Science 4 Technology – Poster Exhibition 2024

Department Polymer Engineering and Science

Chair of Materials Science and Testing of Polymers

Table of contents

Poster Exhibition 2024

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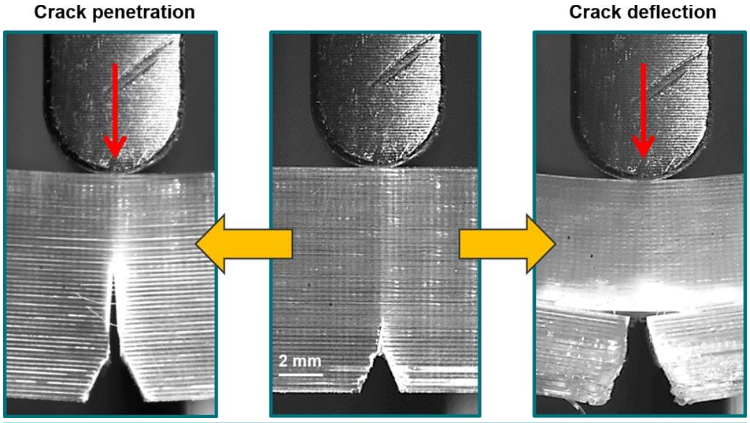
Crack deflection versus penetration in extrusion-based additively manufactured polymeric materials

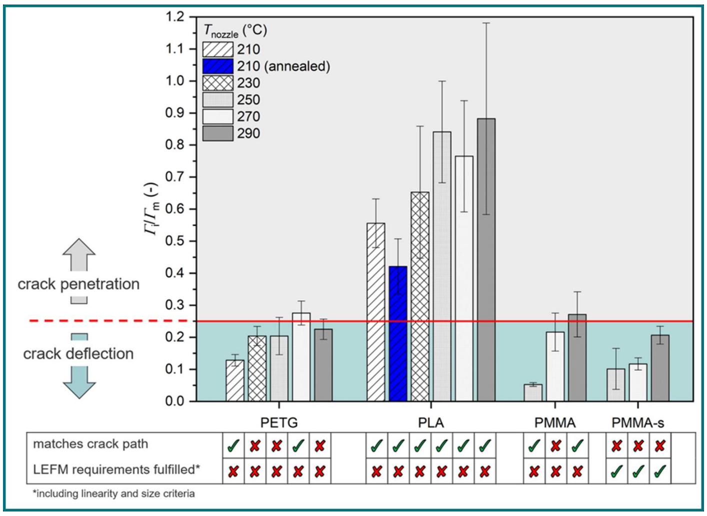
Increasing advances on the part of science and industry in the field of additive manufacturing (AM) in the last few decades increasingly enable 3D-printed components to be used in areas with increased demands, such as medical technology, where the end user has to be assured of function and durability. Owed to the manufacturing process, components produced via polymeric AM, especially extrusion-based methods, possess many either weak or strong interfaces between strands and layers, depending on the used process parameters. When a crack reaches such an interface, two different scenarios regarding further crack propagation can occur (Fig. 1). Either the crack grows into the interface (crack deflection) or penetrate through the subsequent layer (crack penetration).



Possibilities of crack propagation during fracture testing (left: crack penetration; right: crack deflection)[1].

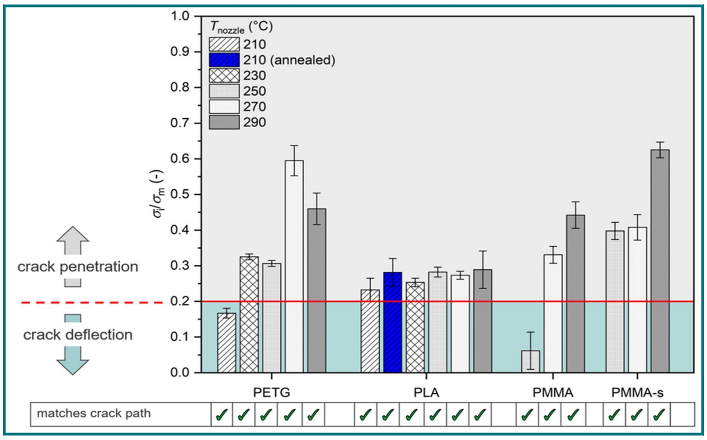
Fig. 1.

In this study, the applicability of two approaches, a strength (Cook & Gordon)- and an energy-based (He & Hutchinson) approach, to predict the failure mode has been tested on four different polymeric materials. The energy-based approach proved unreliable for failure mode prediction (Fig. 2). The strength-based approach, in contrast, correctly predicted the crack path for all tested materials and seems a promising candidate for failure mode prediction (Fig. 3).



Results from the energy-based approach, fracture toughness ratio of the interface to matrix (Γ_i/Γ_m) as a function of the nozzle temperature T_{nozzle}[1]. The red line indicates the transition from crack deflection to penetration according to the suggestion given by He & Hutchinson.

Fig. 2.



Final results of the from the strength-based approach. Strength ratio of the interface to matrix (σ_i/σ_m) as a function of the nozzle temperature T_{nozzle}[1]. The red line indicates the transition from crack deflection to penetration according to the suggestion given by Cook & Gordon.

Fig. 3.

