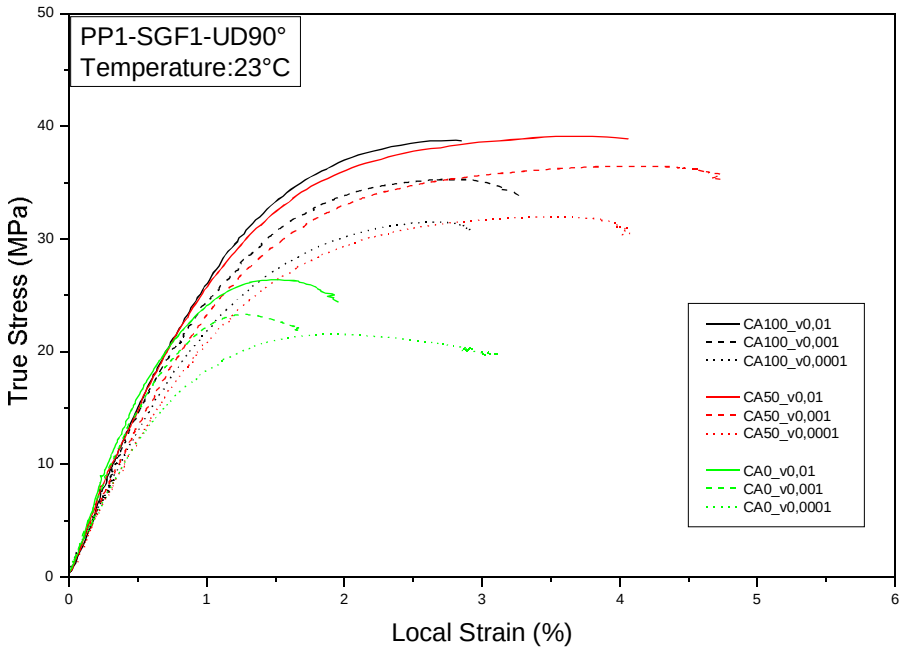
Fiber Orientation Dependence



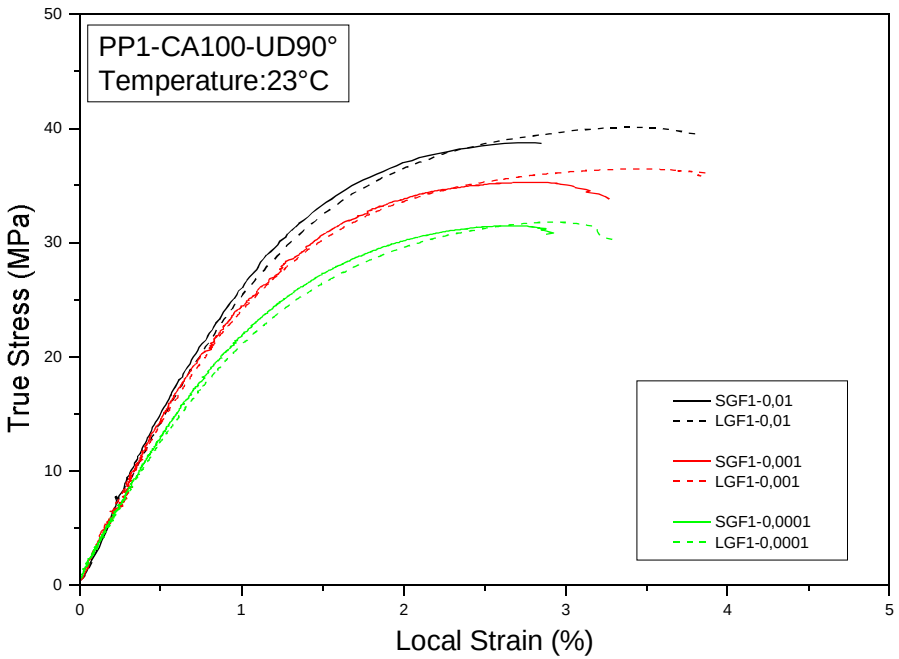
Hartl et al, 2012, ipmt

Short glass fiber reinforced, PP-GF - Experiments

Influence of the Interface Quality



Influence of the fiber (real) length

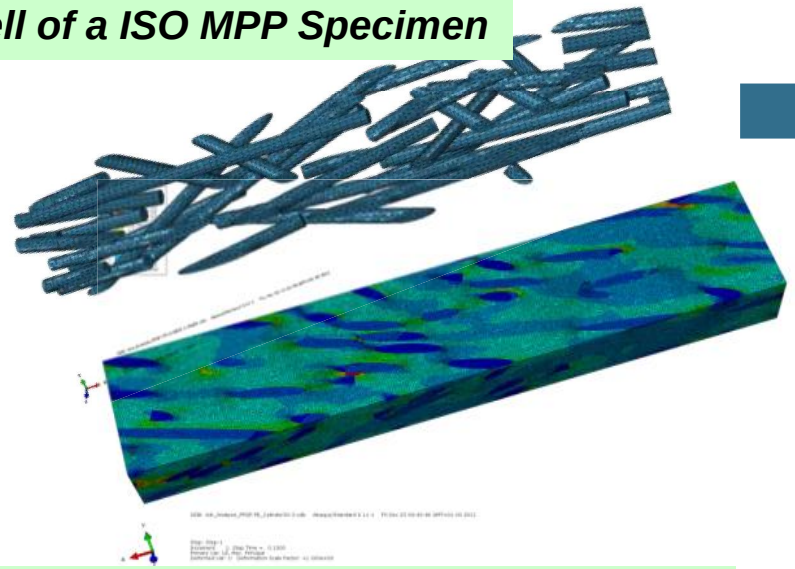


Hartl et al, 2012, ipmt

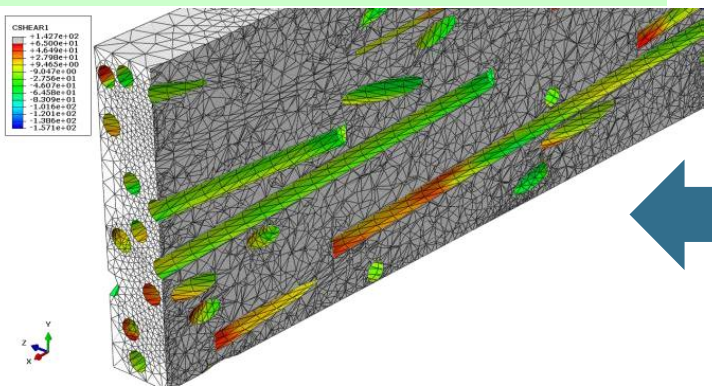
Failure Simulation

Assumption: Perfectly Bonded Interface

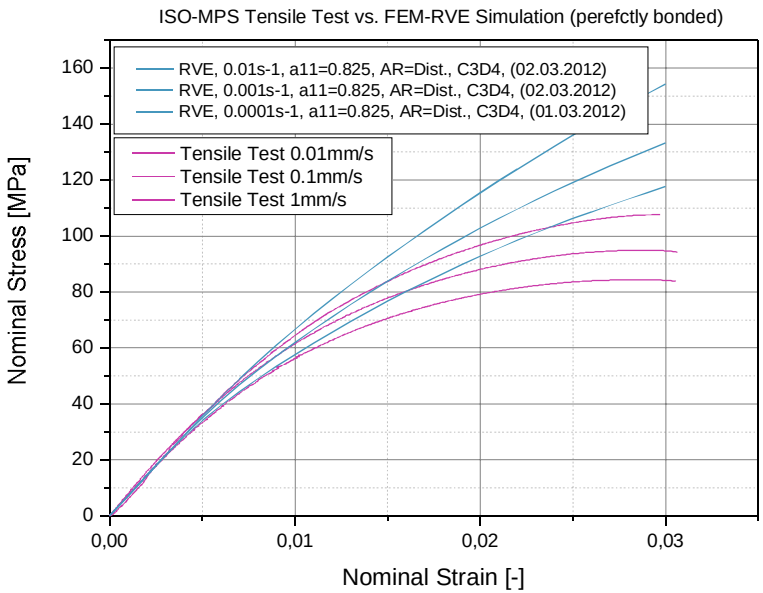
RVE cell of a ISO MPP Specimen

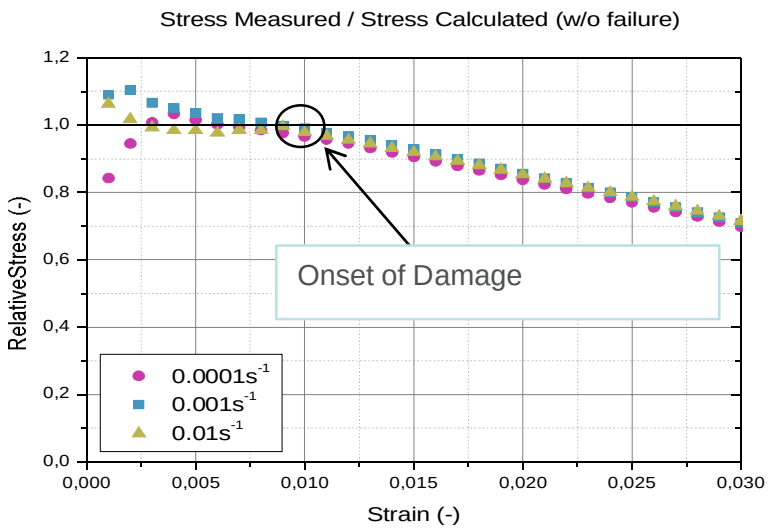


Cohesive Zone Model for the Interface



Comparison of Simulations and Experiments





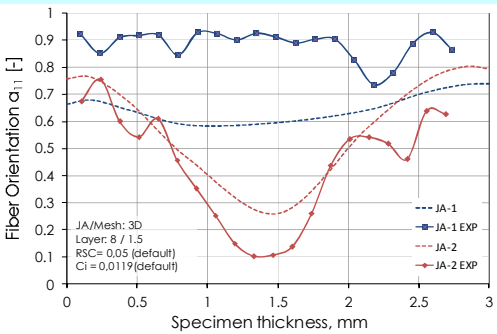
Need for Proper Material Parameters

Reiter, 2012

Component Simulation

Fiber Orientation Simulation

.... and verification (CT)



Meso-model based on first pseudo-grain failure (FPGF)

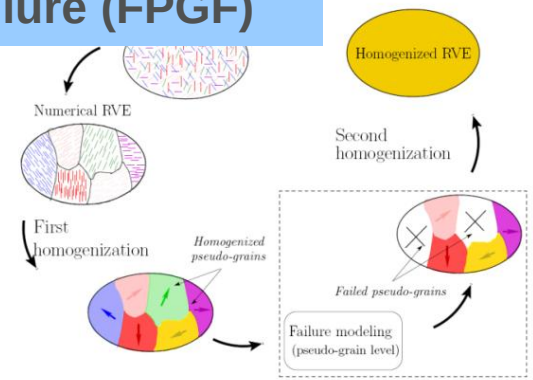
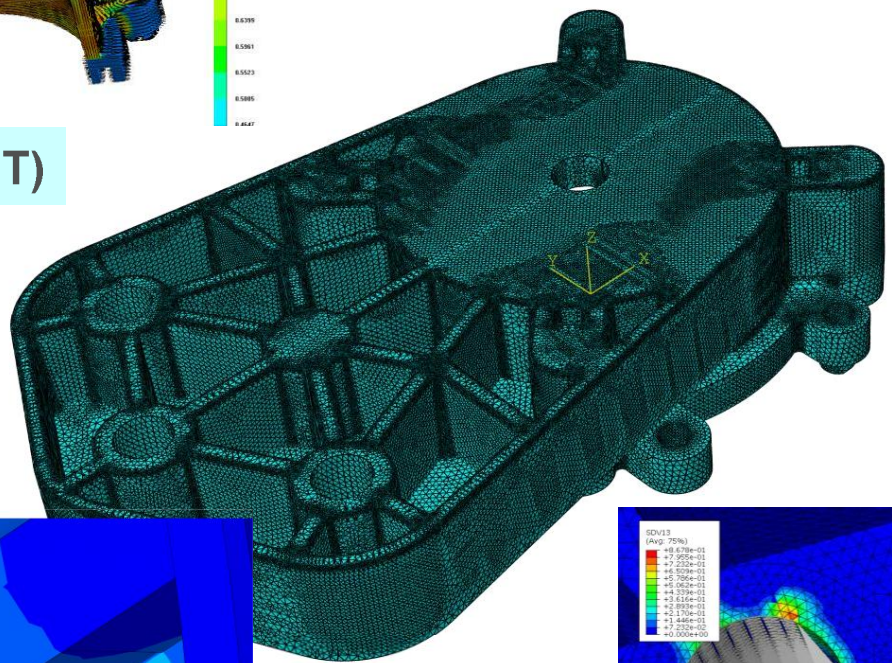
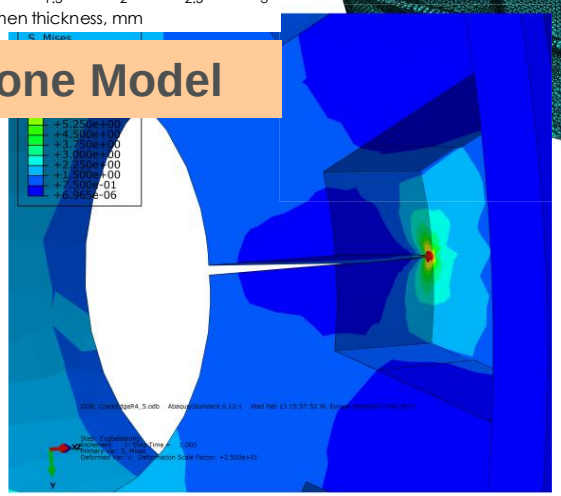


