

# Polymere Netzwerke: Struktur, Theorie und Anwendung



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Durch die Vernetzung von Polymeren werden Flüssigkeitseigenschaften (Viskosität) mit Festkörpereigenschaften (Formbeständigkeit, Lösungsmittelbeständigkeit) kombiniert. In der modernen Polymerforschung und -technologie werden Vernetzungsprozesse zur gezielten Beeinflussung dieser Materialeigenschaften im Zusammenspiel mit strukturierenden Präparations- oder Selbstorganisationsprozessen eingesetzt. Hinsichtlich technischer Anwendungen sind dabei elastomere Werkstoffe ein unverzichtbarer Bestandteil für zukünftige energieeffiziente Leichtbau- und Mobilitätstechnologien. Polymergele erlangen dagegen insbesondere im Bereich der biomedizinischen Anwendungen sowie der Smart Materials für die Aktorik, Sensorik und Mikrofluidik/ Mikrosystemtechnik eine zunehmende Bedeutung mit neuen Herausforderungen bezüglich des Verständnisses dieser Materialien.

Im anwendungsorientierten Bereich des ST3 konnte z. B. ein neues Konzept zur Herstellung Zinkoxid-freier Schwefel-vulkanisierter transparenter Elastomere unter Verwendung von funktionalisierten *Layered Double Hydroxides* entwickelt werden (*Journal of Materials Chemistry* 21 (2011) 7194-7200). Des Weiteren wurden Beiträge zum grundsätzlichen Verständnis des Einflusses der Oberflächeneigenschaften von Füllstoffen auf die dynamisch-mechanischen Eigenschaften von gefüllten Gummis geleistet (*Macromolecules* 44 (2011) 4366-4381). Erwähnenswert ist auch, dass 2011 Herr Dr. A. Das eine Gastprofessur *Elastomere* an der Universität Tampere (Finnland) angenommen und Dr. S. Wießner einen Ruf auf die Juniorprofessur *Elastomertechnik* an der TU Dresden erhalten hat.

Ende 2011 wurde ein zweijähriges Industrieprojekt "Nanoscopic Structure and Dynamics Modeling of Reinforced Rubber Networks" erfolgreich abgeschlossen. Darin wurde ein Theorieansatz zur Beschreibung der viskoelastischen Eigenschaften von gefüllten Elastomeren entwickelt. Auf dem neuen Themengebiet der magneto-sensitiven Elastomere wurde ein analytischer Ansatz zur Beschreibung der statischen mechanischen Eigenschaften entwickelt (*Macromolecular Theory and Simulations* 20 (2011) 411-424) Netzwerke, bestehend aus sternförmigen

Polymeren wurden mit Hilfe von Monte-Carlo-Simulationen untersucht und theoretische Modelle für die Beschreibung ihrer strukturellen Eigenschaften entwickelt (*Macromolecules* 44 (2011) 9464). Ausgangspunkt für diese Arbeiten waren neu entdeckte Hydrogele basierend auf Tetra-PEG-Copolymeren. In enger Zusammenarbeit mit der Arbeitsgruppe NMR an der Universität Halle wurden Defekte in derartigen Netzwerken untersucht und klassifiziert sowie die Eigenschaften isolierter Defektstrukturen in Bezug auf die in der NMR nachweisbare Segmentorientierungs-Ordnung berechnet (*Macromolecules* 44 (2011) 9666). Weiterhin wurde ein theoretisches Modell für die Quellungseigenschaften neuartiger Heparin-PEG-basierter Hydrogele untersucht (siehe auch ST2) sowie Vernetzungsprozesse in gepfropften Polymersystemen (*Physical Review E* 83 (2011) 021803). Herr Dipl. Phys. Max Hoffmann erhielt für seine Diplomarbeit über die Vernetzung von Polymerbürsten den neu gestifteten Brandstädter-Preis für die beste Diplomarbeit am IPF. Die Bedeutung der theoretischen Forschung im ST3 wird auch durch die kontinuierliche und steigende Drittmiteleinwerbung manifestiert. Theorie und Simulation von Polymernetzwerken stehen im Zentrum eines umfangreichen DFG-Projektes mit drei Mitarbeiterstellen sowie eines Industrie-Kooperationsprojektes.