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[1] C. Waly, S. Petersmann, F. Arbeiter (2023); Theoretical and Applied Fracture Mechanics, doi: https://doi.org/10.1016/j.tafmec.2023.104032

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Project: CrackDePe 4 3D-Print

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Plastic STRAW - Smart Technology for Recycling of Assorted plastic Waste

Re-thinking of mechanical recycling in polymer science

Abstract

The recycling of plastics is a current research topic around the world - research is being carried out into more effective recycling methods. Current research in the field of recycling is focusing on the processing of material flows. For example, research is being carried out into multi-sensor-based sorting systems with artificial intelligence or so-called tracing systems. These have the disadvantage that material composites (such as multi-layer structures in packaging) cannot be specifically separated. These waste streams usually end up in the downcycling channel, including thermal recovery, and thus disappear from the material cycle.

The two universities involved in the Plastic STRAW project (Montanuniversität Leoben and Graz University of Technology) have developed a new type of separation process to ensure that plastics that cannot be sorted or are difficult to separate do not disappear from the material cycle. This differs from existing recycling processes in one key aspect: the material streams are separated in the molten state of the polymers. The developed continuously operating centrifuge makes it possible to convert these plastic fractions into unmixed material streams. The process also has a side effect: the use of high temperatures also results in the removal of low-molecular substances (e.g. substances that have diffused into the polymer, such as oils and fats). The process can be integrated into a conventional recycling process in order to ensure industrial implementation following the project.

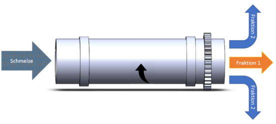

Figure 1: New concept of mechanical recycling in polymer science

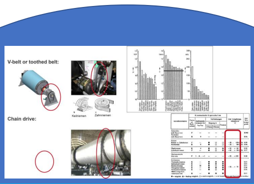

Figure 2: Planning of the prototype

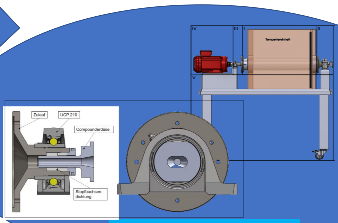

Figure 3: Design steps

Experimental

Within this poster a new idea of mechanical recycling of polymer waste is presented. Starting with the principial idea (see figure 1) via planning, design and construction (see figure 2 – 4) to the first discontinuous tests (see figure 5) of the prototype. Finally this prototype is used in a continuous process for separating a polymer mixture (see figure 6).

Conclusion

It was shown that it is possible to return non-recyclable polymer composites to the material cycle. However, new, unconventional ideas are needed in order to achieve a circular economy for polymers.

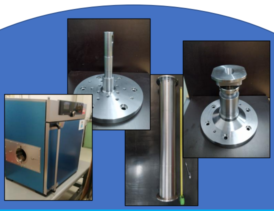

Figure 4: Construction of the prototype

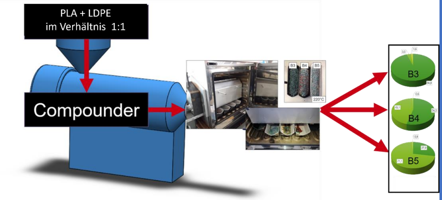

Figure 6: Prototype and first results of the continous process

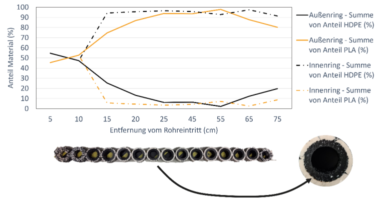

Figure 5: First results of the prototype in a discontinous process

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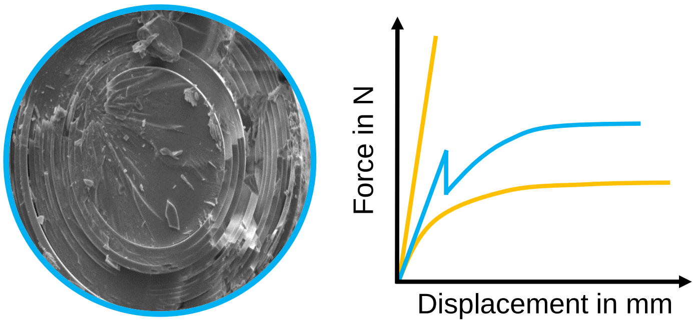
Boosting Stiffness-Toughness Synergy via Lithomers

Pioneering Multi-layered Polymeric Composite Design

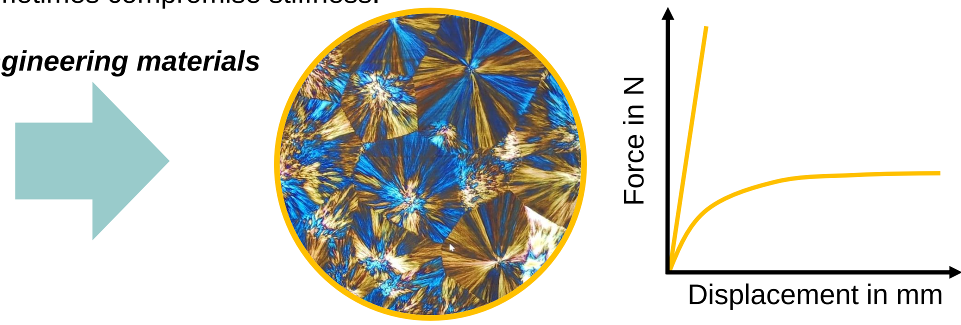
The demand for structurally sound materials in modern applications continually rises. Traditional engineering materials often prioritize one property, like stiffness, or strength, at the expense of others, such as toughness, leading to trade-offs (see a. Engineering materials).

