Montanuniversität Leoben

6TH INTERNATIONAL CONFERENCE ON POLYMER PROCESS INNOVATION

PPI 2026

Book of Abstracts

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Imprint / About PPI 2026

This volume contains the reviewed contributions to the 6th International Conference on Polymer Process Innovation (PPI 2026), held from September 1 to 4, 2026, at Montanuniversität Leoben, Austria. The conference brings together researchers, engineers and industry specialists working across sustainable polymers, smart polymer systems and digital polymer science.

The Book of Abstracts contains 47 accepted contributions: 1 plenary lecture, 7 keynotes, 27 regular oral presentations, and 12 poster presentations.

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Univ.-Prof. Dr. Clemens Holzer studied polymer engineering at Montanuniversität Leoben and spent eight years in industry in Switzerland, working in central R&D and later in production and R&D leadership. He subsequently served as deputy head of an institute and professor at the University of Applied Sciences Northwestern Switzerland before returning to Leoben in 2008 to lead the Chair of Polymer Processing. His research focuses on resource-efficient polymer processing and the systematic interaction between material and process, with particular emphasis on injection moulding, extrusion, recycling and additive manufacturing. He also heads the Department of Polymer Engineering and Science. His contributions to research, teaching and industrial innovation have been recognised with the Golden VÖK Badge of Honor; his materials- and process-oriented work has also been recognised with the H.F. Mark Medal.

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PART I

ORAL PRESENTATIONS

The plenary lecture, keynotes, and oral contributions are arranged in the current official PPI 2026 programme order.

PL01 | Plenary Talk | Plenary Session

From Digitalisation to Digital Transformation - Perspectives and Success Factors

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Digitalization has become one of the defining forces shaping industry, business, and society. Yet, despite the enormous attention devoted to digital technologies, the distinction between mere digitization and genuine digital transformation is often overlooked. Converting analogue information and processes into digital form does not, by itself, create value. Without a clearly defined purpose, measurable benefit, and meaningful application, digitization may simply increase cost and complexity. We explore the journey from digitization and Industry 4.0 towards digital transformation, placing current technological developments, including artificial intelligence, into a broader strategic and socio-technical perspective. Digital transformation is understood not as the implementation of individual technologies, but as the purposeful redesign of business processes, organizational structures, culture, and user experiences to meet changing requirements and create sustainable value. A successful transformation connects technological building blocks with meaningful, user-driven use cases. Technology should therefore not be the starting point or an end in itself; instead, transformation must be guided by user needs, process analysis, innovation potential, and clearly articulated business value. Drawing on academic research and practical experience, we highlight key success factors: a clear value-oriented strategy, strong internal capabilities, scalable cross-functional operating models, accessible and reliable data, distributed technology architectures, and effective adoption and change management. Finally, the growing complexity, costs, risks, and societal implications of digital transformation are addressed. It requires a sound architectural approach, the reuse of fundamental capabilities, and the targeted application of systems engineering, modelling, simulation, optimization, and artificial intelligence.

The central message is clear: there are no technological shortcuts to successful digital transformation; sustainable success requires a coordinated, value-driven, and human-centered approach.

About the speaker

Siegfried Voessner is a Full Professor at Graz University of Technology and conducts research as an analyst and systems architect at the intersection of IT, society, and business. He heads the Institute of Engineering and Business Informatics, which has addressed various aspects of digital transformation for more than 25 years, and serves as Vice Dean of the Faculty of Mechanical Engineering and Economic Sciences at the same university. He was a postdoctoral fellow at the Department of Engineering–Economic Systems and Operations Research at Stanford University (USA) and a project manager at McKinsey & Company, specializing in business strategy, operations, and IT. He has also been a visiting professor at Stanford University, the Naval Postgraduate School in Monterey (USA), and the University of Auckland in New Zealand. He consults for government agencies and the private sector, including in healthcare and public safety. He has also served as Chief Scientific Advisor for Research and Innovation at the Austrian Federal Ministry of the Interior. His consulting focuses on strategy development, operations planning and management, IT and systems security, digital transformation, and AI applications.

Sustainable Polymers

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O01 | Keynote | Session 1 – Recycling

Engineering Circularity in Composite Structures: From End-of-Life Recycling to Reuse, Requalification and Value Retention

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Keywords: Composite structures; circularity; recycling; reuse; requalification; design-for-circularity; EURECOMP

Composite structures have become indispensable in wind energy, aerospace, transport, marine and infrastructure applications, where low weight, durability and high specific performance are critical. At the same time, their end-of-life management remains one of the most persistent sustainability challenges in polymer and composite engineering. Large volumes of glass- and carbon-fibre-reinforced composites are reaching retirement age, while thermoset matrices, bonded assemblies, sandwich architectures, coatings, inserts and uncertain service histories limit the effectiveness of conventional recycling routes. As a result, the transition from composite waste management to true circularity requires more than the recovery of fibres or the diversion of material from landfill. Circularity in composite structures must be treated as an engineering problem of value retention across the full lifecycle. Instead of placing end-of-life recycling as the default solution, circular strategies should be selected according to the residual structural value of the component, the quality and traceability of the material, the performance requirements of the next application and the environmental and techno-economic balance of each route. In this context, repair, reuse, repurposing, remanufacturing, requalification and design-for-circularity can be as important as mechanical, thermal or chemical recycling. This work introduces a structure-level circularity framework for fibre-reinforced composite systems, distinguishing between material-level, component-level and structure-level pathways. Key recycling and reclamation technologies will be reviewed in terms of recovered material quality, scalability and engineering value, while particular emphasis will be placed on often-overlooked value-preserving routes such as structural reuse and repurposing. The talk will also address the main barriers that currently prevent circular composite structures from moving beyond isolated demonstrations: residual mechanical performance, damage assessment, non-destructive testing, fatigue and ageing uncertainty, traceability, certification, standardisation and market acceptance. Building on insights from the EURECOMP project and related developments in circular composite engineering, the keynote will propose a roadmap for moving from end-of-life treatment towards circular design and requalification of composite structures. Short-term priorities include better mapping of composite waste streams, common terminology, application-specific circularity metrics and validated case studies. Medium- and long-term priorities include requalification protocols, digital product passports, design-for-disassembly, circular manufacturing concepts, standardisation pathways and industrial value chains capable of retaining material and structural value. The central message is that the future of composite circularity will not be defined by a single recycling technology, but by integrated engineering decisions that preserve performance, reduce environmental burden and enable safe second-life applications.