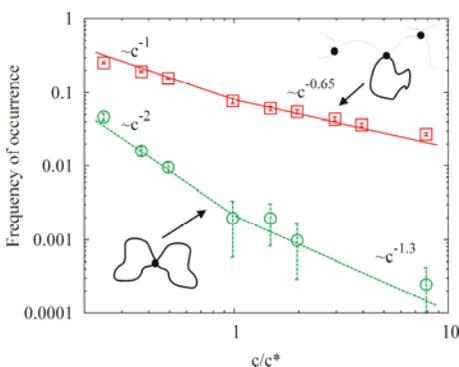
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## The structure of star polymer networks

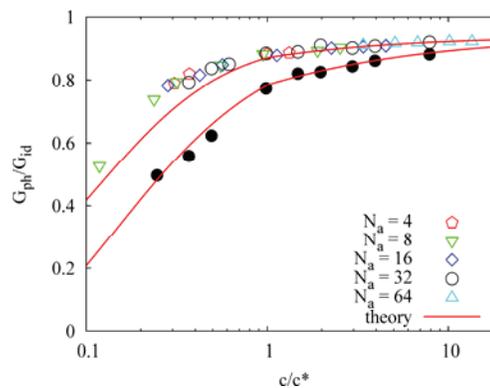
Michael Lang, Konrad Schwenke, Jens-Uwe Sommer

Polymer networks are one of the most prominent examples for a material, in which the structure on the nano-scale entirely determines its macroscopic properties. In particular, the connectivity and overlap of the molecules is of paramount interest for developing models on network elasticity. Therefore, new methods to characterize this micro-structure are essential to improve our understanding of polymer networks.

Recently, a new class of hydrogels was synthesized in the lab of Prof. Sakai [1], which showed a remarkable increase of breaking strain almost independent of polymer concentration at preparation. The difference to previous networks of similar structure was the use of stoichiometric mixtures of two types of four arm stars for which the reactive groups at the ends of the star arms exclusively react with end-groups of the other type of star. The increased performance of these networks was originally proposed to result from an ordered network structure, but we could show by computer simulations, that these networks do not form a long range order. Instead, only even loop-sizes can be realized. This leads to the exclusion of the most predominant network defect – a dangling loop – at high conversion. We developed a theoretical framework to describe loops of any kind as function of polymer concentration  $c$  with respect to overlap concentration  $c^*$ . The predictions of this model as reduced to simple scaling laws [2] are compared to simulation results in the left figure below.



The following figure shows the predictions of the network modulus as computed using the phantom network model also in good agreement with simulation results.



**Fig. 1:**  
Left: Number fraction of cyclic defects. Single dangling loops (top) and double dangling loops (bottom) as possible in A-type networks.

Right: Phantom modulus  $G_{ph}$  of AB-type networks (open symbols) and A-type networks (full symbols) normalized to the phantom modulus of an ideal four-functional network without defects  $G_{id}$ .

In order to test whether our models agrees with experimental data, Kay Saalwächter (Universität Halle) determined the amount of a particular cyclic network defect that shows a clearly separated NMR signal [3]. The results of this study show an overall good agreement with our predictions. Since our theory establishes a link between the frequency of occurrence of any cyclic network defect, the NMR results can be used in future works for a precise estimate of the phantom modulus. The results of the project will aid to improve current models of network elasticity and to optimize material properties by tuning, e.g. cyclic defects in the samples.