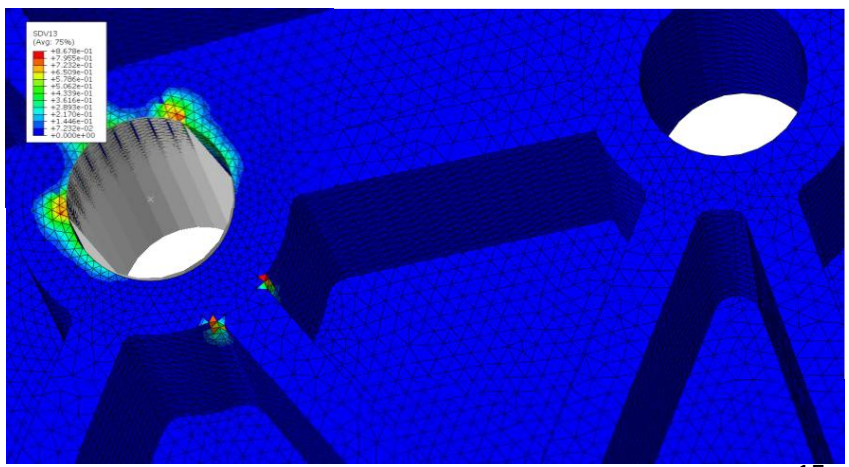
Figure 5: Schematic illustration of the FPGF model: real RVE, numerical RVE, two-step homogenization and PG failure.