Analysis of the Recycling Potential of Engineering Plastics from End-of-Life Ski Binding Plates

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Keywords: end-of-life ski bindings; mechanical recycling; PCR Engineering Plastics; tensile testing; notched impact testing; economic feasibility

End-of-life ski bindings contain high-performance engineering plastics with considerable potential for mechanical recycling. However, reliable data on their properties after long-term exposure to mechanical loading, low temperatures, moisture, ultraviolet radiation, and oxidative ageing remain limited. This study, conducted within the WINTRUST project, evaluates the recyclability of glass-fibre-reinforced polyamide 6 (PA6-GF), acrylonitrile butadiene styrene (ABS), and polyoxymethylene (POM) recovered from discarded ski binding plates. The binding plates were manually dismantled and sorted using material markings on the components. Of 325 sorted parts, 154 were assigned to PA6-GF, ABS, or POM fractions and sufficiently clean for further processing. Following mechanical size reduction, the recovered polymers were injection moulded into standardised test specimens. Material performance was assessed by tensile testing, notched impact testing at 23 °C and -30 °C, and melt mass-flow-rate measurements. The results were compared qualitatively with literature values for corresponding virgin materials. All recyclates remained suitable for injection moulding, although material-specific ageing effects were identified. PA6GF showed the most pronounced loss of mechanical performance. ABS and POM retained comparatively stable tensile properties but exhibited reduced impact resistance. Increased melt-flow rates, particularly for ABS and POM, indicate polymer-chain degradation and must be considered when defining processing conditions and potential applications. The sorting trial and further larger scale trials at the GW-St. Pölten demonstrated that marked components can be separated rapidly using visual identification and minimal equipment. Manual sorting may therefore provide an economically viable preprocessing route, particularly when integrated into existing dismantling or sheltered-workshop operations. The results confirm that end-of-life ski bindings are a promising source of secondary engineering plastics, provided that sufficient material purity and application-specific property requirements are maintained.

A Novel Continuous Recycling Approach for Mixed Thermoplastics Based on Centrifugal Melt Separation

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Keywords: Mechanical recycling; Polymer separation; Centrifugal separation; Multiphase polymer melts; Continuous recycling process; Polymer blend recycling

The increasing complexity of plastic waste streams, particularly multilayer films, polymer blends, and mixed thermoplastic fractions, represents a major challenge for conventional mechanical recycling technologies. Many of these materials are currently directed toward thermal recovery instead of material recycling due to insufficient separation methods. This study investigates the development and validation of a novel centrifugal separation process for mixed thermoplastic polymers in the molten state. The work primarily focuses on the construction and operation of a continuous prototype system as well as on the recycling performance of different polymer mixtures under continuous processing conditions. A prototype consisting of a heated rotating tube integrated with a compounding unit was designed and constructed to enable the continuous feeding and centrifugal separation of homogeneous polymer melts according to density differences. Initial discontinuous experiments with HDPE and PLA mixtures demonstrated the general functionality of the separation principle and confirmed the operational reliability of the prototype. Based on these findings, the system was extended toward continuous operation. During process optimization, a modified discharge system was developed in which the separated polymer melts were extracted along the tube length instead of only at the tube end, significantly improving process stability and preventing outlet blockage caused by melt cooling and viscosity increase. The recycling investigations focused on several polymer combinations, including LDPE/PLA, LDPE/polystyrene (PS), and polyamide (PA)/polyethylene terephthalate (PET) mixtures. Prior to processing, the thermal stability and suitable processing temperatures of the polymers were determined using differential scanning calorimetry (DSC). Parameter studies were subsequently performed to evaluate the influence of rotational speed, residence time, and feed composition on separation efficiency. Samples collected from different extraction positions along the rotating tube were analyzed using density separation methods, thermogravimetric analysis (TGA), and DSC measurements. The experimental results demonstrated successful separation of polymer blends in both discontinuous and continuous operating modes. For LDPE/PLA mixtures, separation purities of up to 95 % were achieved under optimized conditions. Increasing rotational speed improved the separation efficiency, while the axial extraction positions confirmed progressive phase separation along the tube length. Additional experiments with LDPE/PS mixtures showed that the process is also applicable to systems with relatively small density differences. Furthermore, the prototype successfully processed PA/PET mixtures at elevated temperatures and rotational speeds, demonstrating the robustness of the developed apparatus under demanding operating conditions. Beyond material separation, the process also showed potential for additional recycling applications, such as odor removal from contaminated polystyrene waste streams. Complementary numerical simulations of multiphase polymer melt flows under centrifugal loading were performed for both discontinuous and continuous separation processes. The simulations reproduced the experimentally observed separation behavior with high accuracy and demonstrated the strong influence of rotational speed and mass flow rate on separation efficiency. A particularly important outcome of the study is the high correlation between simulation results and experimental observations, enabling future process optimization and automated process control strategies. Overall, the developed centrifugal melt-state separation process demonstrates significant potential for extending mechanical recycling to complex mixed-polymer waste streams that are currently difficult to recycle using conventional technologies. The successful validation of both the prototype and the accompanying simulation models establishes a promising basis for future industrial-scale applications and further development of continuous polymer separation technologies.