Sponsor:  
Deutsche Forschungsgesellschaft  
Projekt LA 2735/2-1

Cooperation:  
K. Saalwächter, Universität Halle  
T. Sakai, University of Tokyo

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# Polymere Netzwerke: Struktur, Theorie und Anwendung

## Stretchable magneto-electronics

Alfredo Calvimontes

Flexible electronic systems have gained a lot of scientific interest over the last years due to plenty of new applications offered by arbitrary surface geometries possible after fabrication. Examples are flexible architectures of paper-like electronic displays [1], light emitting diodes [2], full colour display panels [3, 4], integrated circuitry [5], solar cells [6, 7], and actuators [8]. Even stretchable electronic systems that facilitate elastic tensile deformations are developed for a few years [9]. These are in particular interesting for wearable smart skin and electronic textile applications [9]. The present work adds a new member to this family – the flexible and stretchable magnetic sensor. Magnetic sensor devices on elastically stretchable substrates would make the fabrication of smart biomedical systems possible [10], where large-angle folding of the micrometer-sized functional elements is a crucial prerequisite for a successful implementation [11, 12]. Furthermore, flexible magnetic sensors can be directly integrated into already existing stretchable electronic systems to realize smart hybrid magneto-electronic devices with the functionality to sense and to respond to a magnetic field.

Magnetic multilayers structures revealing giant magnetoresistance (GMR) are crucial components of magnetic sensor devices. Currently, GMR elements are fabricated on rigid substrates. However, magnetic sensor devices on elastically stretchable substrates can open up a variety of new applications due to arbitrary surface geometries possible after fabrication. Here, we study the performance of photolithographically patterned [Co/Cu] GMR multilayers fabricated on free-standing elastic Poly(dimethylsiloxane) (PDMS) membranes. We show that the GMR performance of [Co/Cu] multilayers on rigid silicone substrates and on free-standing PDMS is rather similar and does not change with application of tensile deformations up to about 4.5%. Furthermore, mechanical deformations imposed on the sensor elements are totally reversible, due to the elasticity of the used substrates, which was verified by monitoring the magneto-resistance of the samples upon cyclic loading. The

remarkable performance of the fabricated GMR multilayers upon stretching relies on a thermally induced wrinkling effect of the GMR layer on top of the free-standing rubber membrane.

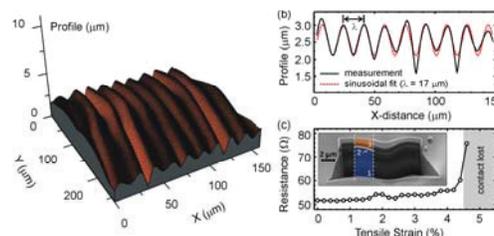


Fig. 1:

### Wrinkled GMR multilayer stack

Thermally induced wrinkling of GMR multilayers on top of a free-standing rubber membrane.

(a) High resolution scandisk confocal microscopy was used to image of the sample surface.

(b) Line scan taken of the data presented in panel (a) at  $Y = 125 \mu\text{m}$  (solid black curve) and the sinusoidal fit (dashed red curve) providing the wrinkle wavelength of about  $17 \mu\text{m}$ .

(c) Electrical resistance of the wrinkled GMR multilayer upon tensile strain. Only gradual increase in the sample resistance is observed up to 4.5% strain. Electrical contact is lost when stretching beyond 4.5%. The inset in (c) shows SEM image of a FIB cut through the sample (1: PDMS; 2: [Co/Cu]50 multilayer stack; 3: protective epoxy), revealing that the magnetic multilayer is firmly attached to the PDMS membrane.

Sponsor:

BMBF project Nanett (federal research funding of Germany FKZ: 03IS2011F)

Cooperation:

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## Mechanical properties of magneto-sensitive elastomers: analytical theory

Dmytro Ivaneiko, Vladimir P. Toshchevnikov, Marina Saphiannikova, Gert Heinrich

Magneto-sensitive elastomers (MSEs), also known as magnetorheological elastomers, are smart materials that can change their shape and mechanical behaviour under external magnetic fields. Nowadays, MSEs have found a wide range of industrial applications in controllable membranes, rapid-response interfaces designed to optimize mechanical systems and in automobile applications such as adaptive tuned vibration absorbers, stiffness tunable mounts and automobile suspensions. Such materials typically consist of micron-sized iron particles dispersed within an elastomeric matrix. The spatial distribution of these particles in an elastomer can be either isotropic or anisotropic, depending on whether they have been aligned by an applied magnetic field before the cross-linking of the polymer. Experimental tests indicate that the magneto-induced deformation and the elastic modulus of the MSEs depend strongly on the spatial distribution of magnetic particles.