Doghri et al, 2010



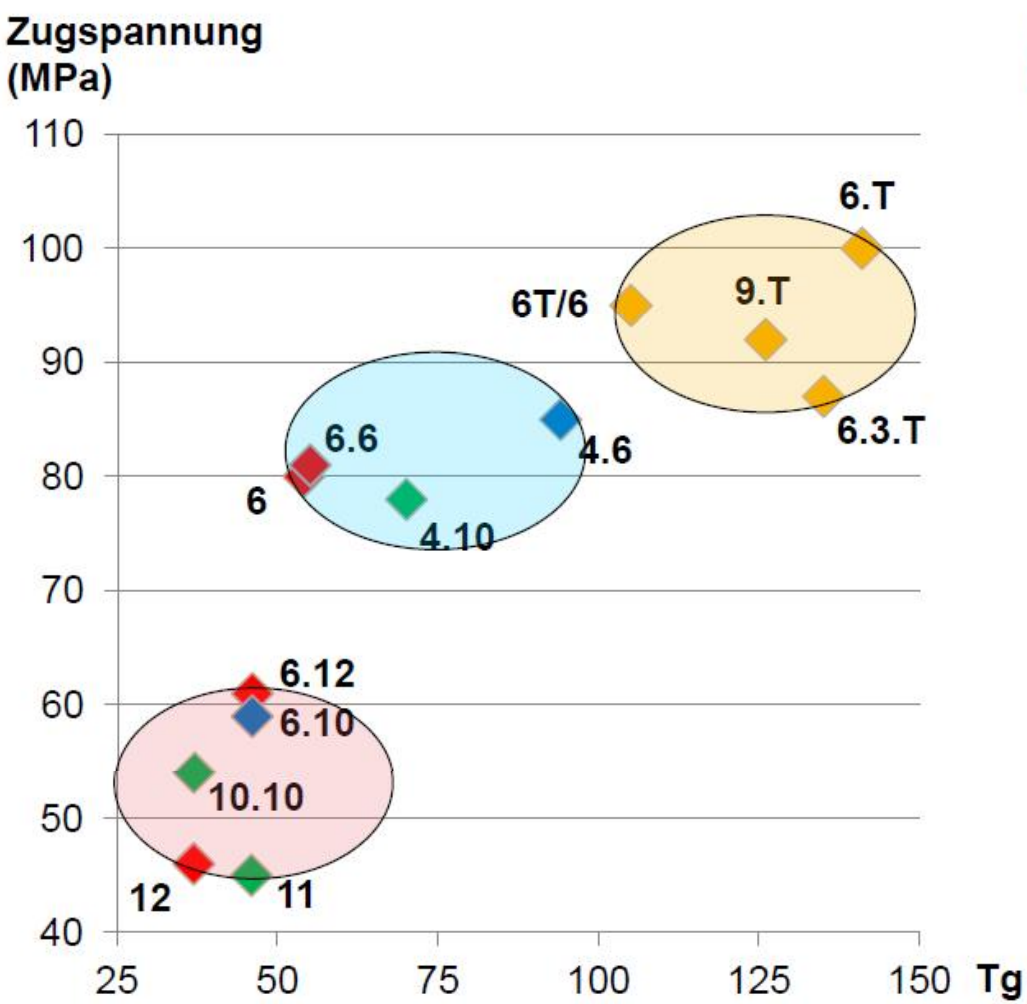
Cohesive Zone Model

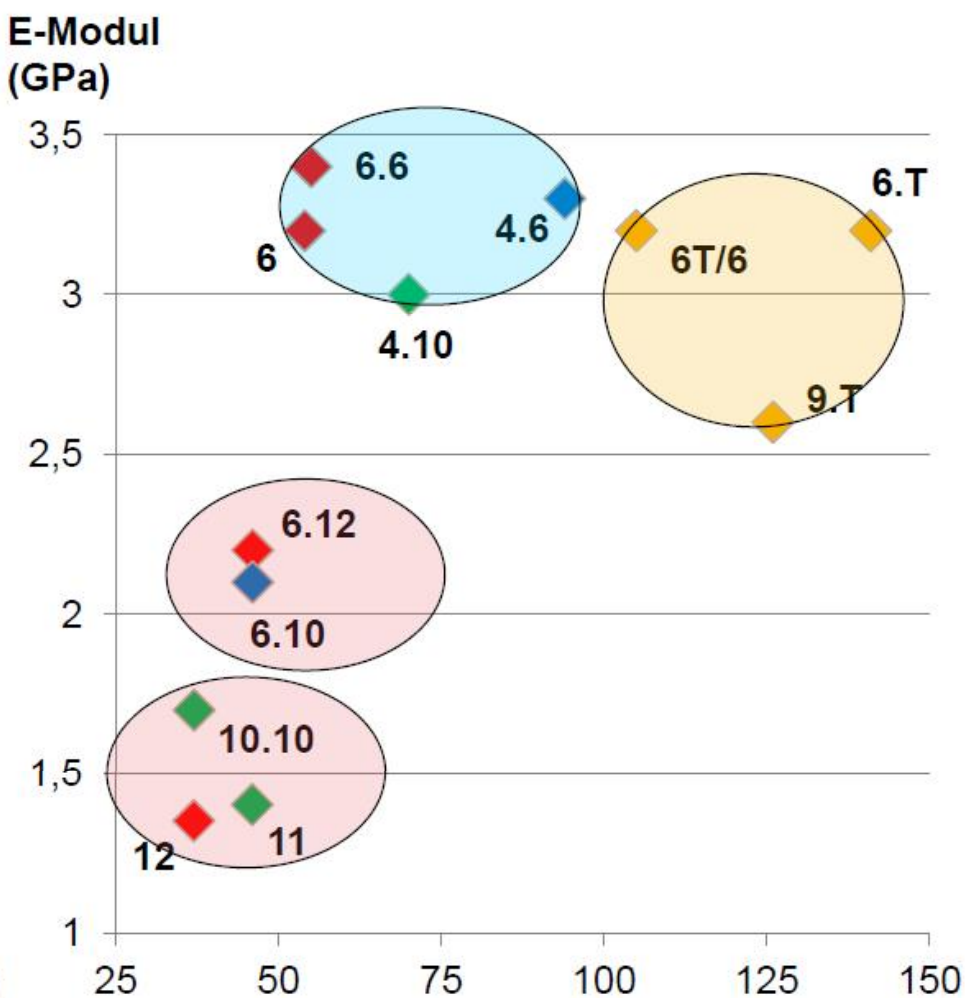




PA, Molekül-Design

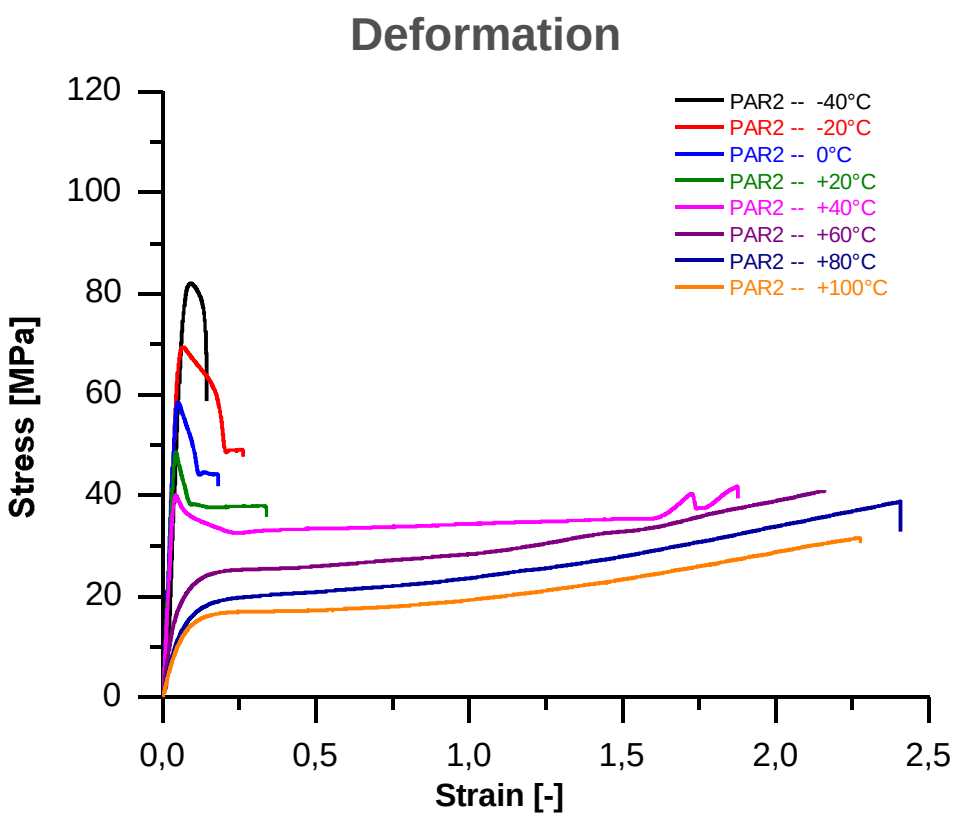
Thermo-mechanische Daten von PAs

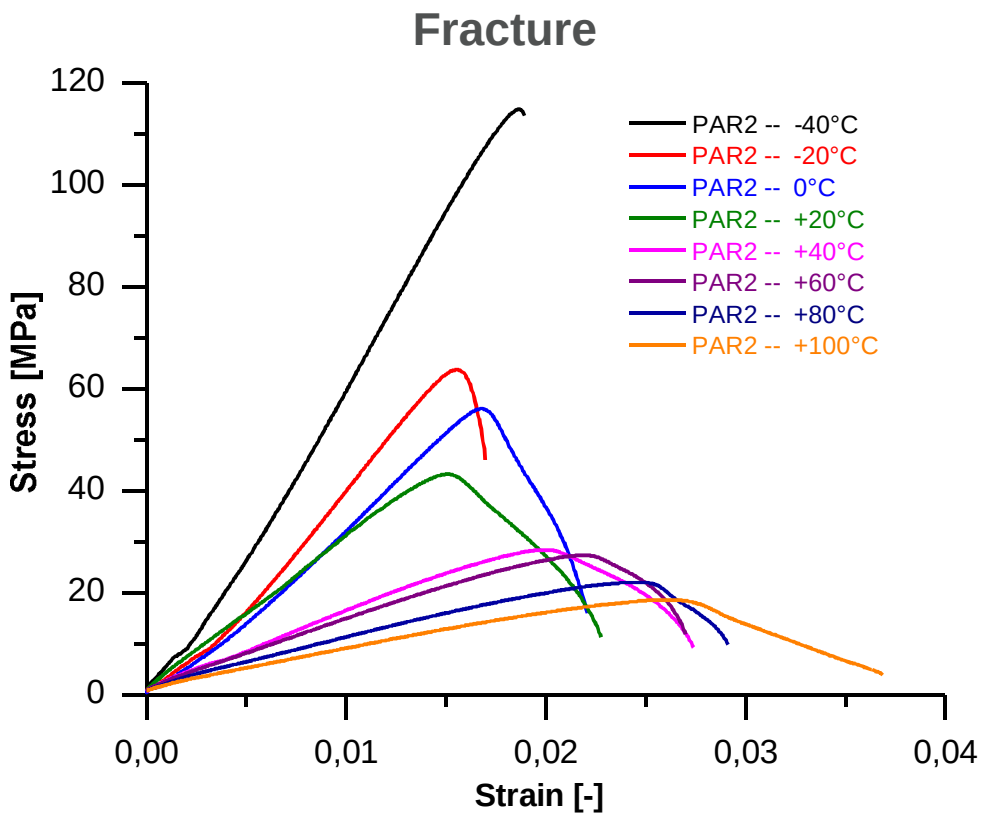




J. Stebami; Polyamid Inovationen,

Deformation and Fracture Behavior of (Soft) Particle Filled Thermoplastics (Polyamide PA)





Classics

Temperature and loading rate dependence

Deformation and Yield Models | **Novel** | **Cohesive Zone Models**

Stress state dependence (constraint)

Rubber Modified PA grades

PAR1; PA6+Ethylen-Okten unmodified,

PAR2; PA6+ Ethylen-Okten MAH grafted,

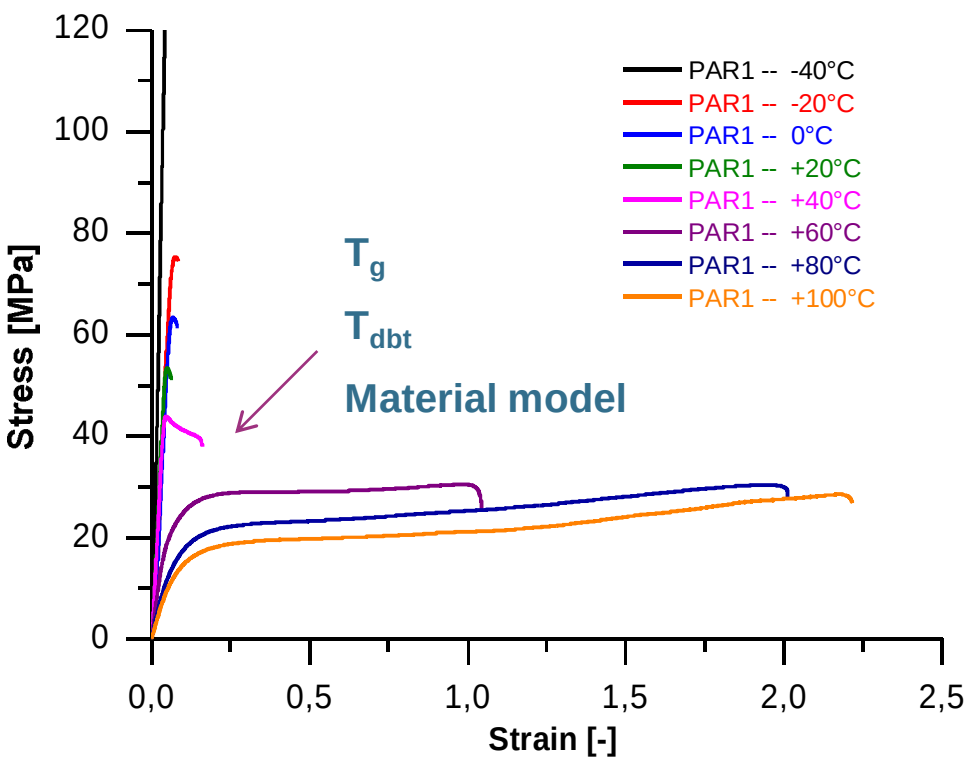
PAR3; PA6+ Ethylen-Okten mixture, unmodified, grafted,

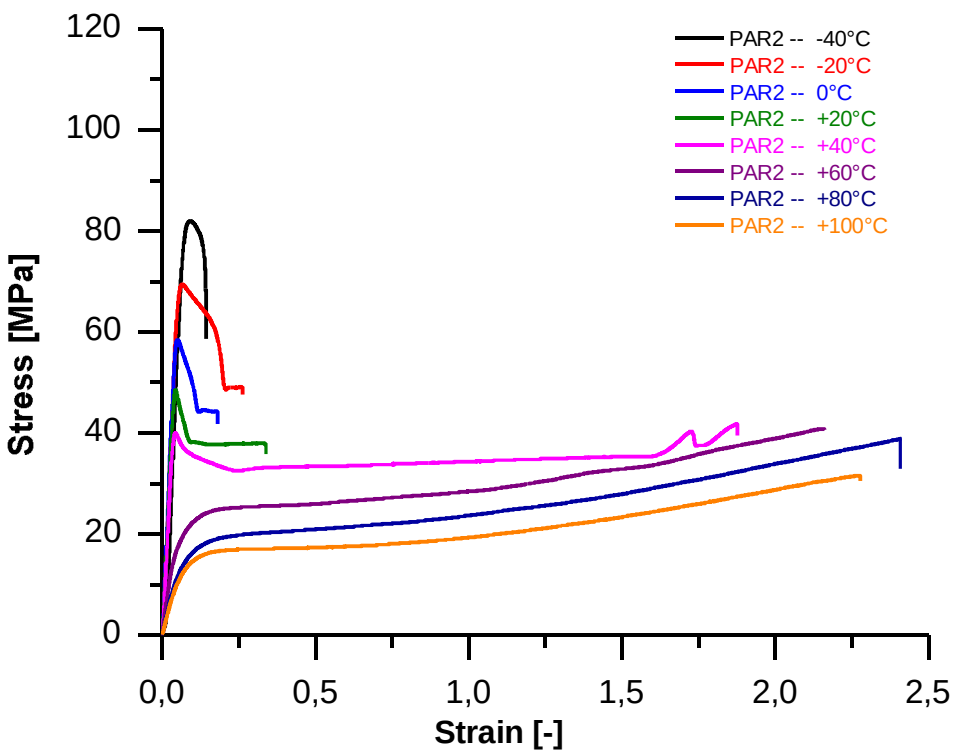
PAR4; PA6+ Ethylen-Okten–Butylen, MAH grafted and

PAR5; PA6+ Ethylen-Okten-Butylen, MAH-grafted with approximately double MAH content,

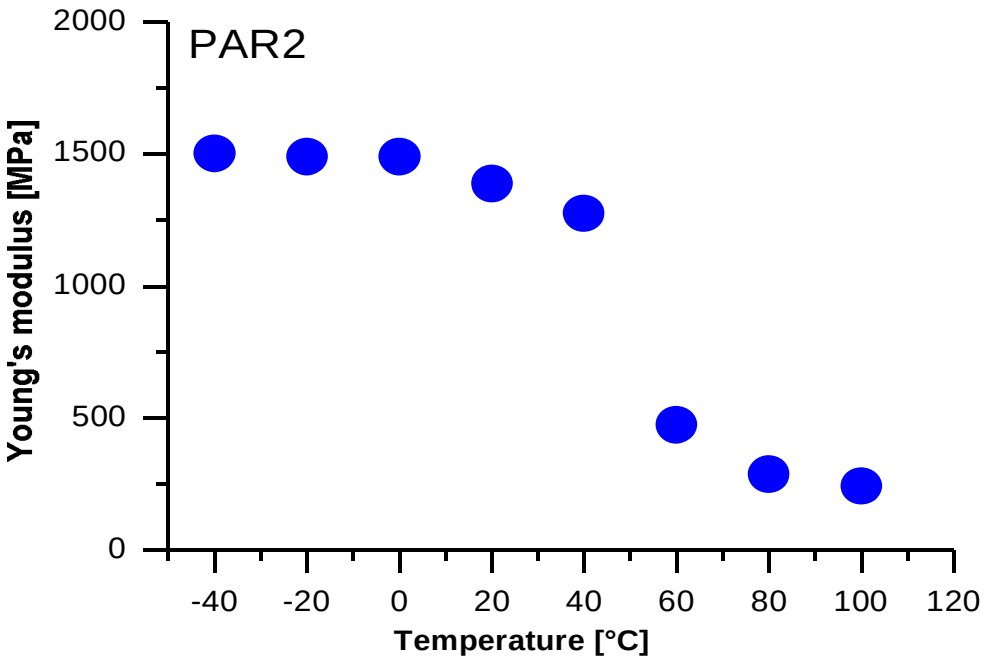
Temperature dependence,

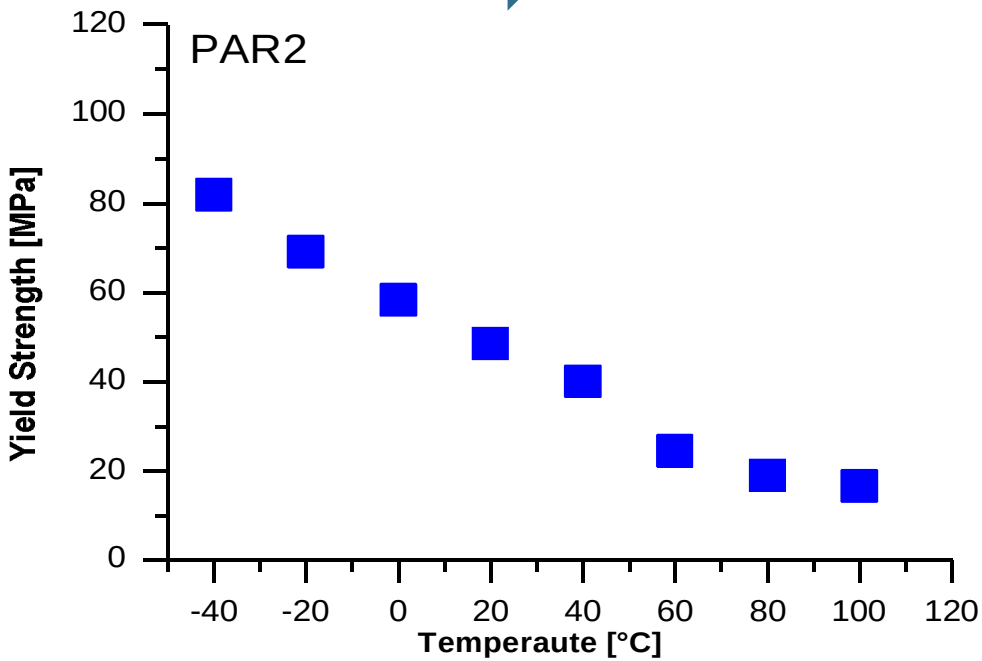
Ductile-brittle transition, modeling approach