To address this issue, engineers and scientists turn to material design, drawing inspiration from nature's diverse solutions. However, natural materials are often too complex to industrially reproduce, due to their hierarchical structures, optimized over millions of years. One less complex example, the skeleton of deep-sea sponges, demonstrates enhanced stiffness and toughness through alternating layers of hard and soft materials (see b. Biological materials). Yet, incorporating soft layers can sometimes compromise stiffness.

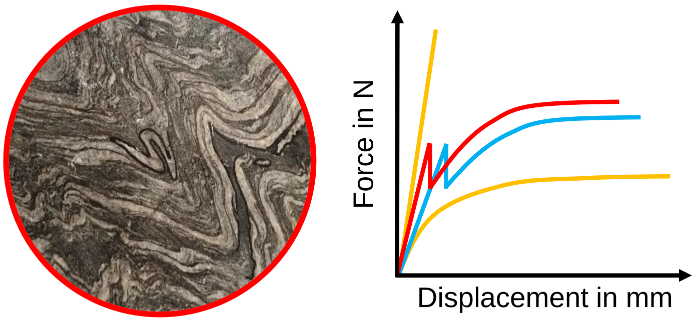


b.) Biological materials

a.) Engineering materials



c.) Lithomers



To tackle this challenge, the concept of Lithomers (<u>Litho</u>mimetics + Poly<u>mer</u>) emerges. These structures (see c. Lithomers), formed akin to processes in the Earth's lithosphere, offer the potential for enhanced stiffness-toughness interaction, while consisting of a moderately complex structure. Soft layers mimic the sponge skeleton to boost toughness. Local constraining and mechanical and geometrical interlocking effects further contribute to stiffness enhancement.

In summary, by mimicking natural structures and leveraging lithomimetic principles, we aim to optimize material properties, overcoming traditional trade-offs and advancing material design for diverse applications.

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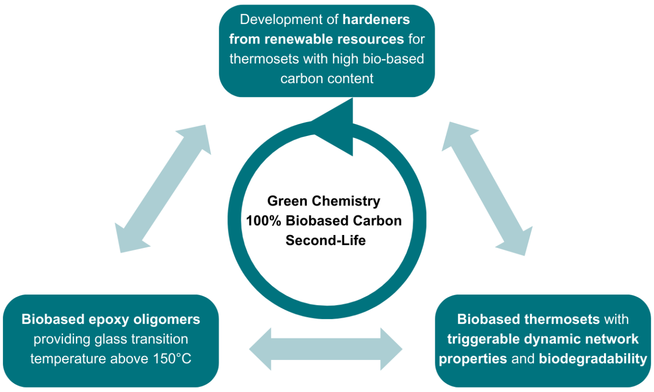
Project: ImproPoly acc. Nature

bio-ART

Biobased and Resource-Efficient Thermosets for Demanding Applications

Epoxy resins are high performance thermosets with manifold and tailorable property profiles, which are essential materials in various fields of applications. By being used in key future technologies such as renewable energy generation, sustainable and intelligent mobility, and energy- and resource-efficient building technologies, epoxy resins are already making a significant contribution to fulfilling the EU Green Deal. Epoxy resins are currently produced mainly from petrochemical and hazardous raw materials (e.g. bisphenol A) and are also not recyclable. However, initiatives of the EU towards a resource efficient and sustainable low-carbon economy require the development of new materials and new consumer products from European biomass, avoiding the need for fossil-based inputs.

bio-ART
Biobased and resource-efficient
thermosets for demanding applications



Development of **hardeners from renewable resources** for thermosets with high bio-based carbon content

Green Chemistry
100% Biobased Carbon
Second-Life

Biobased epoxy oligomers providing glass transition temperature above 150°C

Biobased thermosets with **triggerable dynamic network properties** and **biodegradability**

In terms of epoxy resins, this transition into bio-based industry while meeting the EU's plastics circular economy directives requires interdisciplinary research initiatives addressing complex interrelations of bio-based polymer building-blocks, polymer-physical performance, efficient processability, and recyclability. bio-ART picks up this challenge by teaming up innovative researchers, creative technology developers and visionary end users. The mission is to develop high-performance, eco-friendly, multifunctional, and recyclable epoxy resins based on renewable resources. The strong inter- and multidisciplinary cooperation enables a holistic view of the topic and thus ensures the transferability of the research outcomes into real industrial applications.

Intended technological results are

(1) cost-efficient, highly reactive epoxy resins based on regional and renewable raw materials (ideally 100 %), which exhibit improved mechanical and/or functional properties compared to the state of the art and which are non-hazardous in production, processing and use,
(2) bio-based curing agents and innovative curing strategies and routes for (bio-based) epoxy resins allowing for resource efficient processing following various technologies,
(3) intelligent material designs and functionalizations for epoxy resins allowing for their reuse, repair and/or resource-efficient recycling, and
(4) functional models that illustrate the performance of materials developed.

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Partners: Kompetenzzentrum Holz GmbH, Politecnico di Torino, Department of Applied Science and Technology, Polymer Competence Center Leoben GmbH, Andritz Hydro GmbH, Bruno Bock GmbH, bto-epoxy GmbH, Capita MFG GmbH, Design Composite GmbH , Isovolta AG, Luxinergy GmbH, Poschacher Kompost e.U.

This COMET Project is funded within COMET – Competence Centers for Excellent Technologies – by BMK, BMAW as well as the co-financing federal province Styria. The COMET programme is managed by FFG.