We have proposed a theory that describes mechanical properties of the magneto-sensitive elastomers in a homogeneous magnetic field taking into account microscopic structure of MSEs. For this we used a model where magnetic particles are located on the sites of the regular rectangular lattice. Introducing the structural parameter  $\alpha$ , which describes anisotropy of the lattice, we have considered three types of distribution of magnetic particles inside an elastomer: chain-like ( $\alpha < 1$ ), isotropic ( $\alpha = 1$ ) and plane-like ( $\alpha > 1$ ) distributions ( Fig 1).

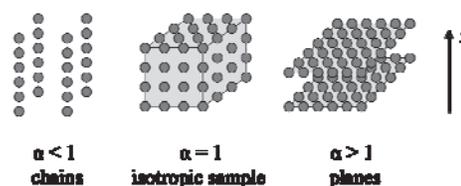


Fig. 1:  
The three different spatial distributions of magnetic particles inside an MSE. The structural parameter  $\alpha$  is equal to the ratio of the distances between nearest particles along and perpendicular to the symmetry axis  $x$ .

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Our theory was based on the equation for the free energy as a function of strain. The free energy was constructed from two components: (i) elastic energy due to entropic elasticity of polymer chains and, (ii) the dipole-dipole magnetic interaction energy between the particles:

$$F = F_{el}(\varepsilon) + F_m(\varepsilon)$$

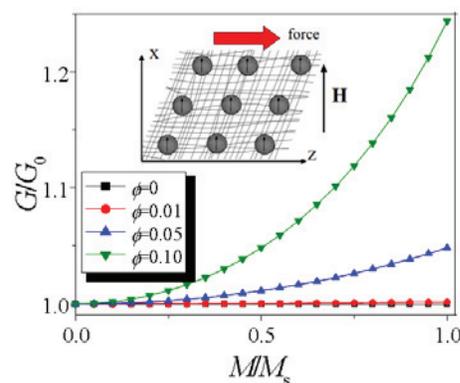
Equilibrium elongation and mechanical moduli (shear and Young moduli) were calculated by minimising the free energy as functions of magnetisation, which depends on the strength of the magnetic field, volume fraction of particles and elasticity of a polymer matrix. We have shown that magneto-induced deformation and mechanical moduli of MSEs depend strongly on the distribution of magnetic particles. The interaction between the magnetic particles results in the contraction of an elastomer along the direction of uniform magnetic field applied along the symmetry axis  $x$ . With increasing magnetic field the shear modulus for the shear deformation perpendicular to the magnetic field increases for all spatial configurations of magnetic particles. Figure 2 shows typical dependences of the reduced shear modulus  $G/G_0$  on the magnetization  $M$  for the case of simple cubic lattice. The Young modulus for the tensile deformation along the magnetic field decreases for the chain-like configurations and increases for the plane-like configurations with increasing magnetic field.

Sponsor:

European Union and the Free State of Saxony

[1] D. Ivaneyko, V.P. Toshchevnikov, M. Saphiannikova, G. Heinrich: Magneto-sensitive elastomers in a homogeneous magnetic field: a regular rectangular lattice model // *Macromolecular Theory & Simulation*, 2011, 20, pp. 411-424

**Fig. 2:**  
In agreement with experiments the shear modulus  $G$  increases with increasing magnetization  $M$  and volume fraction of particles for the simple cubic lattice describing the isotropic distribution of particles.  $M_s$  is the saturation magnetization and  $G_0$  is the shear modulus of the MSE in the absence of magnetic field. The shear modulus  $G$  was calculated for values of  $M_s=1990$  kA/m and  $G_0=1/3$  MPa.