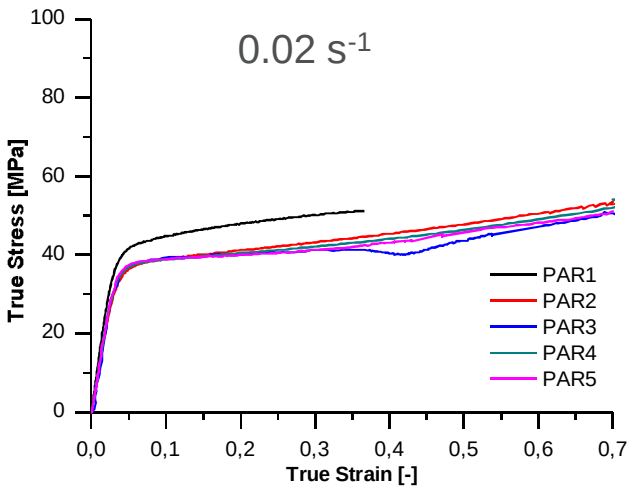


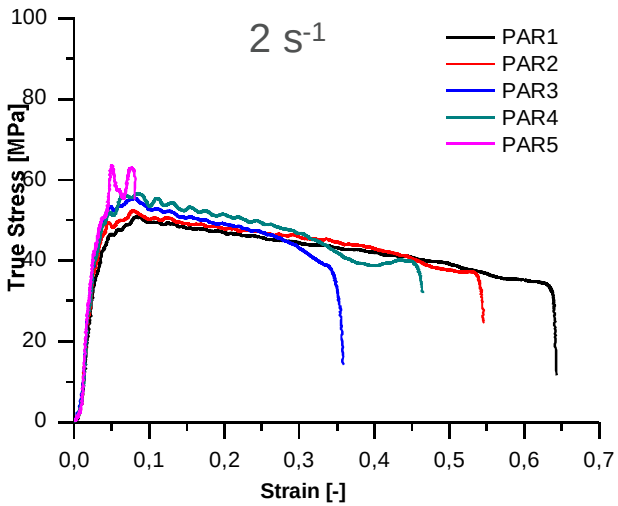
Relevant Model parameters below and above T_g





Rate Dependence



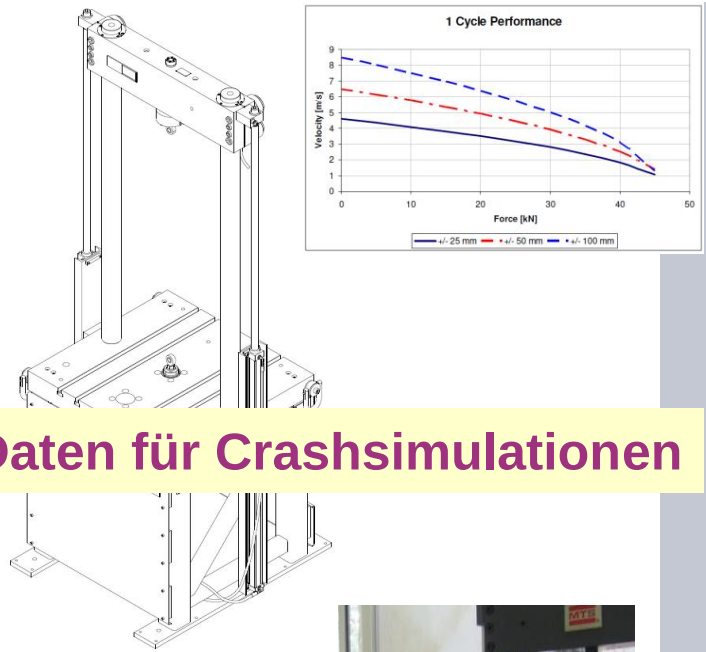


200 s^{-1} ??

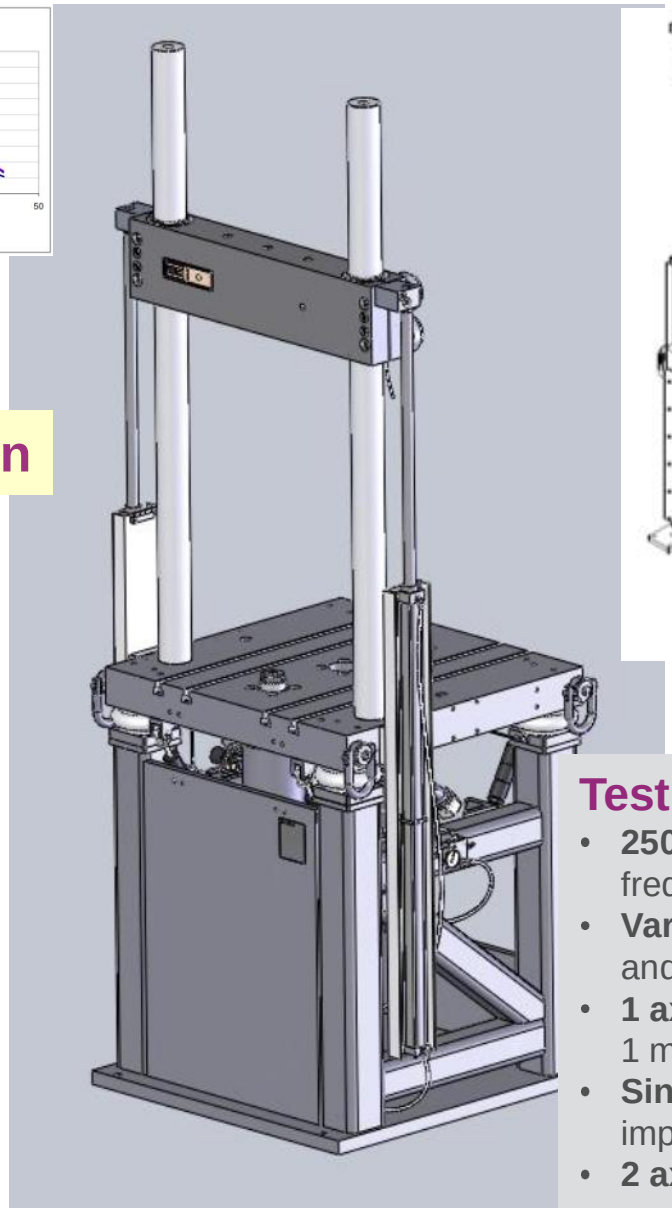
Development of

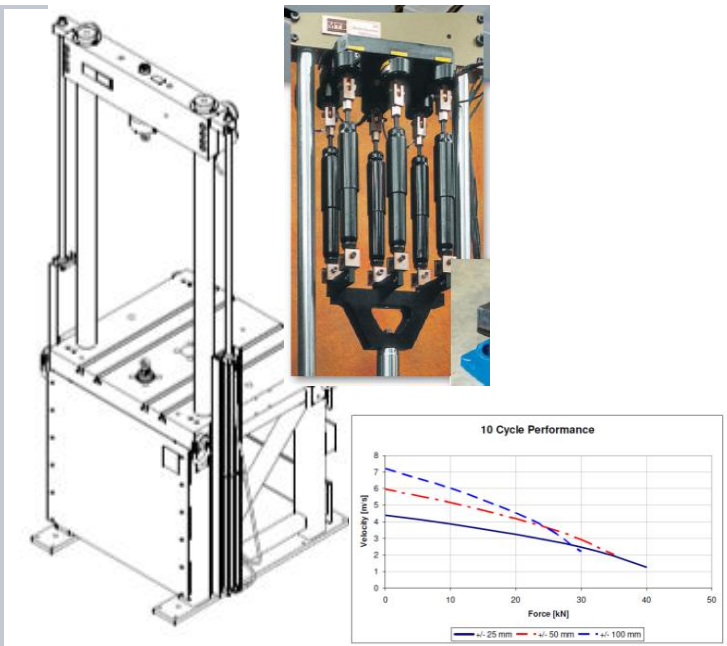
- testing machine
- test methods and
- simulation

Introduction of a novel servohydraulic multiaxial high rate test system



Daten für Crashsimulationen





Bauteilprüfung (Verifizierung)

Test System

- **250 kN load frame** (for quasi-static or low frequency (<20 Hz) loading)
- **Variable position** of the actuator (mid/edge) and the frame (mid/edge)
- **1 axis:** max. **50 kN**, **12 m/s**, 200 Hz/0.2 mm, 1 m/s/50 kN,
- **Single (1 cycle)** and **multiple (< 10 cycles)** impact ! (**4 m/s**)
- **2 axes**: max 7.5 kN, 4 m/s, 200 Hz/0.3 mm

Introduction of a novel servohydraulic multiaxial high rate test system

High Speed Image Acquisition

and

Temperature Chamber

in selection

High Speed Data Acquisition (Gen2i, HBM)

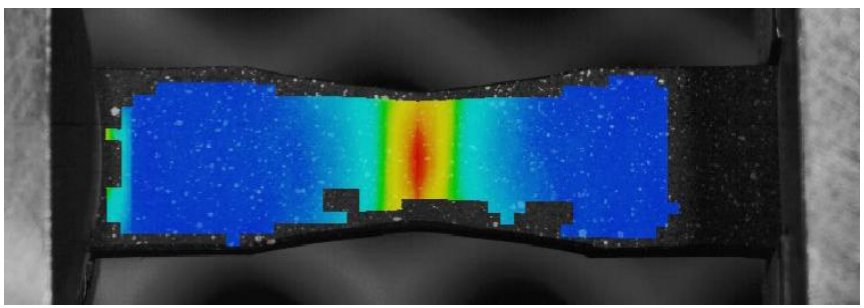
4 Ch SG, 1 Ms/s

4 Ch, U, 25 Ms/s

Impact Test Methodology

Test Specimen Level

- ISO MPP and Cylindrical Specimens
- Tensile (uniax and planar), compression and shear set-up
- High Speed camera (500 kS/s), DIC, FFSA (Aramis)
- -60 ° C < Test Temperature < 180 ° C
- **Biaxial in-plane (out of plane is available for thermoplastics !)**
- **Specimens with varying constraints – GISSMO methodology**



Component Level

- Full Scale testing of Chassis Elements of Passenger Cars and Trucks up to 1.2 x 1.8 x 0.8m, at RT and
- **0.8 x 0.8 x 0.8 m in Temperature Chamber**
- **32 Ch moderate rate and 8 Ch high rate data acquisition**

Service scale loading test of all kind of damping elements for vehicles

- Air springs
- Suspensions
- Shock absorbers

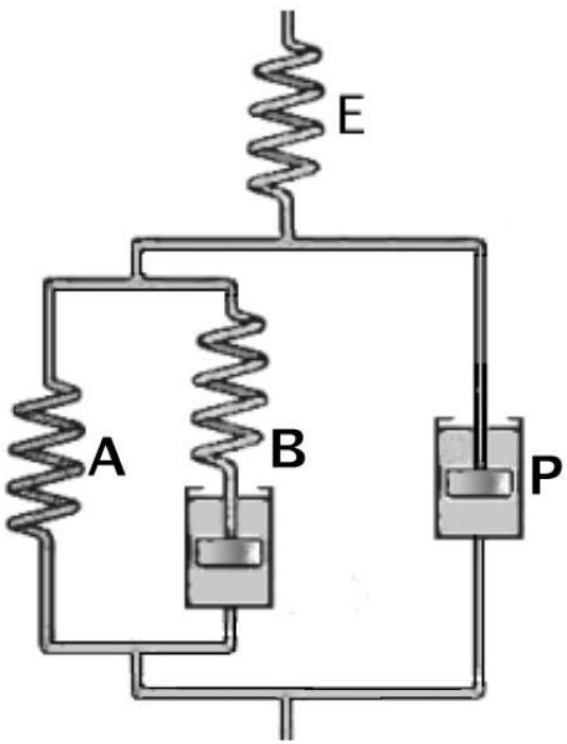
Full scale viscoelastic analysis

Simulation Models - Modeling of soft thermoplastic materials

Bergström-Boyce (BB) Models: Arruda-Boyce (2006), Hybrid (2007), Three Network (2009)

$$T_C = \frac{1}{1+q}\left\{\frac{\mu_C}{J\,\lambda_{chain}}\frac{\Lambda^{-1}(\overline{\lambda^*}/\lambda_A^{lock})}{\Lambda^{-1}(1/\lambda_A^{lock})}dev[B^*] + \kappa(J-1) + q\frac{\mu_C}{J}\left[I_1^* B^* - \frac{2I_2^*}{3}I - (B^*)^2\right]\right\}$$