O04 | Oral Presentation | Session 1 – Recycling

Post-consumer recycled polyolefins for rotational molding applications

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Keywords: circular economy, rotational molding, post-consumer waste, polyolefins, polymer recycling

The mechanical recycling of thermoplastics represents both an opportunity for material recovery and a strategic approach for the plastics industry to add value, reduce waste, and decrease the consumption of virgin raw materials. Driven by global sustainability goals and packaging regulations, post-consumer recycled (PCR) materials from rigid packaging are a rapidly growing segment. The use of PCR materials in demanding processing technologies, such as rotational molding, remains a challenge due to their heterogeneous origin, variable composition, processing history and thermo-oxidative resistance. This study aims to evaluate the suitability of PCR polyolefin-based materials for rotational molding applications, particularly for the production of large and durable components. Its potential for rotational molding was assessed through a comprehensive characterization of its rheological, thermal and physical properties, as well as through the evaluation of the processability and quality of the molded parts. The processing conditions were varied in terms of mold internal air temperature (IAT: 230-250°C) and cooling by air or forced air. The results indicated that the PCR powder provided by SIRPLASTE company (Portugal) consisted predominantly of high-density polyethylene (HDPE), with a minor fraction of polypropylene (PP). Although the material could be processed by rotational molding, the parts produced from the as-received PCR powder exhibited significant warpage and surface pinholes. These defects indicated that, despite its apparent processability, the material required further optimization to meet the quality requirements of rotationally molded products. To improve part quality, blends of PCR material with virgin polyolefins were subsequently investigated. Recycled-to-virgin polymer ratios ranging from 90/10 to 50/50 were prepared and processed by rotational molding. The resulting parts were analyzed using optical microscopy (OM), small-angle light scattering (SALS) and falling-weight impact testing in order to evaluate their morphology and mechanical performance. The incorporation of virgin medium-density polyethylene (MDPE) significantly improved the performance and dimensional stability of the molded parts. Based on impact resistance and morphological analysis, blends containing 40-50 wt.% virgin MDPE provided the most suitable balance between part quality and recycled content. The blend of 50 % PCR HDPE with 50 % virgin MDPE is important to prevent warping; however, using cooling by air is also an effective approach, but at the expense of a significant increase of cycle time. The results highlight the potential of combining recycled HDPE-rich PCR materials with selected virgin polyolefins to produce large, durable rotationally molded parts with improved dimensional stability and mechanical performance.

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Polyolefin recycling into vitrimers

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Keywords: Mechanical recycling; polyolefin; polyethylene; vitrimer

Polyethylene (PE) is the most widely used commodity polymer due to its low cost, versatility, and favorable processing characteristics. Conventional cross-linked polyethylene (XLPE) exhibits enhanced thermal and mechanical performance; however, the permanent covalent cross-links significantly limit recyclability and reprocessability. Vitrimers have emerged as a promising alternative, combining the dimensional stability of thermosets with the reprocessability of thermoplastics through dynamic covalent bond exchange reactions. In this work, polyethylene vitrimer-like materials were developed using two distinct dynamic crosslinking chemistries to investigate the influence of network structure and exchange mechanisms on material performance. Maleic anhydride grafted polyethylene (PE-g-MAH) was employed as the reactive precursor and subsequently crosslinked through either 4,4'-dithiodianiline (DTA) or 1,4-butanediol diglycidyl ether (BDDGE). The DTA-based system introduces dynamic disulfide bonds capable of catalyst-free disulfide metathesis, while the BDDGE-based network relies on transesterification reactions catalyzed by zinc acetylacetonate ($Zn(acac)_2$). Both approaches enable the formation of covalently crosslinked networks while preserving the potential for bond exchange, repair, and reprocessing. The resulting vitrimer materials were evaluated in terms of mechanical performance, viscoelastic behavior, crystallinity, thermal stability, and network dynamics. Particular attention was given to understanding how crosslink density and exchange chemistry affect stiffness, thermal resistance, and processability. The comparison between disulfide metathesis and transesterification provides insight into the structure-property relationships governing polyethylene vitrimer systems. This study demonstrates the feasibility of transforming commercially available polyethylene into recyclable, high-performance vitrimer materials using industrially relevant reactive extrusion and melt-processing routes, thereby contributing to the development of more sustainable alternatives to conventional XLPE.

O06 | Keynote | Session 2 – Sustainability

Design-for-Recycling in Polyethylene Multilayer Films: Controlling Performance via Layer Architecture

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Keywords: Design-for-recycling; flexible films; multilayer packaging; polyethylene; recycled materials; film blowing extrusion

Flexible plastic films are widely used in modern industry due to their versatility and low weight, but their high production volumes contribute significantly to plastic waste and resource use. Their multilayer architectures, typically combining different polymers for performance, strongly limit recyclability. This motivates a shift toward mono-material designs in which performance is achieved through structural architecture rather than polymer diversity. This study explores such an approach using mono-material polyethylene (PE) multilayer films. Five three-layer films were produced via film blowing extrusion using virgin ultra-low-density polyethylene (ULDPE), recycled low-density polyethylene (rLDPE), and a 50/50 shredded blend of both, with varying recycled content and layer architecture (Figure 1). The influence of multilayer composition on chemico-physical and mechanical behavior was systematically evaluated, showing largely comparable properties between precursor materials and resulting films, with only minor processing-induced changes. A rheological compensation effect was observed, where chain scission in virgin ULDPE and crosslinking in recycled LDPE partially offset each other, contributing to flow stability during processing. Mechanical performance depended on the balance between recycled and virgin material, indicating the need to optimize recycled LDPE content to preserve functional integrity. Migration experiments using complementary proxy contaminants further demonstrate that outer-layer thickness is the dominant factor controlling contaminant transport in PE films. Overall, this work establishes a design framework for balancing high recycled content with mechanical performance and functional requirements in polyethylene-rich multilayer films.

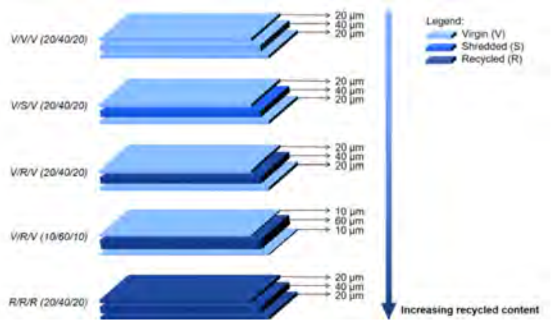

Figure 1. Outline of the different three-layer films with their composition and thickness (µm), ranked by increasing recycled LDPE content from top to bottom.