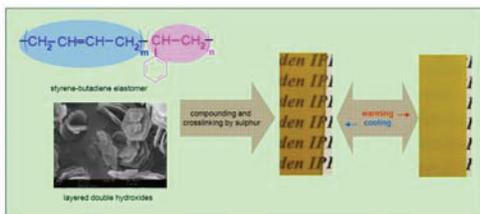


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## Elastomer materials with novel optical, high-temperature and conductivity properties

Kalaivani Subramaniam, Sandip Roj, René Jurk, Amit Das, Klaus Werner Stöckelhuber, Gert Heinrich

Polymeric materials that exhibit reversible optical properties, which vary as a result of an external stimulus are of great scientific and practical importance. An unexpected thermo-tropic behaviour of elastomers based on LDH-SSB (LDH: Layered Double Hydroxide; SSB: solution styrene-butadiene copolymer) has been also reported. Sulphur-vulcanized SSB elastomers exhibit novel thermotropic behaviour when they are compounded with high amounts of LDH. Thereby they do not lose any of their important mechanical properties [1]. Fig. 1 documents the effect of temperature on the degree of transparency of the elastomer. The material develops great transparency at cool temperatures, while becoming totally opaque upon warming. It should be noted here that a sulphur cured rubber with high amount of filler content is reported at the first time to be optically transparent and/or translucent. In Fig. 2 some pictures of the compounded rubber and sulphur vulcanized sheets are shown.



**Fig. 1:** Thermotropic behaviour of LDH-SSB elastomers: From opaque to transparent reversibly with a temperature change. Picture is a digital photograph of a sample with 2 mm thickness taken during cooling and heating experiments. In this case the rubber was filled with 100 phr LDH.

Fluoroelastomers (FKM) are well-known for their excellent high temperature properties. The use of naturally occurring aluminosilicate nanotubes the so-called Halloysite nanotubes (HNTs) as fillers in FKM exhibits an even higher level of thermal resistance properties for this material. The thermal decomposition temperature of FKM/HNT composites was in-

creased from 400°C to 450°C due to the addition of only 5 phr (parts per hundred rubber) HNTs to the polymer matrix [2]. This material could be applied i.e. for high temperature and high pressure seals for deep-oil excavation systems or aviation and space technology.



**Fig. 2:** Translucent rubber compounds filled with layered double hydroxide. After sulphur vulcanization this type of materials can show reversible thermo-tropic properties.

Carbon nanotubes (CNTs) are difficult to disperse in polymer matrices, as they show a high tendency to entanglement and exist in the form of bundles or clusters. In order to improve the dispersion of CNTs in elastomer matrix, which is determining the electrical conductivity and the mechanical properties of the nano-composite, a novel two-step mixing technique has been developed using an ionic liquid (1-butyl 3-methyl imidazolium bis (trifluoromethylsulphonyl) imide, BMI) and multi-walled carbon nanotubes (MWCNTs) [3]. In the first step, MWCNTs are modified, using the ionic liquid and in a second step, the modified tubes are incorporated into polychloroprene rubber (CR). This rubber composite obtained from ionic liquid modified MWCNTs exhibits an excellent electrical conductivity in the range of 0.1 S/cm. Such high values are in flexible materials, like elastomers and cannot be reached by conventional mixing techniques. The formation of a CNT-CNT super filler-filler network along with the rubber crosslinked network contributes to high electrical conductivity of the composite, which was further explored by a 'Payne effect' analysis. Not only the high electrical conductivity but also a tremendous enhancement of thermal stability was found when the chloroprene rubber was treated with this ionic liquid; this new method of increased degradation temperature both in aerobic and anaerobic (nitrogen) conditions is registered for patent approval [4].

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Fig. 3:  
Two samples, conducting (1) and non-conducting (2) can be mounted on the set up and the respective sample can be chosen to close the circuit using a switch.

a) shows a non-conducting sample (2) and b), the conducting composite (1) in action. In the latter, the LED glows due to high conductivity of the composite.