The Cauchy stress acting on network C is given by the eight-chain model with first order I_2 dependence given by above Eq., where q gives the I_2 dependence



Bergström, 2012

Index	Symbol	Umat Name	Unit*	Description
1	μ_A	muA	S	Shear modulus of network A
2	$\hat{\theta}$	thetaHat	T	Temperature factor
3	λ_L	lambdaL	-	Locking stretch
4	κ	kappa	S	Bulk modulus
5	$\hat{\tau}_A$	tauHatA	S	Flow resistance of network A
6	a	a	-	Pressure dependence of flow
7	m_A	mA	-	Stress exponential of network A
8	n			nential
9	μ_{Bi}			lus of network B
10	μ_{Bf}	muBf	S	Final shear modulus of network B
11	β	beta	-	Evolution rate of μ_B
12	$\hat{\tau}_B$	tauHatB	S	Flow resistance of network B
13	m_B	mB	-	Stress exponential of network B
14	μ_C	muC	S	Shear modulus of network C
15	q	q	-	Relative contribution of I_2 of network C
16	α	alpha	T^{-1}	Thermal expansion coefficient
17	θ_0	theta0	T	Thermal expansion reference temperature

*where: - = dimensionless, S = stress, T = temperature

17 material parameters

PA's vs PEEK

Combination of bulk and tribological loading – plastic gears

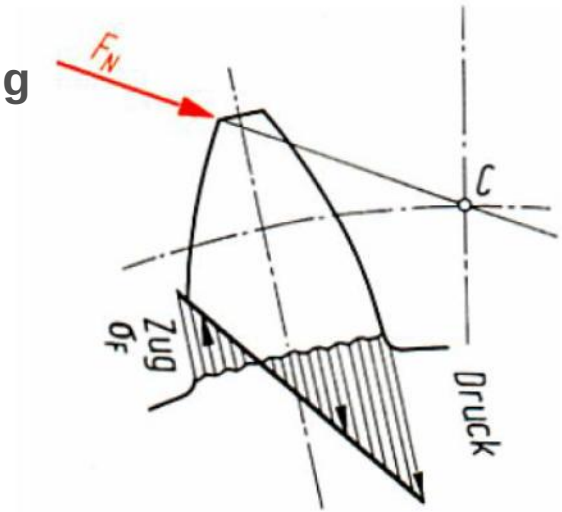
Tooth bending

σ–ε(T, SR, Co)

Strain accumulation

Fatigue

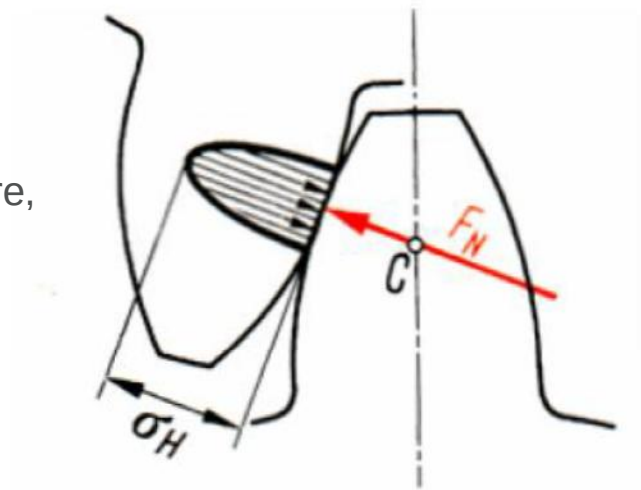
Fretting fatigue



Cyclic Loading

Contact

- Contact pressure, confined compression
- Friction
- Wear



Rapid Prototyping

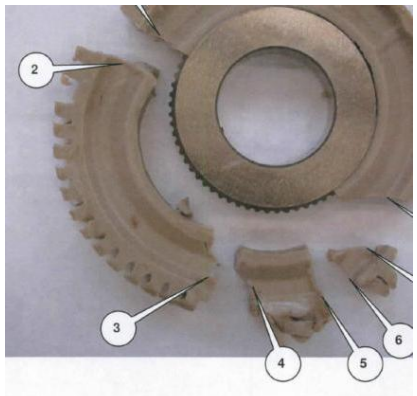
- **Fused Deposition Modeling (FDM)**
  - ABS
  - PC, PC-ABS
  - PPSU
  - amorphous thermoplastic polyetherimide (PEI)
- **3D printing**
  - Single and multiple Objet materials
  - **Meso-Scale Models**
- **Selected Laser Sintering**
  - PA's
  - PEEK

No pressure in the process

Plastic Gears

PA's vs PEEK

Fig. 2. Polymer composite gear.



Fatigue

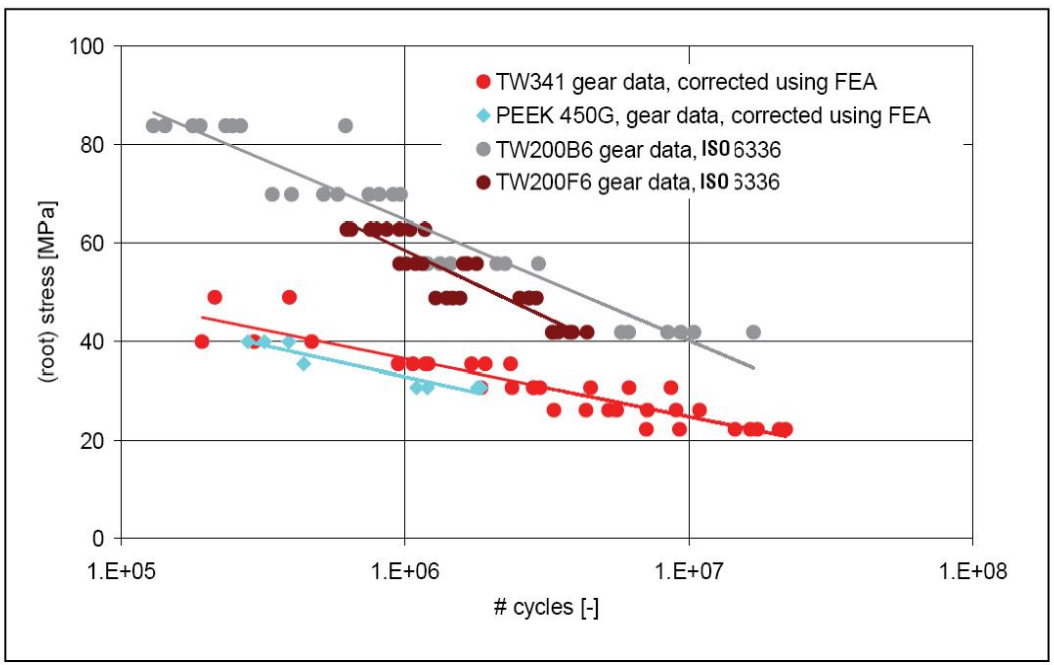
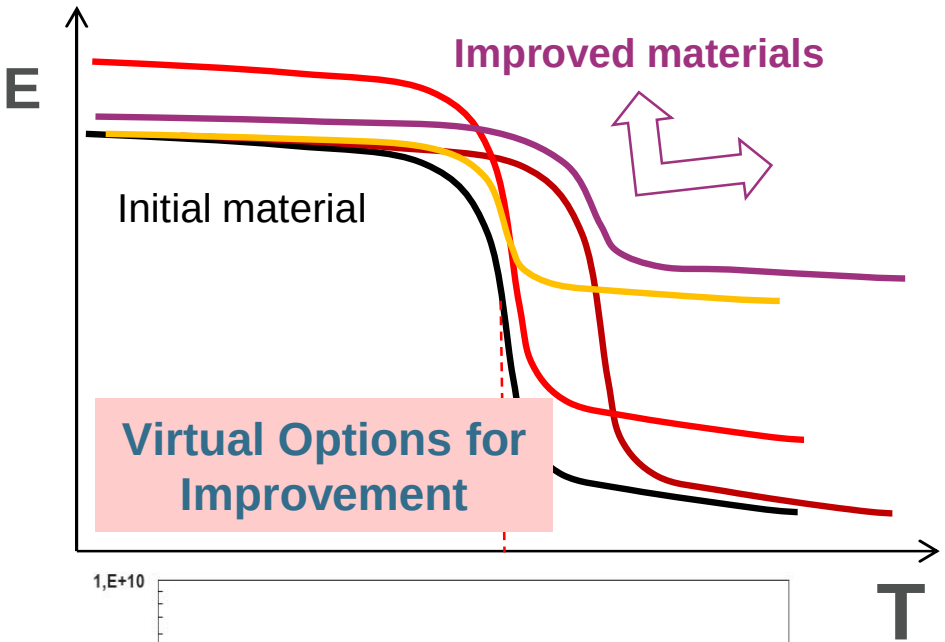
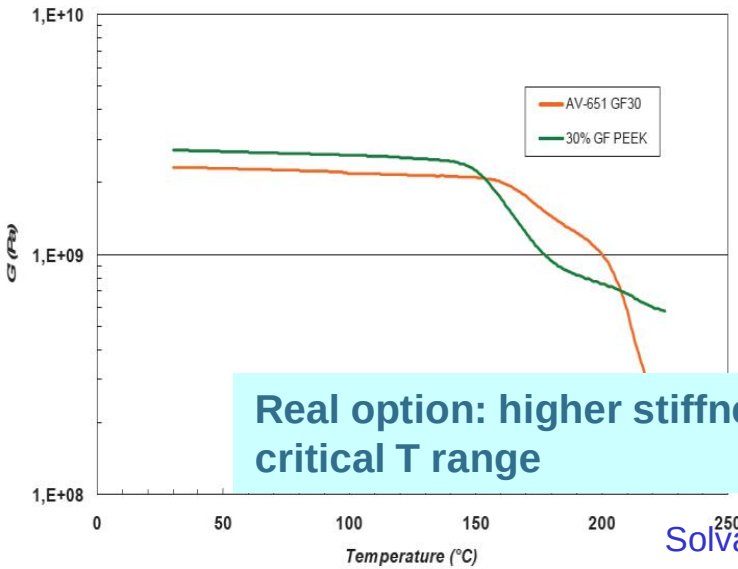


Figure 12—Gear fatigue results at 140°C under oil lubrication for various Stanyl grades and a PEEK material.