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In-situ detection of damage in FRP laminates

Application of optical crack detection and acoustic emission analysis

Introduction

Fiber reinforced polymer (FRP) laminates exhibit a series of complex damage mechanisms throughout their lifetime. In order to accurately model their fatigue behavior, it is essential to characterize damage evolution and its effects on the mechanical properties. Here the focus is on the characterization of laminates, where the dominating mechanism is the formation of off-axis cracks, which is typically accompanied by a significant decrease of stiffness.

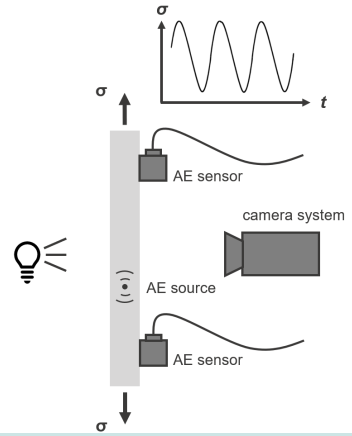


Figure 1: *Schematic illustration of test setup for optical crack detection and AE analysis.*

Methods

Optical crack detection

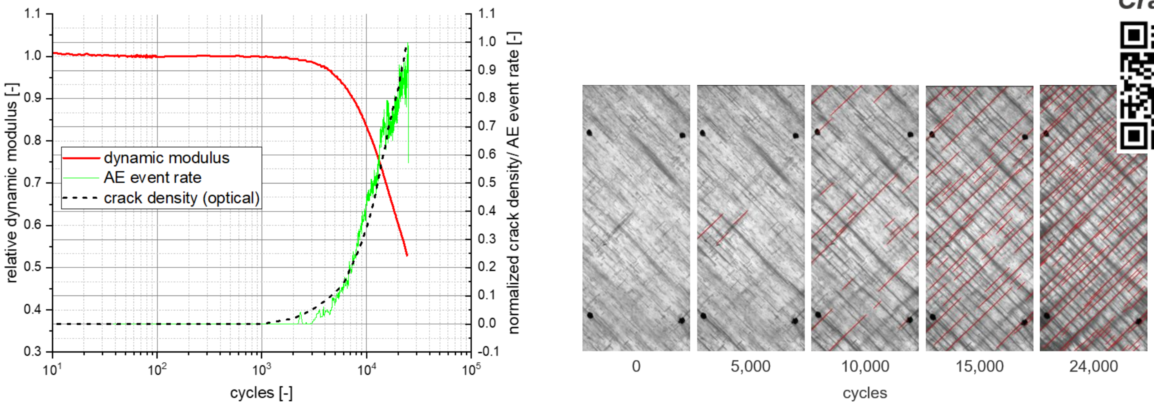
For semi-transparent laminates, a source of light shining through the specimen can be used to visualize cracks, because they scatter the light and therefore appear as dark lines. With the help of *CrackDect*, an automated algorithm, crack density during fatigue life can be determined from images recorded during testing.

Acoustic emission (AE) analysis

Another method for the in-situ detection of damage is AE analysis. Thereby, each occurring damage event generates an elastic wave, that propagates through the material and is detected by a piezoelectric sensor as vibration of the specimen's surface. Compared to optical crack detection, AE analysis is not limited to semi-transparent laminates.

Results

Figure 2 on the right side shows the automated crack detection using *CrackDect* during a fatigue test of a ±45° glass-epoxy laminate. The diagram on the left side shows the evolution of optically determined crack density and the respective reduction of stiffness over fatigue life. Besides off-axis crack formation also friction of crack faces can be sources of AE signals during cyclic loading. However, it was found a good correlation of optically determined crack density and AE event rate for the investigated laminates. Signals originating from friction appear regularly every cycle. Hence, AE event rate is a good indication for off-axis crack density, because it considers the newly formed damage and neglects periodically occurring signals due to friction.



CrackDect

Figure 2: *Fatigue test of a ±45° glass-epoxy laminate (R = 0.1, f = 3 Hz, σ_{max} = 0.6 σ_m) – Left: Correlation of stiffness degradation, optically determined crack density and AE event rate during fatigue life, Right: Automated crack detection using CrackDect.*

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Reycycling of multilayer films

From a packaging waste to a shrink film

I. Introduction

Multilayer films found in food packaging are typically discarded after a single use, mainly due to their composition of immiscible polymers such as PE, PA6, and EVOH. Analyzing their precise composition enables us to prepare blends with specific polymer ratios. This allows us to prepare recycled material with desired properties and facilitate their reintroduction into packaging applications.