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W. Stöckelhuber, V. Galiatsatos, G. Heinrich, *Macromol. Rapid Commun.* (2011), 10.1002/marc.201100735

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## Compounding and processing studies of rubber compounds reinforced with short aramid fibres

Christian Hintze, Sven Wießner, Udo Wagenknecht, Gert Heinrich

The rapid increase of world population as well as the advancing industrialisation of emerging countries leads to dramatic growth of transportation sector. At the same time the resources, especially the oil reserves, are limited and will force corresponding industries to further increase of sustainability and efficiency. Therefore, as an example, tyre labels, referring to rolling resistance, wet grip and noise classification, will be introduced in the EU (in 2012), the USA and Japan.

Short fibre reinforcement in elastomers can contribute to this development, since it decreases rolling resistance and improves abrasion resistance of tyre tread rubbers with respect to conventional compounds. To ensure that an optimum reinforcement is achieved the following factors have to be fulfilled: complete dispersion, avoidance of fibre breakage during mixing, fibre orientation in the direction of the desired application and good fibre matrix interaction.

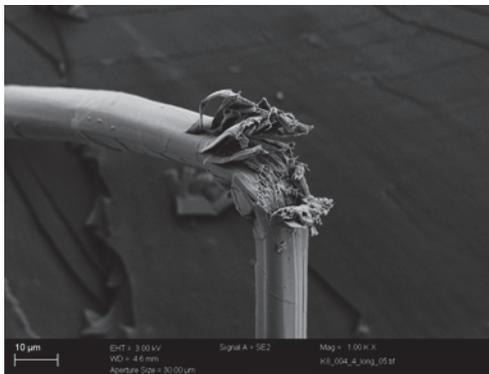
This work is part of the joint Dutch Polymer Institute (DPI) project 664 SUSTFIBER between the groups of Elastomer Technology and Surface Technology and Tribology, both University of Twente (The Netherlands) and the IPF. The project was supported by Teijin Aramid B.V. with aramid fibres and DSM elastomers B.V. with elastomers and curing additives.

At IPF the process induced dispersion, orientation and fibre length distribution of short aramid fibres in ethylene-propylene-diene rubber (EPDM) and natural rubber (NR) and their influence on the mechanical properties of the resulting elastomer composites were investigated. Poly(para-phenylene terephthalamide) (PPTA) and co-poly-(para-phenylene/3,4'-oxydiphenylene terephthalamide) (PP/ODPTA) fibres with an initial length of 3 mm and a filament diameter of 12  $\mu\text{m}$  were investigated. The fibres had either a standard oily dip or Resorcinol-Formaldehyde-Latex (RFL) dip for im-

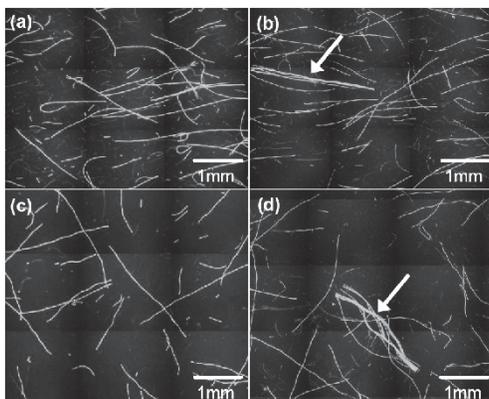
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proved adhesion. For characterisation of the composites optical and electron microscopy as well as static and dynamic material tests were performed. Since most optical characterisation methods were hampered by the use of carbon black in typical industrial formulations, this study focused on carbon black free model systems.

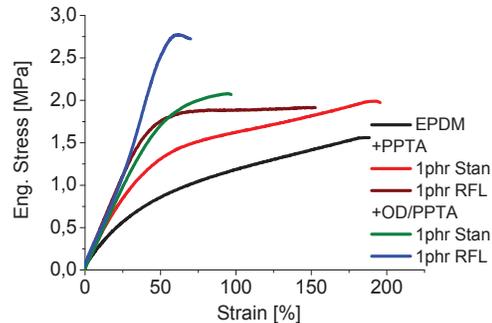
We found that the dispersion and fibre breakage was mainly dependent on the amount of applied total shear strain during the mixing process. PPTA fibres showed significant fibre breakage (Fig.1), while PP/ODPTA was almost unaffected [1]



The application of the RFL dip led to agglomerates of PPTA filaments (Fig.2) for both matrices [2].