Using Python as an Open-Source Solution for Statistical Evaluation and Optimization of Polymer Blends containing Post-Consumer TPU Recyclate

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Keywords: open-source tools, design of experiment, statistical modeling, recycled plastics, polymer blends, circular economy

Drawing statistically robust conclusions in polymer science often requires complex mathematical computations, which have traditionally been handled using either non-optimal software with limited functionality or highly specialized tools that demand significant financial and time investments. As industries increasingly prioritize customizability, automation, and sustainability, the need for accessible and flexible solutions has grown. Python, a free and open-source programming language, offers researchers and technicians a powerful alternative, supported by a vast ecosystem of packages such as NumPy, Pandas, and Matplotlib. While Python requires basic coding skills, its user-friendly syntax and extensive learning resources make it an ideal choice for scientific applications. In this study, Python was used to design, validate, and evaluate an experimental design (DoE) for optimizing polymer blends containing post-consumer TPU recyclate (PCR). The formulations included small amounts (≤5 %) of polymeric additives such as an impact modifier, compatibilizer, and processing aid, and their effects on key material properties were systematically analyzed. Mechanical testing was conducted to evaluate impact strength at 23, 0, and -20 °C (ISO 179-1), bending properties at 23 °C (ISO 178), tensile properties at 23 and -15 °C (ISO 527-2), and indentation hardness at 23 °C (ISO 868). The PCR was sourced from the FFG-funded WINTRUST project which aims to improve recycling streams for winter sports hard goods, such as ski boots. TPU recyclates were selected for this study due to their availability, market value, and efficient separation processes. The results revealed that the compounding step generally reduced tensile strength, while the addition of polymeric additives further decreased tensile and bending stiffness. However, at low temperatures, the use of an impact modifier and compatibilizer significantly improved impact strength and tensile properties, making the formulations suitable for winter sports applications. All blends demonstrated acceptable Shore D hardness, highlighting their potential for industrial use. This study underscores the value of Python as a digital tool for advancing sustainable polymer formulations and optimizing recyclate performance.

Natural fibre reinforced bio-based polymers

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Keywords: Bio based polymers, bio based fibres, polymer processing

The project CircularBioMat investigates the processing of bio-based polymers as replacements for oil-based polymers in the construction sector, which accounts for roughly one-fifth of polymer consumption in Europe. Substituting with bio-based materials could significantly reduce the sector's CO2 footprint. Because many applications require fibre reinforcement to achieve higher stiffness, we evaluated natural fibres as sustainable reinforcements. Fibres were sourced from fir wood and bark, beech wood and bark, miscanthus, and wheat straw. Each fibre type was used both untreated and with a chemical surface treatment. Acetylation was performed using acetic acid and sulfuric acid under carefully controlled temperature conditions. The treatment was applied to decrease the hydrophilicity of the fibres, thereby reducing moisture uptake and enhancing their dimensional stability. These improvements are expected to contribute to more consistent mechanical behaviour during subsequent testing. In addition, both untreated and acetylated fibres were characterized by Fourier-transform infrared (FT-IR) spectroscopy to evaluate the chemical modifications resulting from the acetylation process. Comparative analysis of the FT-IR spectra was performed to identify characteristic changes in the functional groups of the fibre constituents induced by the chemical treatment. Dried fibres were compounded with a bio-based polyethylene (PE) from Tecnaro using a Leistritz co-rotating twin-screw extruder. An initial trial with PHB was unsuccessful: subsequent injection moulding produced specimens that were too brittle for reliable testing. The bio-based PE compounds were injection moulded into test specimens and characterised by standardised tensile testing. Rheological measurements were conducted to assess changes in the flow behaviour, and NIR spectra of the tensile specimens were compared to detect potential changes in chemical composition. The presentation will detail the processing methods and discuss the mechanical, rheological, and spectroscopic results.

Recovering SLS processed PA12 for rotational molding applications

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Keywords: SLS processed PA12, Rotational molding, processing conditions, structure-processing-relationship

Selective Laser Sintering (SLS) is an additive manufacturing technology that uses polymer powders to produce parts. During the process, approximately 80 % of the powder serves only as support material, not being directly incorporated into the final components. Although this powder can be reused in subsequent manufacturing cycles when mixed with new material, the number of reuse cycles is limited due to changes in its properties caused by repeated processing. This results in the accumulation of processed powder with reduced potential for further use in SLS, creating logistical, environmental, and economic concerns. Therefore, it is important to explore alternative applications for this material to improve its sustainability and economic value. To this end, the study explores the use of rotational molding process as a route to end-use SLS processed powder of PA12 (PA2200, supplied by EOS GmbH, with an average particle size of 56 µm). The study first focuses on the physical and thermal characterization of PA12 powder upon using it to the limits of usability in SLS process, with no further treatment or modification. Then, parts were produced by rotational molding with different processing conditions to understand the effect of PIAT (Peak internal air temperature: 220, 225, 230, 235 °C), rotational speed (3,5-8,5 rpm) and cooling rate (forced or natural) on the part quality and resulting morphological and mechanical properties. The effect of material drying and mold shape were also explored. The results demonstrate that processed PA12 powder derived from SLS can be transformed by rotational molding, although its processing window is particularly narrow. This limitation is mainly associated with the variation in melt properties within the processing temperature used in rotational molding. At low PIAT the consolidation of the part is compromised, whereas at high temperature thermo-oxidative degradation occurs. Signs of thermal degradation becomes apparent at PIAT above 230 °C, highlighting the importance of careful thermal control during processing. Furthermore, a lower mold rotational speed seems to promote a better uniformity in material distribution, resulting in improved wall thickness homogeneity. Dried recycled PA12 processed at a PIAT of 230 °C and cooled by natural convection exhibited the most favorable overall performance, providing the best combination of part quality and mechanical properties. Material drying proved beneficial in reducing porosity and improving the surface quality of the molded parts, which was also reflected in enhanced mechanical performance. However, this pre-treatment may negatively affect material distribution within certain areas of the mold, especially when squared like molds are used compared to rounded geometries. In addition, slower cooling under natural convection conditions favors the morphological development, improving mechanical properties. This research suggests that SLS-processed powder can be effectively used in rotational molding when the processing parameters are carefully controlled within a narrow processing window. This approach represents a promising opportunity to create a value-added application for SLS powders, contributing to a more sustainable use of such materials.

Acknowledgements: To the contribution of the students Afonso Oliveira, Carolina Silva, Gonçalo Castro, João Oliveira, Rita Torrinha, pursuing their Bachelor's degree in Materials Engineering, for contributing to some of the experimental work carried on. This work was carried out within the framework of the “Agendas para a Inovação Empresarial” (Project nº 49, acronym “INOV.AM”, with reference PRR/49/INOV.AM/EE, operation code 02/C05-i01.01/2022.PC644865234-00000004), supported by the RRP - Recovery and Resilience Plan and by the European Funds NextGeneration EU. http://www.recuperarportugal.gov.pt/. It was also funded by National Funds through FCT - Portuguese Foundation for Science and Technology, Reference UID/05256: Institute for Polymers and Composites (IPC/UM).