III. Material properties

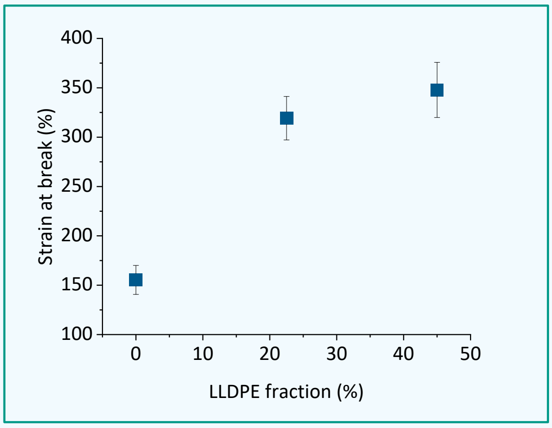
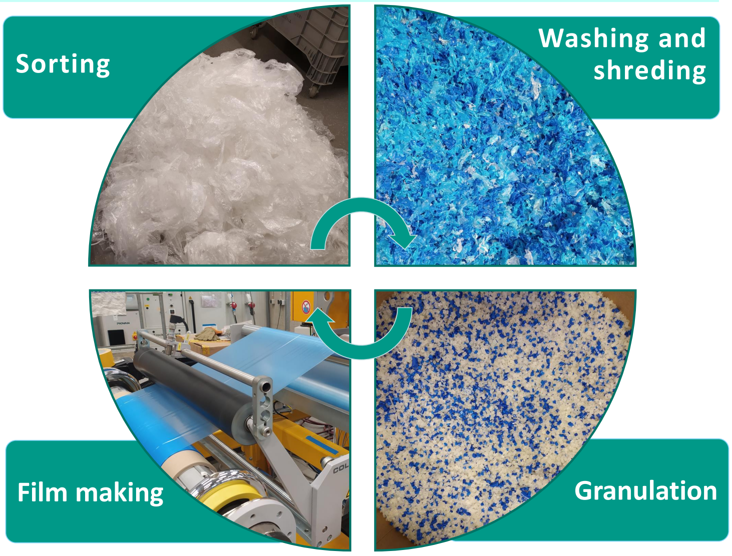


Fig. 1. Influence of LLDPE amount in the blend on strain at break

The strain at break and tensile strength were influenced by the ratio of polymers in the blend. The best strain-strength ratio was observed in blends containing 13% PA6, 5% EVOH, and 82% PE. The composition of the PE fraction (LDPE+LLDPE) did not affect tensile strength; however, a higher LLDPE content significantly improved the strain at break (Fig. 1).

II. Recycling process


Sorting

Washing and shreding

Film making

Granulation

IV. Shrinkage

The shrinkage of recycled films is comparable to that of shrink film within the typical working time range used in industry packaging lines (8-12 seconds).

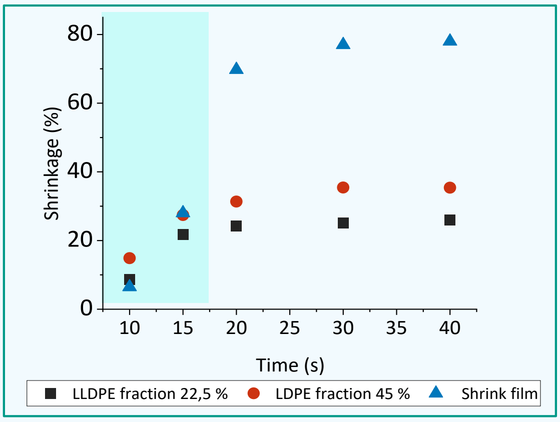


Fig. 2. Comparison of shrinkage at 200 °C between virgin shrink film and recycled films.

V. Conclusion

- ❖ It is possible to recycle multilayer packaging films and reintroduce the product into industry packaging.
- ❖ For succesful process, knowlage about film‘s composition is paramount
- ❖ Every step of mechanical recycling influences the properites of the end product.
- ❖ The combination of LDPE and LLDPE results in better mechanical properties than using LDPE alone.

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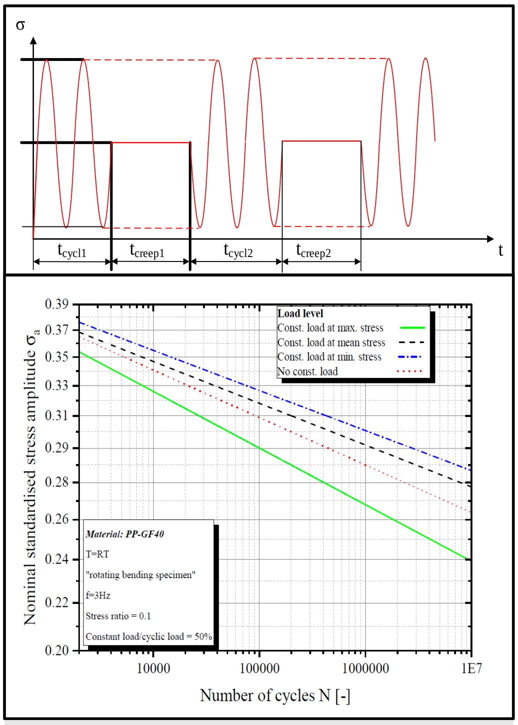
Research focus: polymer recycling, photo-induced force microscopy and Raman spectroscopy analysis of polymers and composites

Influence of viscoelasticity on the fatigue behavior of short fiber reinforced polymers

Characterization of creep-fatigue loads on the material behavior

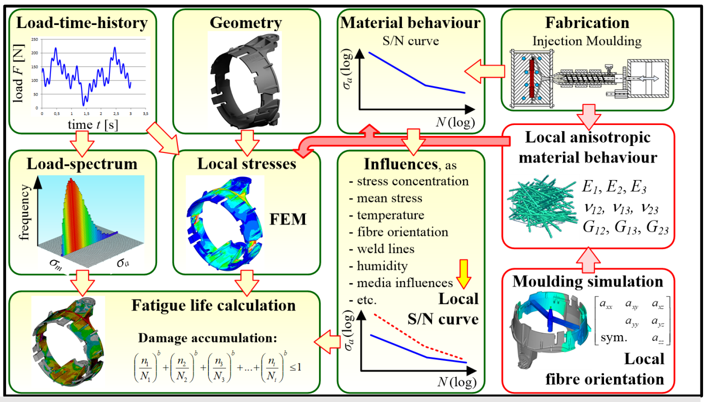
Lightweight structure components for different applications are necessary to reach environmental goals. Since such components are loaded cyclic interrupted by resting times where creep or/and relaxations effects occur. These effects influence the fatigue behavior of short fiber reinforced polymers (sfrp). So, a load sequence was developed to capture the interaction of creep and fatigue loads (Fig. 1).