PEEK vs PEK/PAEK

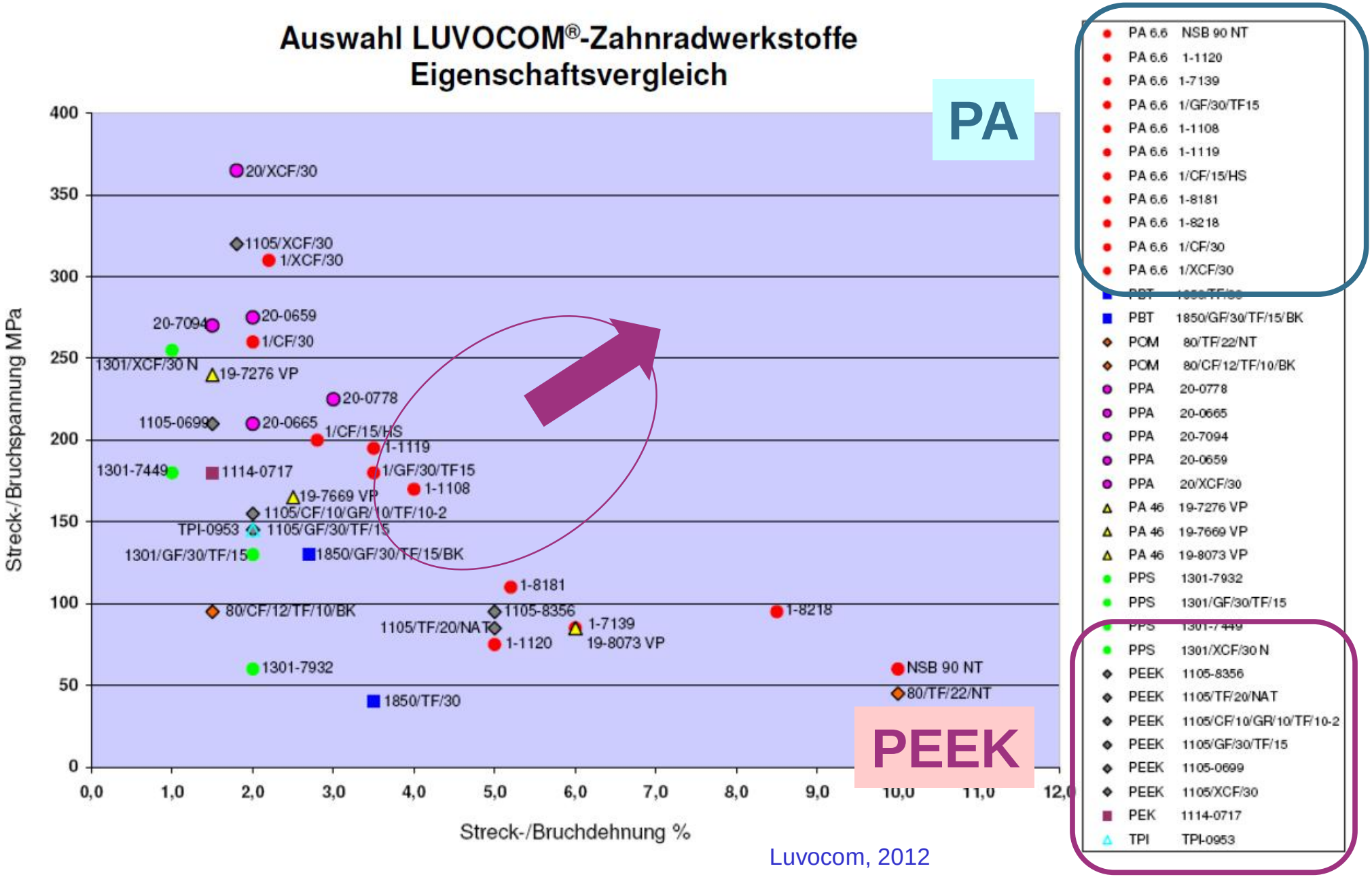




Real option: higher stiffness in critical T range

Solvay, 2012

Case Study 3 – PEEK's for Gears



Luvocom, 2012

Bulk vs Tribological Performance

Wear Resistant Compounds

Polymer Matrix

- HT resistance,
- easy processibility

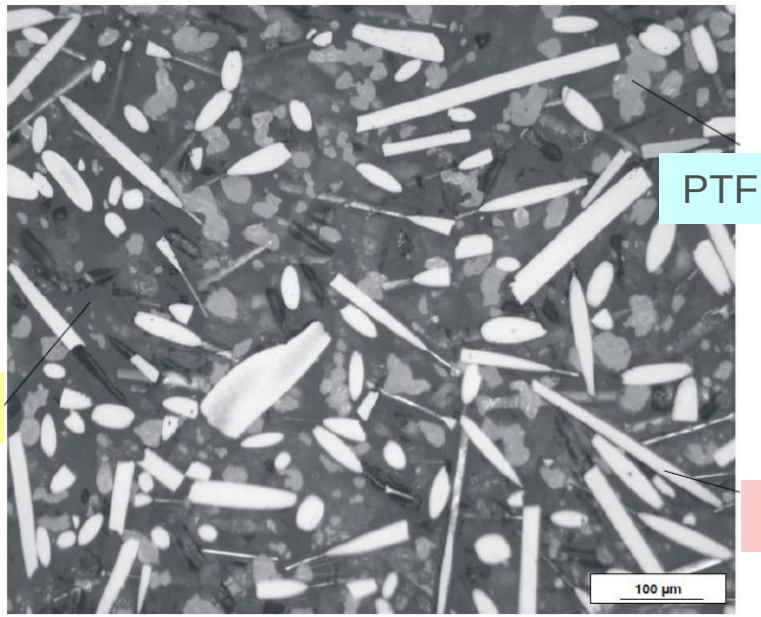
Fiber reinforcements

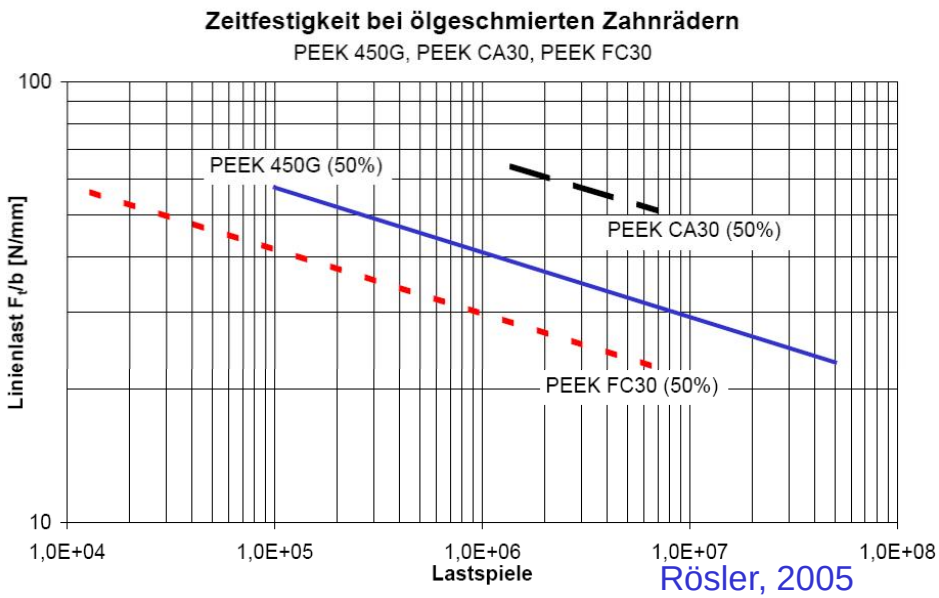
- Improved, stiffness and creep resistance
- Improved strength and wear resistance

Additive fillers

- Internal lubrication, transfer film formation
- Increased heat conductivity
- Smoothening of the surface roughness