Effects of an external magnetic field on ferromagnetic biocomposites obtained by foam injection molding

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Keywords: Injection molding; Magnetic field; Composites; Biodegradable polymers; CIP; MAP

The use of a magnetic field during the injection molding of thermoplastic composites with carbonyl iron particles (CIP) can be highly effective for controlling the production of structural and multifunctional lightweight materials based on polymeric foams. An aluminum mold was engineered to integrate an electromagnet that allows the application of a magnetic field (MF) throughout the injection and solidification phases. The produced Multifunctional Advanced Porous Composites (MAPs) exhibit an anisotropic distribution of the particles. The use of a biodegradable polymer matrix allows the reduction of the environmental impact of the produced MAPs. In this work, multifunctional composites were prepared using 50 wt% carbonyl iron particles (CIPs) and 2 wt% expanded graphite (EG) incorporated into a PLA/PBAT matrix. The injection-molded samples were characterized in terms of morphology, thermal conductivity, physical and mechanical properties. These results demonstrate that samples molded in the presence of a MF exhibited an alignment of iron particles along the magnetic field lines. These alignments led to an enhancement of the mechanical properties in the direction of the magnetic field with respect to samples in which the particles were randomly dispersed. The use of micro-particles resulted in a remarkable improvement of the cellular morphology of foamed samples, which showed a significant reduction in density and thermal conductivity compared to the corresponding compact materials. Moreover, the alignments within the multifunctional composites induce sensitivity to the application of an external magnetic field.

Smart Polymers

CONTRIBUTIONS IN PROGRAMME ORDER

>>> Function-integrated materials

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Ludwig Cardon
Direct Extrusion Additive Manufacturing of Pellet-Based Feedstocks: A Bottom-Up Approach for Process Optimization by use of an Innovative Flow-Controlled printing head

Francesca Aliberti
Shear-Induced Carbon Nanotube Alignment in FFF-Printed ABS Composites for Smart Applications

Pedro Martinho
Performance of Hybrid Moulds using moulding blocks manufactured via different AM technologies: A comparative study

New perspectives for NIPUs: linear polyhydroxyurethanes of high-molecular weight obtained by fast polymerization

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Keywords: Non-isocyanate polyurethanes; Polyhydroxyurethanes; aromatic cyclic carbonates; reactivity

Conventional methods for synthesizing thermoplastic polyurethanes (TPUs) typically rely on isocyanates and catalysts, both of which present significant environmental and safety risks. To mitigate ecological impact and health hazards, the development of non-isocyanate polyurethanes (NIPUs) is crucial. Polyhydroxyurethanes (PHUs) in particular show great potential due to the low toxicity of the monomers and the relative ease of synthesis, but suffer from slow polymerization kinetics [1, 2, 3] and side reactions that decrease their degree of polymerization (DPn) and materials properties. In particular, DPn values for these materials tend to plateau around 30 and rarely exceed 40 [4]. This study reports a new, rapid PHU polymerization from di-functional monomers achieved without macromonomers, catalysts, or post-condensation reactions [5, 6]. Thanks to the unique reactivity of aromatic cyclic carbonates (ACC) with amines, particularly cycloaliphatic secondary amines (CAAs), model systems give 100 % conversion within minutes with minimal secondary reactions. This approach has been successfully extended for the first time to the rapid synthesis of linear PHU chains. A range of difunctional ACC and CAA monomers with diverse chemical structures have been utilized to optimize reactivity, minimize side reactions, and achieve high DPn and molecular weights (Mn). The synthesized PHUs were characterized using nuclear magnetic resonance (NMR), Fourier-transform infrared spectroscopy (FTIR), gel permeation chromatography (GPC), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). The highest DPn and Mn obtained were ~220 and ~105,000 g/mol, respectively. These PHUs were subsequently molded into bars and analyzed via thermo-mechanical techniques, demonstrating significant potential for future applications. [1] Besse, V. et al., How to Explain Low Molar Masses in PolyHydroxyUrethanes (PHUs). Eur. Polym. J. 2015, 71, 1-11. DOI: 10.1016/j.eurpolymj.2015.07.020. [2] Blain, M. et al. S. Hydrogen Bonds Prevent Obtaining High Molar Mass PHUs. J. Appl. Polym. Sci. 2017, 134 (45), 44958. DOI: 10.1002/app.44958. [3] Ecochard, Y. et al. Hybrid Polyhydroxyurethanes: How to Overcome Limitations and Reach Cutting Edge Properties? Eur. Polym. J. 2020, 137, 109915. DOI: 10.1016/j.eurpolymj.2020.109915. [4] Benyahya, S. et al. Optimization of the Synthesis of Polyhydroxyurethanes Using Dynamic Rheometry. Polym. Int. 2012, 61 (6), 918-925. DOI: 10.1002/pi.4159. [5] Zubkevich, S.V. et al. Method for the synthesis of high molecular weight polyhydroxyurethanes. LU509504, 2024. [6] S. V. Zubkevich et al. Highly Efficient Approach to High-Molecular Weight Polyhydroxyurethanes. Macromolecules, 2026, 59, 5140-5150. DOI:10.1021/acs.macromol.5c02932

Negative Thermoresponsive NIPAAm/HPMC Hydrogel for Textile Coating Applications

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Keywords: thermoresponsive hydrogel; N-isopropylacrylamide (NIPAAm); hydroxypropyl methylcellulose (HPMC); smart textiles; thermoreversible behavior

Thermoresponsive hydrogels are attractive materials for smart textile applications due to their ability to reversibly respond to temperature changes. In this study, a hybrid hydrogel based on N-isopropylacrylamide (NIPAAm) and hydroxypropyl methylcellulose (HPMC) was developed to increase the bio-based content of the material while maintaining its thermoresponsive functionality. The hydrogels were characterized by rheological measurements, attenuated total reflectance (ATR) spectroscopy, swelling degree analysis, and stereoscopic observations during heating and cooling cycles. Rheological measurements showed a reversible sol-gel transition with an apparent gel transition temperature (Tgel) between 29.5 and 33 °C, close to the lower critical solution temperature of NIPAAm. The incorporation of HPMC preserved the thermoresponsive behavior of NIPAAm, although a reduction in storage modulus was observed compared to pure NIPAAm hydrogels. ATR spectra confirmed the characteristic chemical functionalities of the hybrid system, while stereoscopic observations demonstrated reversible shrinking and re-swelling during temperature cycling. These findings indicate that NIPAAm:HPMC hybrid hydrogels retain their thermoresponsive properties while incorporating a bio-based component, highlighting their potential as sustainable functional coatings for smart textile applications.