Fibres with RFL dip obtained higher remaining lengths after mixing, since the dip acted as protective layer. The fibre orientation and the remaining fibre length in EPDM were higher compared to NR, which resulted in higher anisotropy of the mechanical properties of the EPDM specimen (Fig.3).



**Fig. 3:**  
Engineering stress vs. strain for EPDM samples tested in fibre direction

Sponsor:  
Dutch Polymer Institute (DPI) within the DPI-Project #664 SUSTFIBER

Cooperation:  
J. W. Noordermeer, Elastomer Technology and Engineering, University of Twente, The Netherlands  
D. Schipper, Surface Technology and Tribology, University of Twente, The Netherlands  
Teijin Aramid B. V.  
DSM Elastomers B. V.

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**Fig. 1:**  
Scanning electron microscopy image for fibre breakage of PPTA fibre after mixing

**Fig. 2:**  
Optical microscopy images for dispersion: EPDM with PPTA Stan a) and RFL dip b); NR with PPTA Stan c) and RFL dip d); arrows show PPTA RFL agglomerates

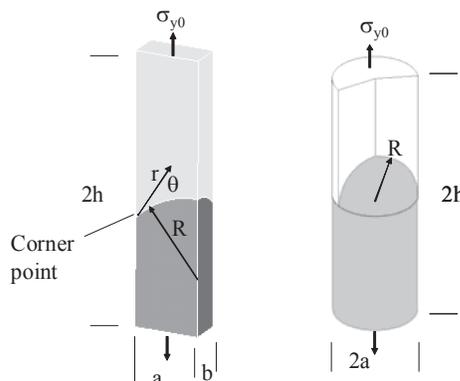
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## Doubly-curved interfaces for adhesion strength testing

Bernd Lauke

It is worthwhile to have a uniform stress distribution within the interface in order to properly determine adhesion strength between materials. In the case of elastic material properties most test geometries cause stress singularities at the edges of the sample as well as no uniform stress distributions along the interface. To avoid this, a curved interface test was proposed in Ref. 1. However, stress singularities appear again in the thickness direction where the sample shows ninety degree corner angles. A specimen with a doubly-curved interfaces, see Fig. 1, was proposed, cf. Ref. 2, to eliminate this problem.

Fig. 1:  
Specimen geometry for a quarter of a prismatic (left) and a cylindrical specimen (right).



Depending on the ratio of the Young's moduli of the two materials, there exist certain radii,  $R$ , of interface curvature for which stress singularities disappear. After the determination of the appropriate  $R$  and associated wedge angles at the edges of the sample with a 2D-finite-element model, a 3D modelling of doubly-curved interfaces was carried out for stress calculation.

The stress near the wedge between the two bonded materials has the following structure:

$$\sigma \approx \frac{K_k}{r^{\lambda_k}} \quad \text{with } \lambda_k = \omega_k + i\varepsilon_k \quad (1)$$

where  $\omega_k$  and  $\varepsilon_k$  are the real and complex solutions respectively (can be more than one) of the corresponding eigenvalue equation and  $K_k$  as the stress intensity factors. For real solutions as well as for complex solutions,  $\omega_k$

describes the strength of the stress singularity. This value can be determined by using the numerically calculated stresses on the left hand side of the logarithm of eqn (1) as a function of the distance,  $r$ , from the corner point ( $r=0$ ). These results in the following relation between the stresses  $\sigma_{\theta\theta}$  and  $\sigma_{r\theta}$  (relative to a cylindrical coordinate system with the origin at the corner point, i.e.  $\sigma_{\theta\theta}$  normal stress at the interface near the corner point) and the stress exponent,  $\omega$