Load sequence of the combined tests and resulting S/N curves. Depending on the constant load level, the lifetime will be reduced or elongated for a certain cyclic stress amplitude**.

Fig. 1.

The load sequence is distributed into constant (creep) and cyclic (fatigue) load blocks. Based on this sequence, the constant load level was switched between the minimum, mean and maximum of the cyclic loading.



$$\begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ & a_{yy} & a_{yz} \\ \text{sym.} & & a_{zz} \end{bmatrix}$$

$$\left(\frac{n_1}{N_1}\right)^b + \left(\frac{n_2}{N_2}\right)^b + \left(\frac{n_3}{N_3}\right)^b + \ldots + \left(\frac{n_i}{N_i}\right)^b \leq 1$$

Simulation chain for a lifetime estimation of sfrp. This chain covers beside a complex loading sequence, influence parameters like: temperatures, notches, stress ratios, fiber orientation etc.*.

Fig. 2.

These tests are also performed at higher temperatures. As a result, this effect is more pronounced and corresponds to applicational use. To consider this effect in a lifetime estimation, models are derived and implemented in an existing simulation chain (Fig. 2). Additionally, the effect of frequency, mean stress and fiber orientation on the lifetime behavior are investigated in this research.

*Mösenbacher, A.; Pichler, P. F.; Brunbauer, J.; Guster, C.; Pinter, G.; (2013) Lebensdauerberechnung an Strukturbauteilen aus kurzfaserverstärkten Thermoplasten. In: DVM-Arbeitskreis Betriebsfestigkeit (Hg.) 2013 – Die Betriebsfestigkeit als eine Schlüsselfunktion.

** Stadler, G.; Primetzhofer, A.; Jerabek, M.; Pinter, G.; Grün, F.; (2020) Investigation of the Influence of Viscoelastic Behaviour on the Lifetime of Short Fibre Reinforced Polymers. In: Polymers. DOI: 10.3390/polym12122874

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- Research focus: Fatigue of polymers with focus on (short) fiber reinforced polymers, computer-aided service life assessments

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Tailor-made optical properties for carbon reinforced polymers

I. Introduction

Carbon fiber-reinforced polymer (CFRP) composites have emerged as indispensable materials in various industrial domains due to their exceptional mechanical strength and lightweight properties. In recent years, there has been an increasing focus on customizing CFRP composites to align with the evolving needs of modern technology and design. Changes in optical behavior, including light transmission, reflection, and absorption, hold significant implications for both the functionality and aesthetic appeal of these materials across diverse applications.

III. Carbon Fiber Coatings

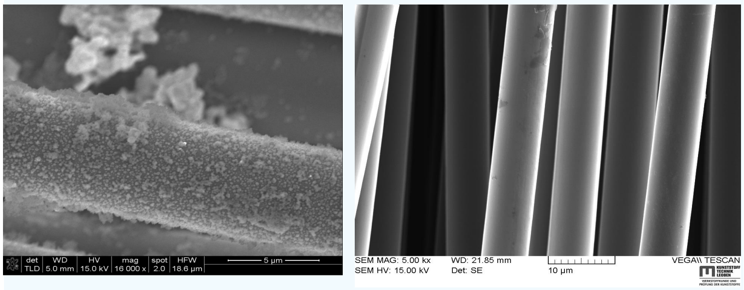


Figure 1: SEM images comparing silica (SiO2) deposition on carbon fibers via EPD on the left and PVD on the right.

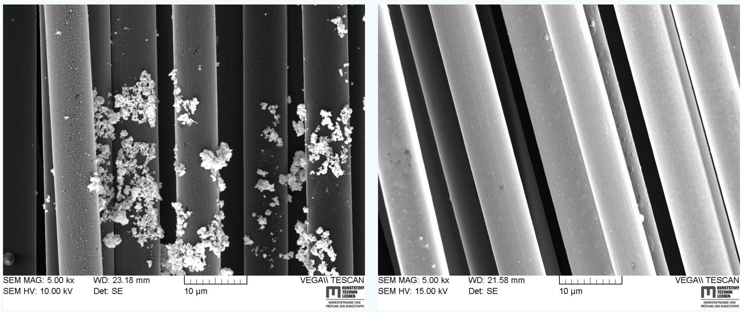
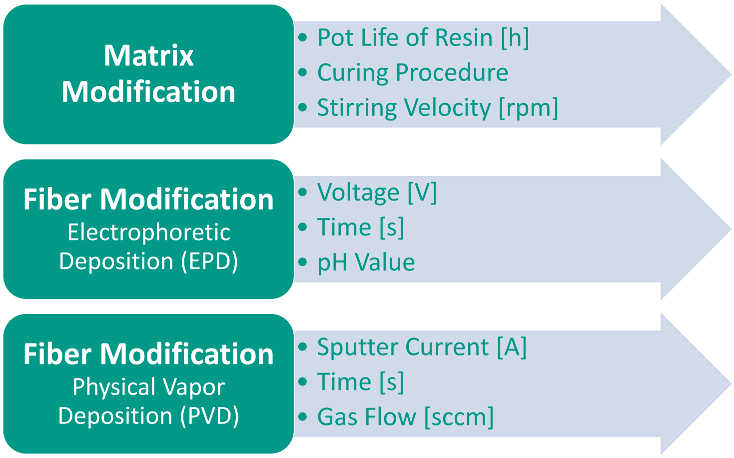


Figure 2: SEM images depict silver nanoparticle deposition on carbon fibers using both the EPD process (left) and the PVD process (right).