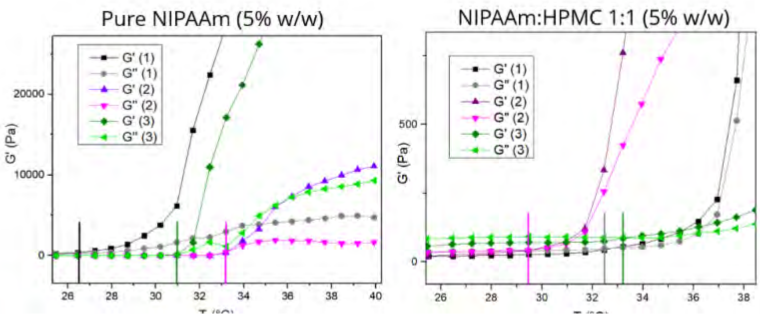

Figure 1. Rheological measurements showed a reversible sol-gel transition between 29.5 and 33 °C, with HPMC reducing the storage modulus compared to pure NIPAAm.

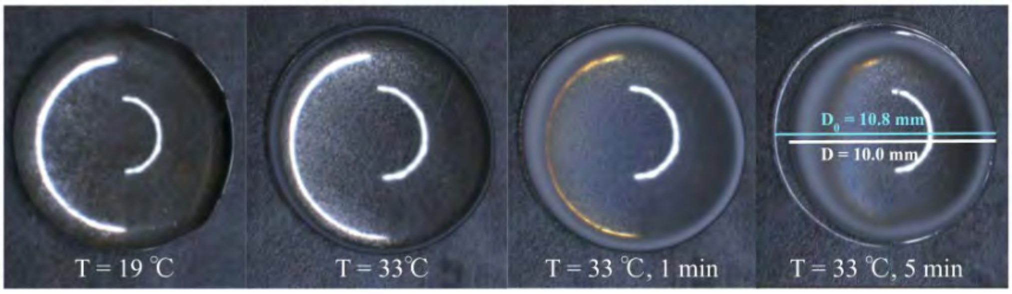

Figure 2. Stereoscopic images of the NIPAAm:HPMC hydrogel showing temperature-induced shrinkage at 33 °C over 5 min.

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Blending Behavior of Polyhydroxyalkanoates: Investigation of PHB, PHBH, and P34HB Systems

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Keywords: Bioplastic, Polyhydroxyalkanoate (PHA); Blends; Ductility, Miscibility

Bio-based and biodegradable bioplastics currently represent a promising alternative to conventional plastics. Although well-known examples such as polyhydroxybutyrate (PHB), a member of the polyhydroxyalkanoate (PHA) family, fulfill the requirements for a sustainable alternative, material properties such as very low ductility limit their range of applications. To optimize the properties of PHB, additives such as plasticizers are typically used, or physical blends are prepared with other polymers such as PLA. However, the resulting improvements in material properties are often limited and/or the biocharacter is compromised. To enable the development of a broad range of material properties while maintaining the biological characteristics of the material, this study therefore investigates blends within the PHA family. For this purpose, various blends of the homopolymer polyhydroxybutyrate (PHB) with the copolymers poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH), containing 10 mol% 3HH, and the nearly amorphous poly(3-hydroxybutyrate-co4-hydroxybutyrate) (P34HB), containing 30-35 mol% 4HB, were prepared by twin-screw extrusion. The blends were thermally characterized using differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA), with a particular focus on the glass transition temperature as an indicator of miscibility. Rheological characterization was carried out using a plate-plate rheometer, molar masses were determined by gel permeation chromatography (GPC), and mechanical properties were evaluated by tensile testing. Due to the pronounced ductile behavior of P34HB, the ductility of the blends was significantly improved over a wide composition range. Blending with P34HB reduced the average tensile strength of the blends by up to 80.7 %, while increasing the average yield strain by up to 858 %. Similarly, but to a lesser extent, blending with PHBH reduced the average tensile strength by up to 37.6 %, whereas the average yield strain increased by up to 119 % (Figure 1). Consequently, the mechanical properties of the blends can be adjusted over a broad range by varying the blend composition. As expected, the complex viscosity decreased over the measurement period due to the thermal sensitivity of the materials. Furthermore, the complex viscosity increased with increasing P34HB content, whereas it decreased with increasing PHBH content. This behavior is mainly attributed to the different molar masses of the blend components, namely PHBH (Mw = 423,010 g/mol, Đ = 2.41) and P34HB (Mw = 606,289 g/mol, Đ = 2.17), as determined by GPC. In addition, blending significantly affected the crystallization behavior by shifting the onset of crystallization to lower temperatures and reducing the crystalline fraction through incorporation of the less crystalline PHBH and the nearly amorphous P34HB.

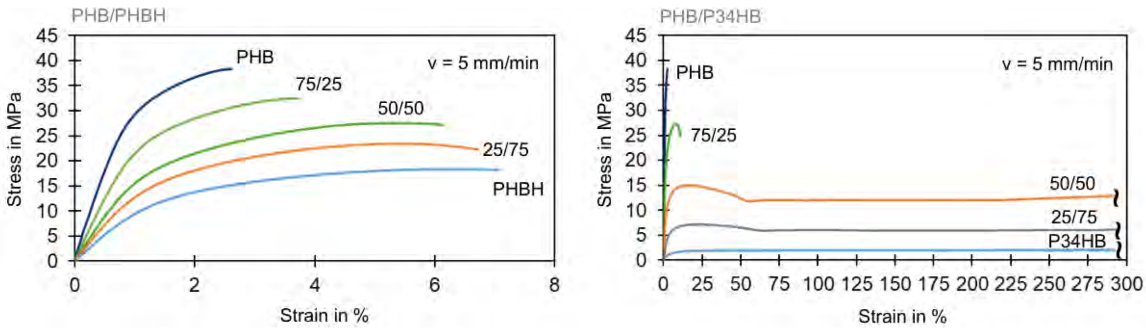

Figure 1. Stress-strain curve for PHB/PHBH and PHB/P34HB blends.