$$\ln(\sqrt{\sigma_{\theta\theta}^2 + \sigma_{r\theta}^2}) = \ln|K| - \omega \ln(r/r_0) \quad (2)$$

with  $r_0$  as a characteristic length that does not influence the value of  $\omega$  and the stresses. A linear regression analysis of the finite-element results of the stresses in this equation provides  $\omega$  as the slope of a linear function in  $\ln(r/r_0)$ . The corresponding 3-D modelling provides all stress components anywhere in the specimen. The stresses are given relative to a cylindrical coordinate system with the origin in the specimen centre with  $R$ -direction perpendicular to the interface. Most interesting for the task is the calculation of the maximum radial stress,  $\sigma_{RR,max}$ , which is a function of the elastic properties of the components and the applied stress,  $\sigma_0$ . In the elastic region, the maximum radial stress is a linear function of applied stress. It is supposed that debonding starts at the moment when the maximum normal stress at the interface reaches the debonding strength. This maximum stress criterion for the determination of adhesion strength,  $\sigma_d$ , can be written as:

$$\sigma_d := \frac{\sigma_{RR,max}}{\sigma_{y0}} \times \sigma_{y0,cr} \quad (3)$$

$\sigma_{RR,max}$  is determined on the basis of the finite-element solution whereas the critical applied stress,  $\sigma_{y0,cr}$ , must be determined by experiment.

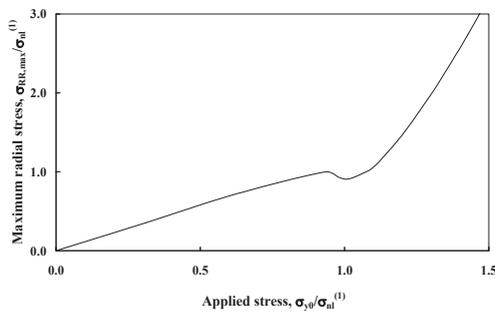
For the components of the bimaterial specimens two polymers are used which are produced by injection moulding. The relatively rigid material is polyoxymethylene (POM) and the soft material is thermoplastic polyurethane (TPU). TPU behaves linear elastically until strains of about 5% with an elastic modulus of  $E_1=330$  MPa and Poisson's ratio of  $\nu_1=0.49$ . Because it shows stable necking during tensile

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loading, it is necessary to consider true stresses  $\sigma$  (force relative to the actual cross section) and logarithmic (Henky) strain  $\epsilon$  (summation of the changes of displacement relative to the actual sample lengths); for more details about the mechanical properties cf. Ref. [2].

- [1] B. Lauke: Composites Interface: 14 (2007), 307-320  
 [2] B. Lauke: Composites Interface: 18 (2011), 121-133

The relation between the applied stress and the maximum radial stress, which is needed for the experimental realization of the adhesion test, is given in Fig. 2. After the linear increase till applied loads slightly smaller than the yield stress of TPU a local minimum is passed through with a subsequent nonlinear increase.



**Fig. 2:**  
**Figure 2. Relation between applied load  $\sigma_{y0} / \sigma_{nl}^{(1)}$  and maximum radial stress  $\sigma_{RR} / \sigma_{nl}^{(1)}$  of the cylindrical specimen with non-linear properties of the TPU material, the non-linear point is given by the yield stress:  $\sigma_{nl}^{(1)} = 15.38$  MPa**

The curve shown in Fig. 2 provides a maximum normal interface stress of about

$$\sigma_{RR,max} / \sigma_{nl}^{(1)} \approx 1 \text{ at an applied load of}$$

$$\sigma_{y0} / \sigma_{nl}^{(1)} \approx 0.9.$$

For the considered material system produced by the injection moulding technique, this stress is sufficient for debonding at the interface and the linear relation between  $\sigma_{RR,max}$  and

$$\sigma_{y0} \text{ for } \sigma_{y0} / \sigma_{nl}^{(1)} \leq 1.0 \text{ can be used.}$$

However, if the debonding strength should be higher than the yield stress of TPU then the corresponding point in the nonlinear curve must be used for the determination of the adhesion strength.