II. Modifying Optical Properties



Matrix Modification

- Pot Life of Resin [h]
- Curing Procedure
- Stirring Velocity [rpm]

Fiber Modification
Electrophoretic Deposition (EPD)

- Voltage [V]
- Time [s]
- pH Value

Fiber Modification
Physical Vapor Deposition (PVD)

- Sputter Current [A]
- Time [s]
- Gas Flow [sccm]

IV. Optical Properties

Matrix modifications show higher overall reflectivity while fiber modifications, especially PVD, are promising for tailor-made colored appearances for carbon reinforced composites.

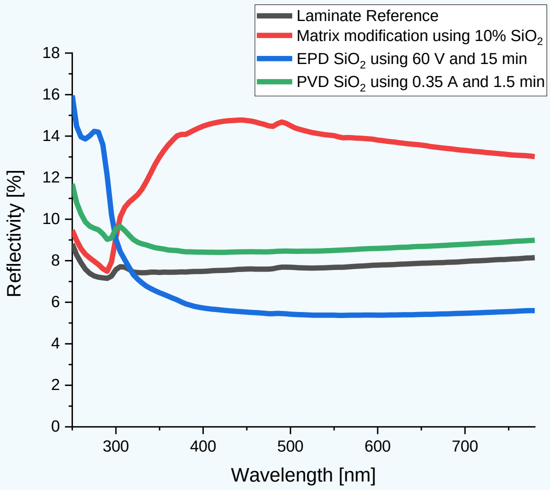


Figure 3: Comparative reflectivity analysis of laminates with different modifications across UV and visible ranges, in comparison to unmodified laminate.

V. Conclusion

By controlling particle distribution and film formation, we customize surface reflectivity and light transmission. This improves visibility in aerospace, enhances automotive aesthetics, and boosts sporting equipment functionality.

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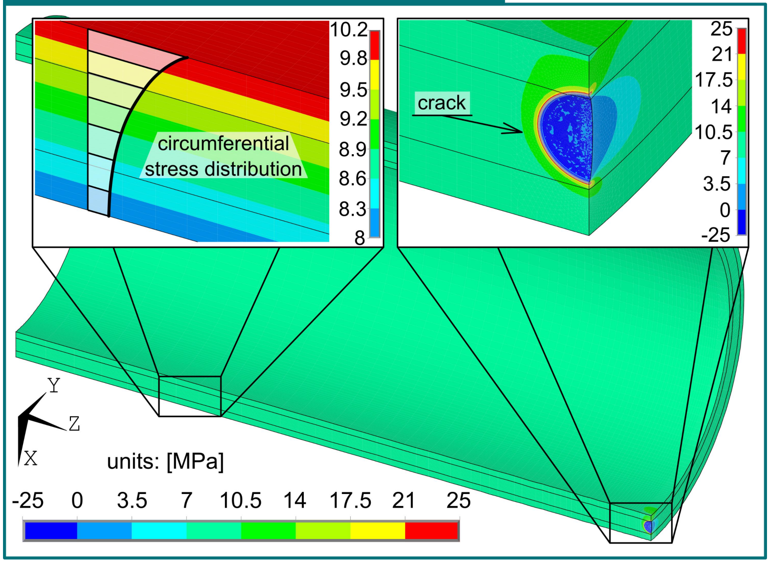
The possibility of using recycled material for plastic pipes production

Numerical modeling of crack propagation in multilayer pipes

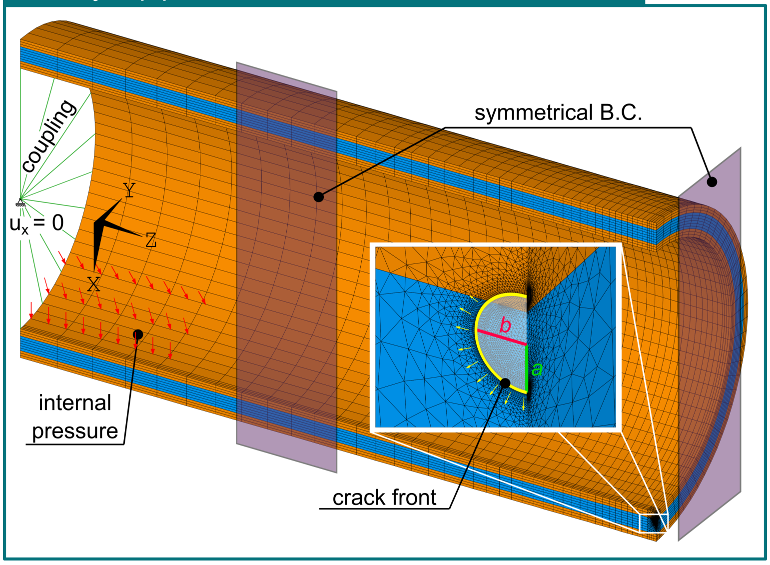
The lifetime of plastic pipes for pressurized systems is demanded to be at least 50 years. At the same time, the potential for recycling plastic waste is unexploited, therefore, using recycled material in pressurized plastic systems might become a reality in the future. However, the main drawback of recycled material is its low and non-consistent long-term properties (fatigue, creep) in comparison with virgin material, and thus, it is restricted for pressurized pipe applications. These two contradictory conditions can be combined using a pipe consisting of a few layers of different materials.