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Polymer Matrix Contributions to Cu@Ag Filler Network Formation

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Keywords: Silver coated copper flakes; LDPE; Thermoplastic polyurethane; Conductive polymer composite

The Abstract is written in E Conductive polymer composites (CPCs) filled with metallic particles have become attractive materials for use in flexible electronics, sensors, and electromagnetic interference shielding [1]. This is mainly because they combine the relatively easy processing of polymers with functional properties of metallic fillers. Another advantage is that these composites can be formed into complex, application-specific shapes using common polymer processing methods, such as injection moulding and additive manufacturing. An important question in the preparation of these composites is how the polymer matrix influences the formation of the conductive filler network and how this affects the final composite properties. In this study, metallic Cu@Ag core-shell flakes were melt-compounded and injection-moulded with two different polymer matrices: low-density polyethylene (LDPE), a semicrystalline thermoplastic, and thermoplastic polyurethane (TPU), a segmented elastomer with a hardsoft phase-separated morphology. LDPE is widely used due to its low density, good processability and low moisture absorption. TPU, on the other hand, exhibits high flexibility owing to its segmented elastomer structure. Metallic fillers, Cu@Ag flakes, used in this study, are particularly promising because the thin Ag shell enhances the surface oxidation resistance of Cu during processing at elevated temperatures and consequently the Cu core maintains high electrical and thermal conductivity at lower cost compared to pure Ag particles [2]. The Cu@Ag fillers were added to two above mentioned polymer matrices in different concentration, i.e., from 0 to 40 vol.%. The injection-moulded composites were characterised using rheological analysis, thermal analysis (DSC and TG), mechanical testing (DMA and tensile testing) and electrical conductivity measurements. The results showed that the processability and physical properties of the composites studied strongly depended on the polymer matrix used. However, in both LDPE and TPU polymer, the mechanical reinforcement and electrical percolation were observed at the same critical concentration, i.e., Φvol ~7.5 %. These results indicate that the critical filler concentration is primarily determined by the formation of conductive network. Nevertheless, the final properties (processability, mechanical and electrical performance) of such polymer composites for specific applications remain highly dependent on the selection of the polymer matrix.

Acknowledgements: The results were obtained with the financial support by financial support from Slovenian Research Agency, grant number P2-0264. References: [1] Sankaran, S., et al., Composite Part A: Applied Science and Manufacturing 2018, 114, 49-71 [2] Mihelčič, M., et al., Polymers 2024, 16 (12), 16020

Mechanical Spreading of Heavy-Tow Carbon Fibers via Forced Conveying

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Keywords: fiber spreading; forced conveying; carbon fiber rovings; design of experiments; process control

The uniform spreading of fiber rovings into homogeneous filament carpets is a fundamental process step and critical prerequisite for manufacturing high-quality continuous fiber-reinforced plastics. Conventional deflection-based spreading systems often struggle to compensate for input width fluctuations, which are not sufficiently equalized during subsequent processing. Consequently, variations in the width of the spread filament carpet remain, directly affecting process stability and final product quality. These fluctuations typically originate from variations in filament packing, handling, and tension history of the incoming rovings, in particular for heavy tows due to their large filament count and inherent structural inhomogeneities. To address this, this study systematically investigates a novel spreading technology based on the principle of forced conveying using mechanically grooved spreading roller (see Figure 1). Two groove configurations, interrupted and continuous, were examined under co-rotating and counter-rotating operating modes. Using a 60K heavy-tow carbon fiber roving with highly variable input width, the ability of each configuration to compensate for pronounced inlet-width fluctuations was evaluated. Four independent rotatable Central Composite Experimental Designs (CCD) were conducted to mathematically quantify the impact of the circumferential roller speed and the roving wrap angle on the final spreading width and its consistency. We found all 4 roller configurations to effectively decouple the final spread width from the fluctuating initial width. The statistical evaluation identified the wrap angle as the dominant linear process parameter; the circumferential roller speed exerted a significant, non-linear (quadratic) secondary influence. Continuous grooves operated in counter-rotating mode achieved the best spreading (i.e. yielding the largest final width), in contrast, interrupted grooves provided superior damping of inlet fluctuations, thus significantly improving process robustness at the cost of slightly smaller final widths. The derived quadratic regression models showed excellent predictive accuracy (R^2 up to 0.97), indicating a controllable process behavior. Therefore, the forced-conveying spreading approach enables targeted parameter adjustment and offers a promising basis for robust industrial closed-loop process control in UD-Tape composite manufacturing.

Figure 1. Schematic of a spreading roller with surface grooves for geometry-driven fiber spreading.

Processing-induced microstructure controls fatigue crack growth in injection-molded NBR: cavity pressure and extraction-position effects

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Keywords: Nitrile butadiene rubber; fatigue crack growth; injection molding; cavity pressure; flow-induced anisotropy