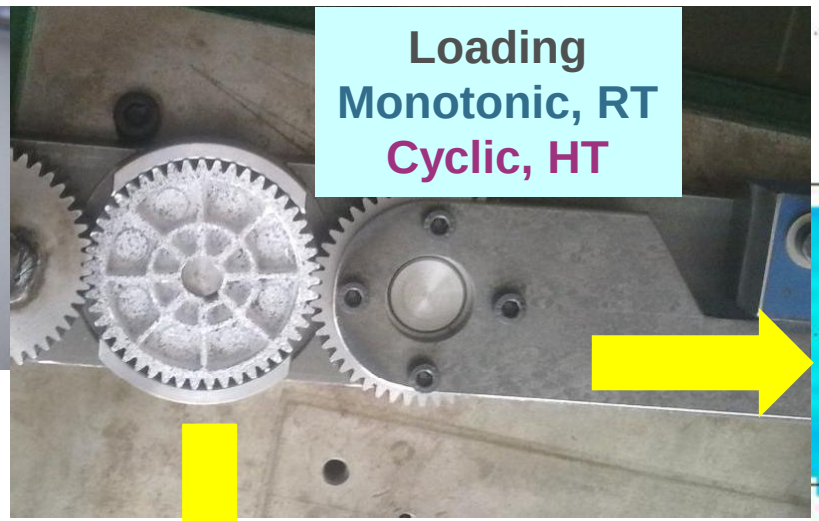
Friedrich, 2008

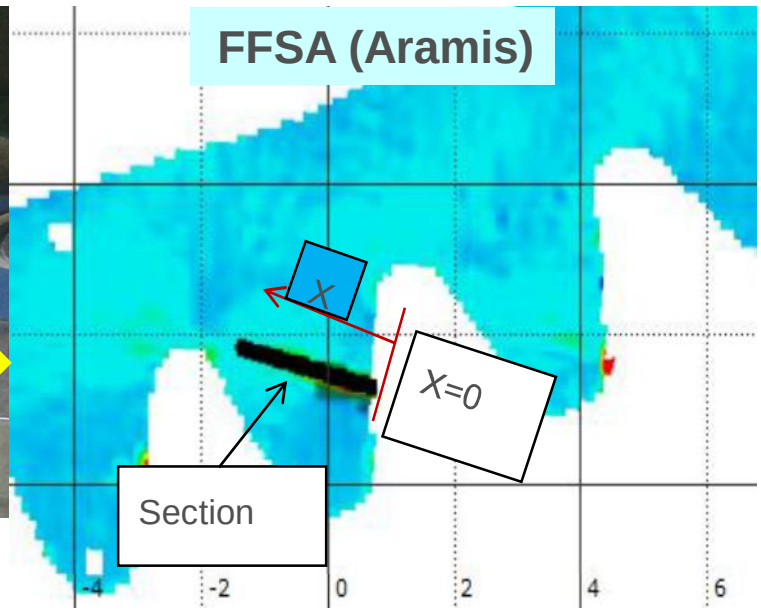


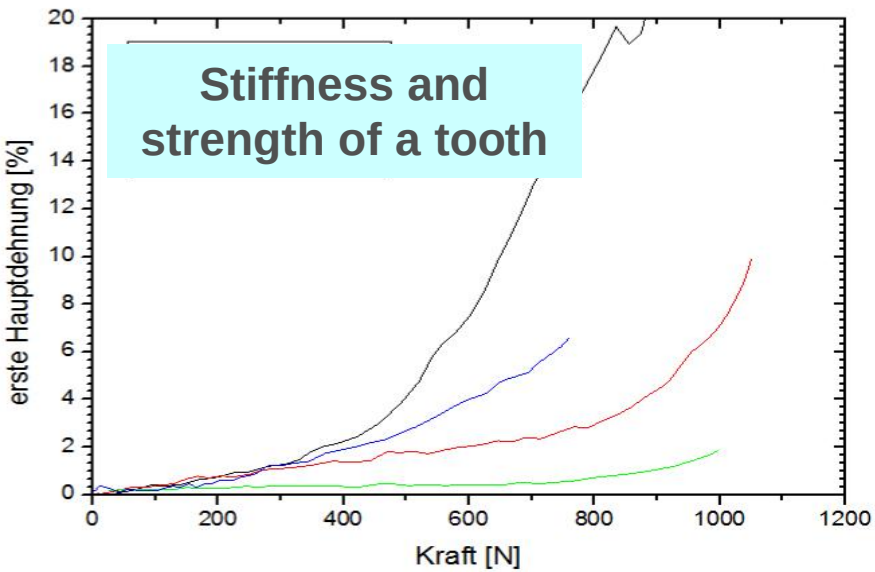


Rösler, 2005

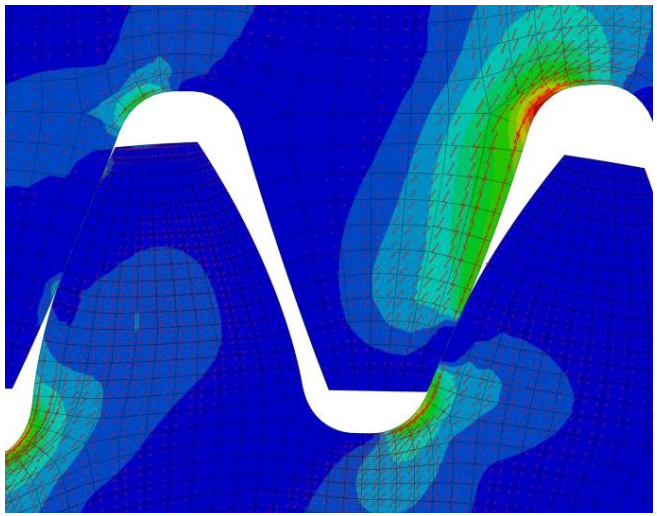
Component level - Experiments

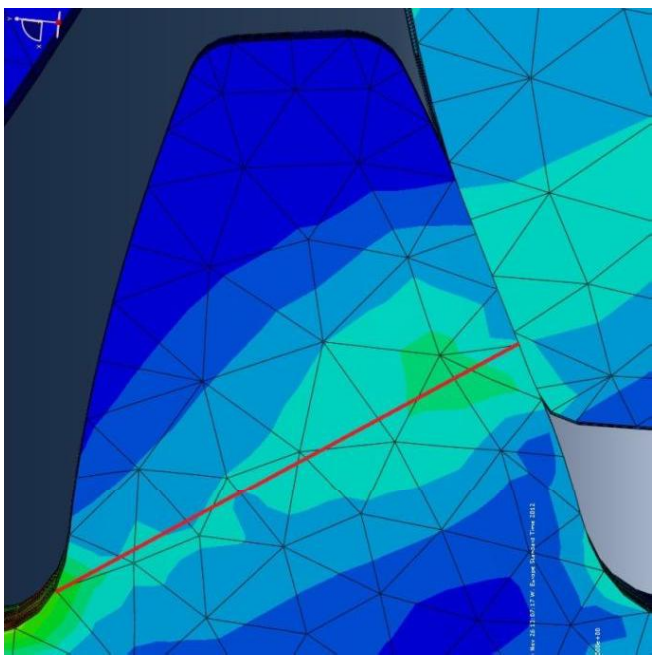




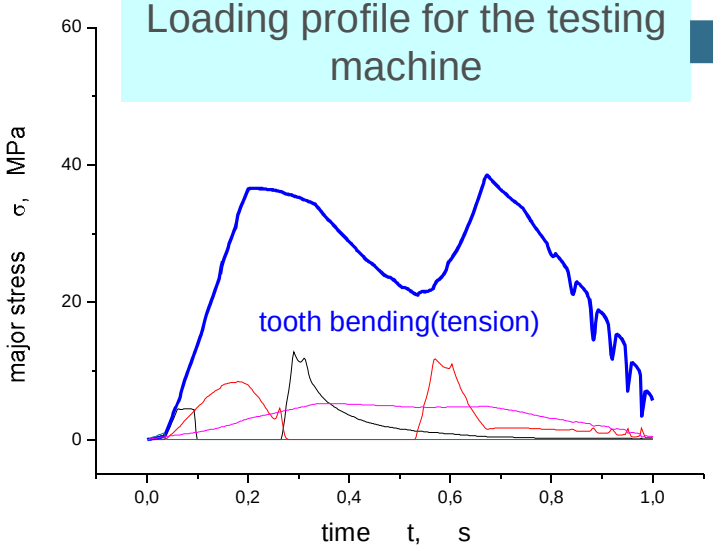


Component level – Simulations 1

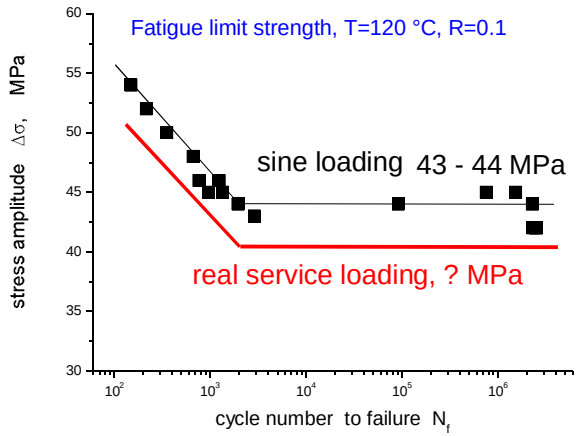




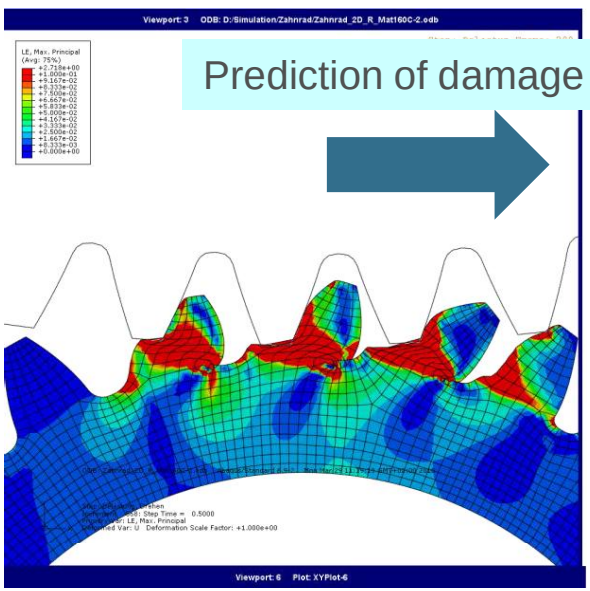
Loading profile for the testing machine

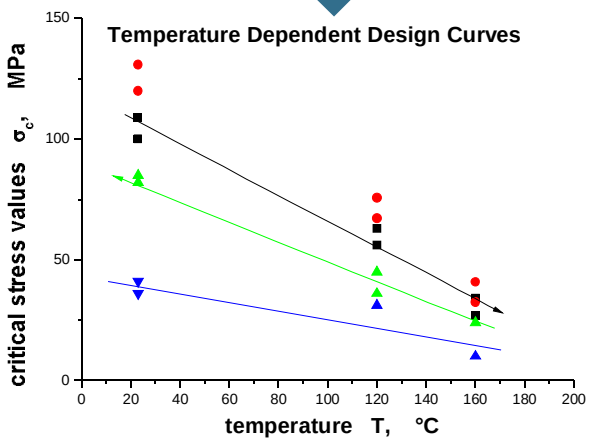


Fatigue Test



Prediction of damage

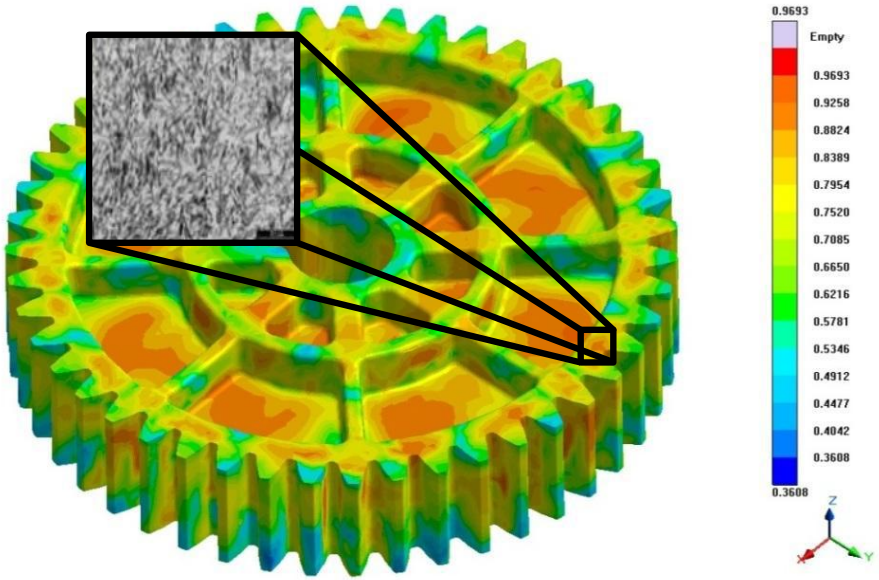




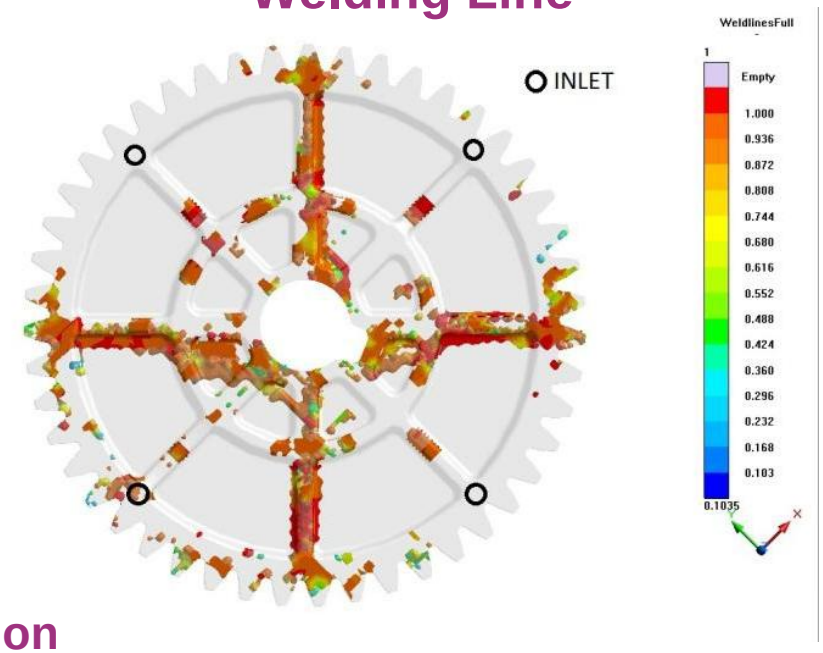
Component level – Simulations 2

Injection Molding

Fiber orientation

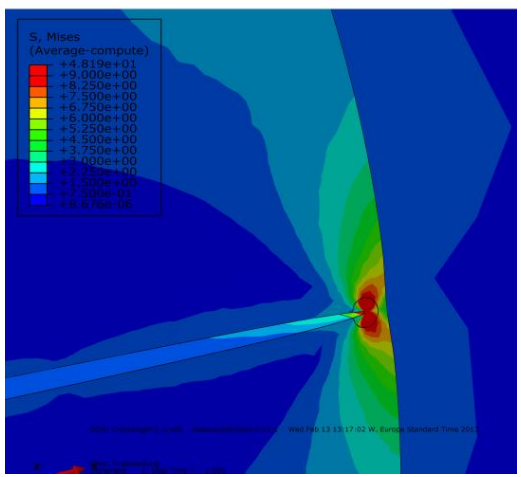


Welding Line

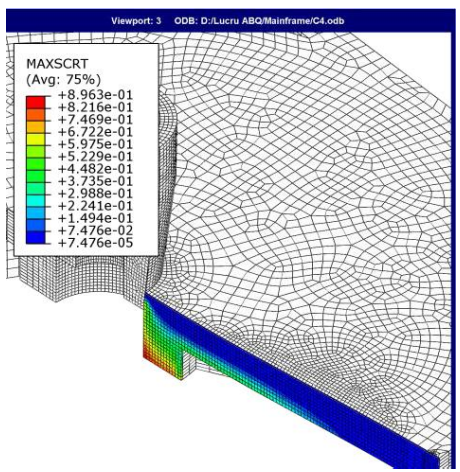


Failure Simulation

- In addition to the models of $Fe_{\mu cell}$ und FPGF
- Defects are characterized by CT
- Crack models



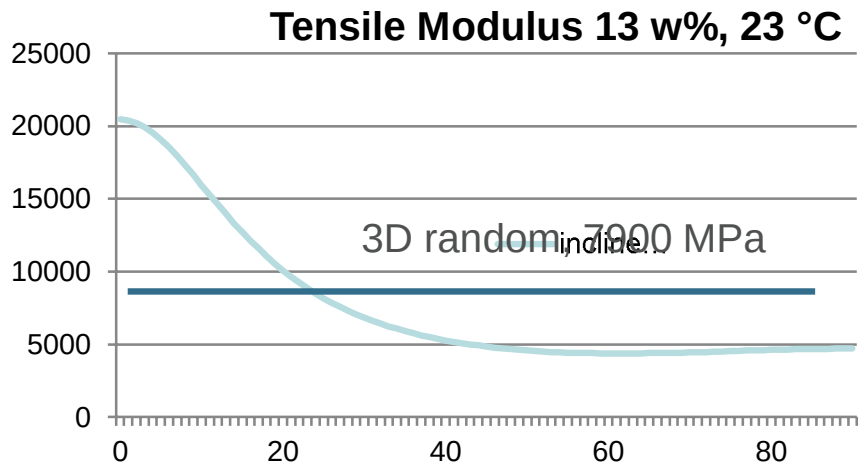
- Cohesive elements are used in the welding line
- The CZ parameters are determined experimentally (Major and Miron, 2012)