The main role of the inner protective layer is to increase the resistance against crack initiation and slow crack growth from the inner surface, which is critical.

Circumferential stress distribution in a multilayer pipe with the internal crack



Finite element model of the internally pressurized multilayer pipe with an internal crack



The outer protective layer serves as a resilient cover against scratches caused by poor handling or created during trenchless installations that may weaken the pipe wall substantially. For these critical parts – inner and outer layers – using modern, durable material is a necessity. On the other hand, for the middle part of the pipe, it is possible to use material with worse properties – recycled material.

This configuration may result in the change of the critical place from the inner pipe wall surface, which is typical for homogeneous pipes, to the interface of the inner protective layer and the middle layer. Therefore, the presence of a defect at this critical spot has to be analyzed, which was done by the presented 3D finite element models.

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Crack growth detection in short fiber reinforced polymers

A novel method for crack growth detection based on thermography analysis

The typical S-N curves are indicative of lifetime estimation for components under cyclic loads, as long as there are no existing technical cracks within the component. However, once a technical crack develops within the component, the S-N curves can no longer be used for lifetime estimation, and fracture mechanics models should be employed for this purpose. determine fracture mechanics parameters, it becomes imperative to measure crack growth in specimens subjected to cyclic loading. These tests demand significant time investment and necessitate the continuous monitoring of crack growth over the course of the testing period.

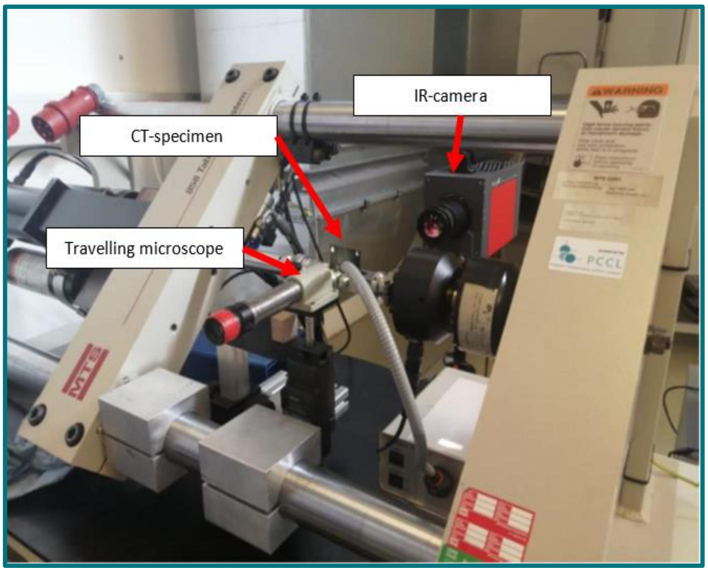
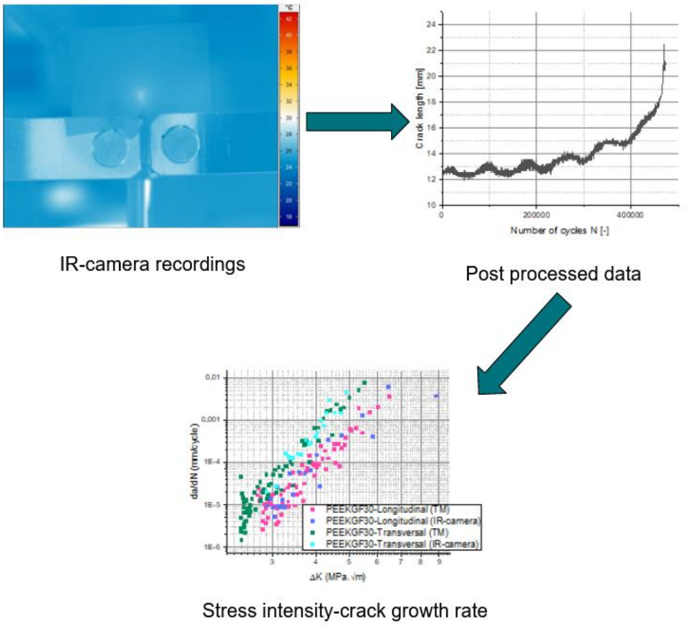


Fig.1

The developed testing setup equipped with an IR-camera for crack growth detection



In an inventive approach, an infrared (IR) camera is employed to monitor the temperature on the rear surface of the compact tension (CT) specimen, according to ISO 15850:220(E). Simultaneously, a traveling microscope (TM) is mounted on the frontal side of the specimen to facilitate manual measurement of crack growth, as illustrated in Fig. 1.

Utilizing a purpose-developed Python code, the specific point demonstrating the highest temperature on the specimen is considered as the crack tip. The method's precision and reproducibility were validated for diverse composites (PPGF30, PPGF40, and PEEKGF30) and in two different finer orientation direction. An overview of the entire process is presented in Fig. 2.

Fig. 2

An overview on the postprocessing flow, from image processing to ‘stress intensity-crack growth’ curves

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Research focus: Fatigue analysis, fracture mechanics, thermomechanical behavior of short fiber reinforced polymers