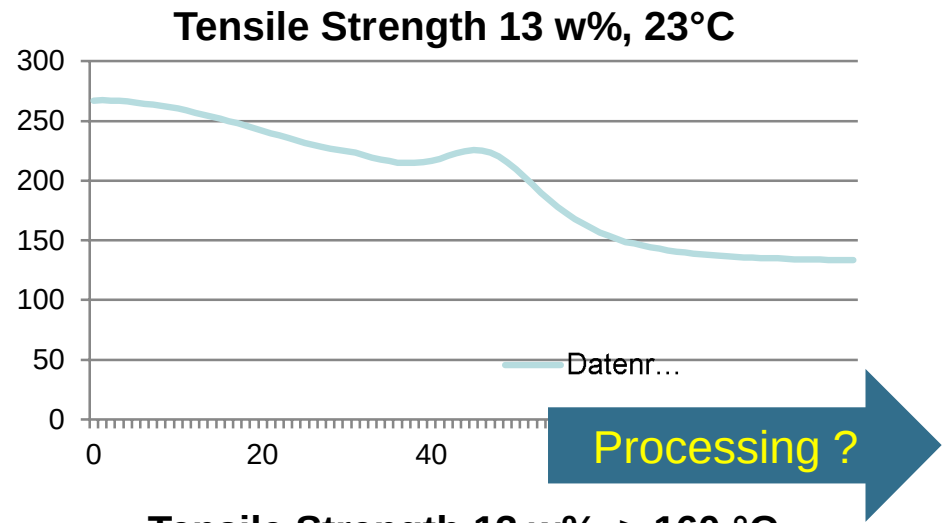


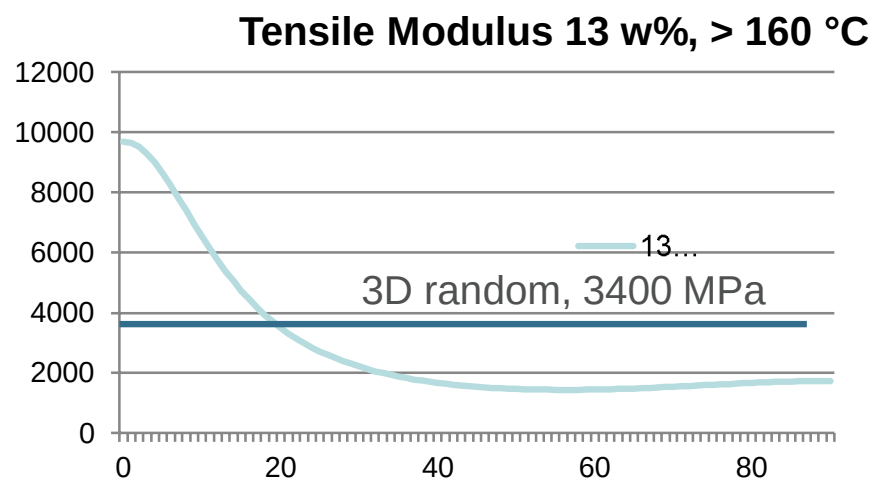
Prediction of Material Behavior

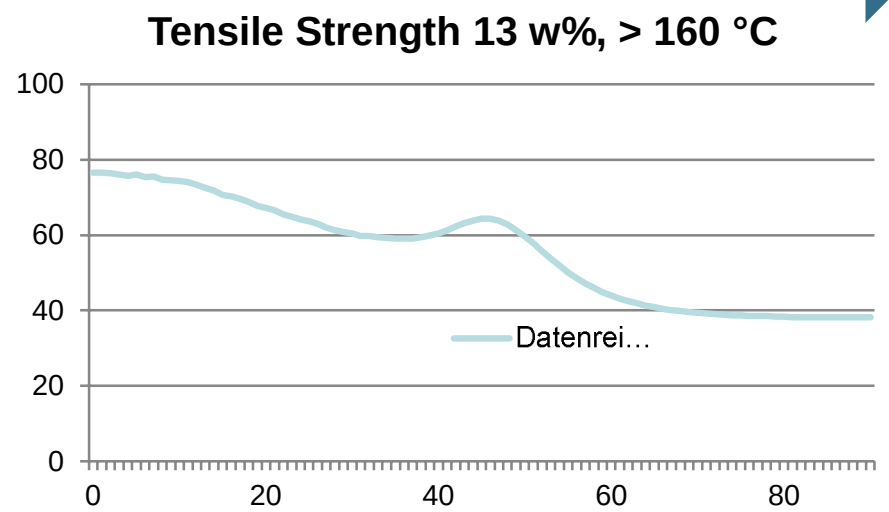
PEEK homogenization simulation (DigiMat MF)

Temperature dependent matrix and fiber properties, perfect interface, varying AR, fiber content, orientation





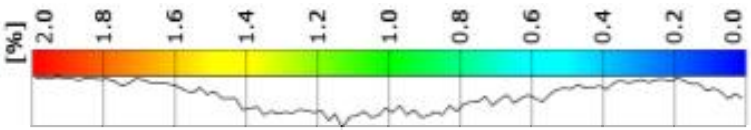


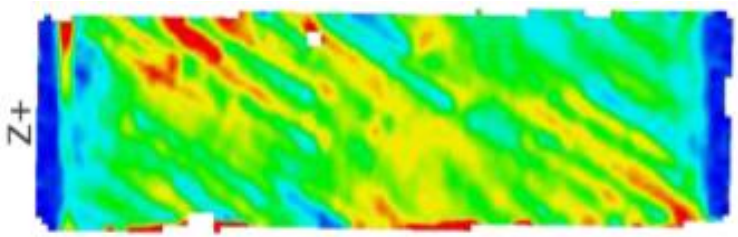


RVE Prototyping

Virtual representative element with fiber orientation of 0° (RVE).

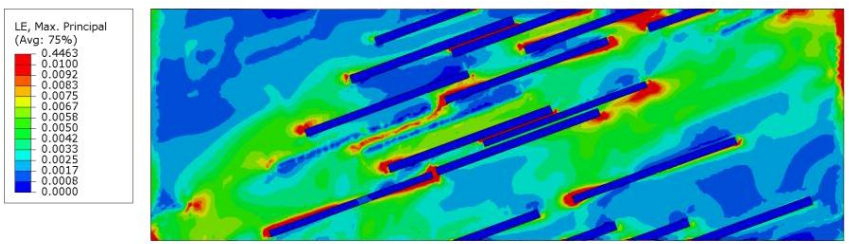
A representative test specimen





Full-field Strain Analysis of the test specimens with 60° fiber orientation

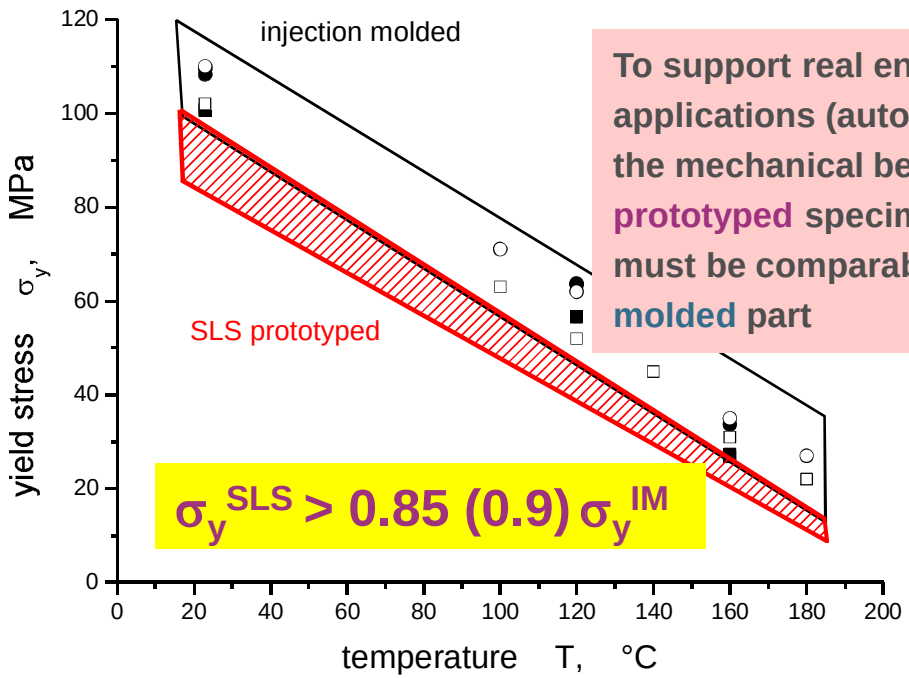
FE simulation of the test specimens with 60° fiber orientation



Reiter and Major, 2011

Selected Laser Sintering

Specimen level



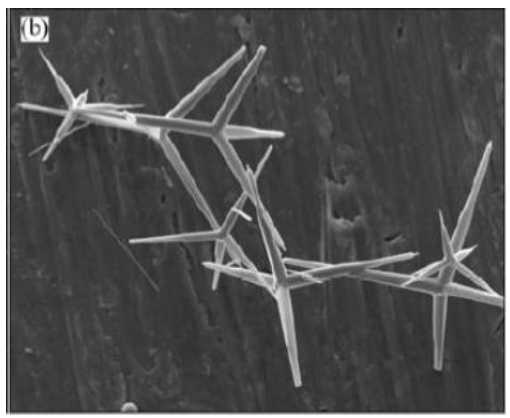
$\sigma_y^{SLS} > 0.85\ (0.9)\ \sigma_y^{IM}$

To support real engineering applications (automotive, medicine) the mechanical behavior of the prototyped specimen/component must be comparable to the injection molded part

Value	Test method	PEEK-HP3	PA2200
Tensile strength [MPa]	ISO 527	90	48
Young´s modulus [MPa]	ISO 527	4250	1700
[%]	ISO 527	2,8	20
Pa]	ISO 178	133	58
Pa]	ISO 178	4100	1500
ered part	ISO 1183	1,315 [~99%]	0,93 [>>90%]
[°C]	DSC	370 - 385	172 - 180
perature [°C]	DSC (EOS)	163	~ 50
erature A Heat distortion temperature B	ISO 75	205 352	55 128
Continuous use temperature [°C] Electrical Static mechanical Dynamic mechanical	UL746B	180* 240* 260*	95
Flammability	UL94	V-0*	HB

Improve of the Stiffeness/Strength

Application of special fillers (Pana Tetra®)



Micro-mechanical simulations for predicting the properties (DigiMatFE)

Conclusions and Future Work

- Price and performance competition of all components of compounds (polymer matrix, stiffening and functional fillers and interface treatments (compatibilization)
- The stiffness prediction is of sufficient quality both for hard particle filled and for soft particle toughened compounds over a wide temperature range
- Various methods at various length scales of the microstructure are investigated to model and predict the failure behavior of sfr polymer composites. In all cases adequate material parameters are needed. The simulation complexity is different and the application depends on the availability of models and data and practical considerations (time)
- Increasing number of phases may support additional functionality, but cause unexpected complications (failure behavior)
- Combined macro and microstructure based optimization of the components

INVITATION

13 of May, Opening of the Polymer Technology Center at the JKU in Linz

in Science Park 2 and 3

Acknowledgement

The results of these study were generated in a variuos research projects supported by

- **PCCL (Borealis), until 2009**
- **K_{APMT} (Borealis), since 2010 and**
- **ACCM (ECS), since 2011**

Thank you for your attention

iPPE Institute of Polymer Product Engineering

Prof. Dr. **Zoltan MAJOR**

Adresse: Altenberger Straße 69, A-4040 Linz

E-mail: zoltan.major@jku.at

Tel: +43 (0)732 / 2468 6591

Internet: www.jku.at/ippe