Fatigue failure of elastomers is quantified through the Paris-Erdogan power law, whose parameters C and m depend on formulation and on processing-induced microstructure. In injection-molded parts, the parabolic flow profile and pressure-temperature history produce anisotropic networks with locally varying filler orientation and defect distribution. Their influence on fatigue crack growth, however, remains scarcely investigated. This work quantifies two largely overlooked processing variables, cavity pressure and specimen extraction position, in a single mineral-filled, sulfur-cured nitrile butadiene (NBR) system. A mineral-filled, sulfur-cured NBR was injection-molded on a Maplan MTF750/160editionS machine (160 °C, 499 s) into pure-shear strips (200 × 16 × 4 mm^3). Cavity pressure was varied via shot volume (121 cm^3 vs 123 cm^3, ≈290 and ≈380 bar). For the position study, three specimens were cut from a single 121 cm^3 strip: middle (core), side (gate region, laboratory standard), and full (200 mm). Fatigue tests were strain-controlled (12 steps, 14-36 %, 1Hz, R = 0.2, 5000 cycles/step) with both crack tips monitored by in situ camera. The 121 cm^3 and 123 cm^3 conditions yielded Paris-law fits intersecting at a transition tearing energy of approximately 2.5 kJ/m^2 (Figure 1(b)). Strain-energy partition analysis showed nearly identical dissipated energy fractions (26.4 % vs 25.6 %); dissipation therefore explains less than 15 % of the Paris-law difference. The crossover is the signature of two competing mechanisms: higher network stiffness raises local crack-tip stress, dominant at low tearing energies, while a reduced microvoid population from compressive consolidation lowers crack-coalescence-site density, dominant at high tearing energies. The three extraction positions produced Paris-law fits spanning a factor of 4.5 in slope (Figure 1(c) and Table 1). The crack-growth-rate differences exceed one decade at 3.5 kJ/m^2. In all asymmetric specimens, the gate-side crack tip consistently advances faster than the far-side tip (Figure 1(d)), a direct signature of flow-induced anisotropy. Cavity pressure and extraction position act at different microstructural levels, averaged bulk consolidation versus spatial gradient and must be treated separately in process-property models. Paris parameters of injection-molded elastomers cannot be interpreted as intrinsic material properties without specifying extraction position and flow direction.

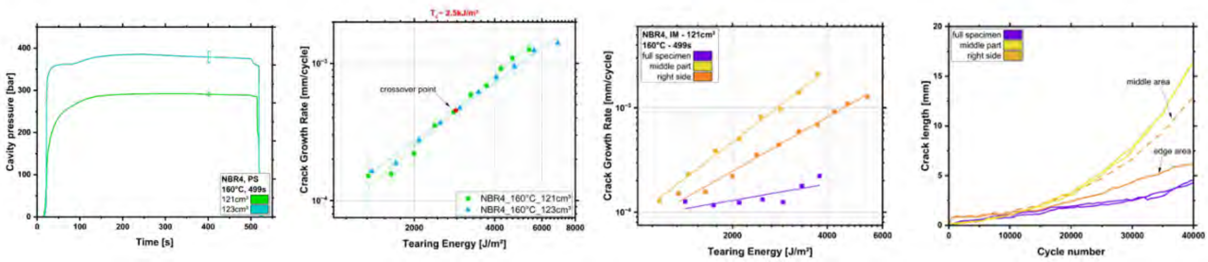

Figure 1. (a) Cavity pressure curves of 121 cm^3 and 123 cm^3 specimens. (b) Paris-Erdogan plot for the two pressure conditions. (c) Paris-Erdogan plot for three extraction positions from a single 121 cm^3 molded strip. (d) Crack length versus cycle number.

Table 1. Paris-Erdogan parameters for the four experimental conditions.

Condition	log C	m
123 cm^3, side	-8.38	1.45
121 cm^3, side	-9.16	1.68
121 cm^3, middle	-11.31	2.42
121 cm^3, full	-5.62	0.53

Acknowledgment: This research project (grant number: 911658) was funded by COMET - Competence Centers for Excellent Technologies - through BMIMI, BMWET, and the co-financing federal provinces (Styria through SFG, Upper Austria, Vorarlberg) and carried out with the participation of scientific and company partners. The COMET program is managed by FFG.

Development of solutions to increase comfort in helmets through polymer additive manufacturing

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Keywords: Comfort Pads, Additive Manufacturing, Lattice Structures, Numerical Simulation, personal protective products

The sports industry has been undergoing a transition towards a greater emphasis on personalised solutions, with additive manufacturing (AM) being a technology that exhibits considerable potential to meet this need. In the case of cycling helmets, comfort is a pivotal factor in their acceptance and utilisation, directly related to their capacity to adapt to the user's anatomy and to pressure distribution. In the initial phase of this study, a range of lattice structures and materials were analysed using Maxwell's criterion, finite element analysis (FEA) and compression tests. The results obtained enabled the identification of topologies with suitable behaviour for comfort applications, notably Kelvin Cell, Diamond and BCC, as well as Silicone 40A, which was identified as the most suitable material due to its high capacity for deformation and elastic recovery. Simultaneously, usability tests were conducted to identify areas of discomfort, thus informing the development of a modular comfort system produced by FA. The validation of the developed solutions demonstrated significant improvements over the baseline system, notably in the reduction of pressure points, improved load distribution and enhanced comfort perceived by users. The results confirm that the combination of polymeric additive manufacturing, lattice structures and a user-centred approach constitute a viable solution for the development of customised comfort systems in cycling helmets.

Acknowledgements: This work was carried out within the framework of the "Agendas para a Inovação Empresarial" (Project n° 49, acronym "INOV.AM", with reference PRR/49/INOV.AM/EE, operation code 02/C05-i01.01/2022.PC644865234-00000004), supported by the RRP - Recovery and Resilience Plan and by the European Funds NextGeneration EU. http://www.recuperarportugal.gov.pt/. It was also funded by National Funds through FCT - Portuguese Foundation for Science and Technology, Reference UID/05256: Institute for Polymers and Composites (IPC/UM).

Polymer Stir Welding as a Sustainable Joining Technology for Lightweight Multi-Material Systems

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Keywords: polymer stir welding (PSW); joining technology; aluminum, steel; wood; thermoplastic polymers

Mobility is currently facing major challenges due to rising energy demands and the transition toward new drive technologies such as electrification and hydrogen-based systems. In this context, lightweight multi-material structures are becoming increasingly important for achieving climate targets and reducing CO_2 emissions [1]. However, established joining technologies such as adhesive bonding, screwing, or riveting often limit recyclability, process efficiency, and design flexibility in lightweight applications [2]. In addition, these approaches still exhibit limitations regarding design for recycling and the joining of non-adhesive or difficult-to-process material combinations. Therefore, alternative and innovative joining technologies are gaining increasing relevance to produce function-oriented lightweight components [3]. The patented "polymer stir welding" (PSW) process developed by royos (see Figure 1(a)) has already been introduced to the market and is currently being validated in industrial applications. By eliminating adhesives and enabling separable multi-material joints, the PSW process supports circular product design and improved recyclability. In a current application, a material combination of polycarbonate and aluminum 6082 is utilized to achieve high-strength joints with IP65 sealing performance. A partial factorial design of experiments (DoE) was applied to investigate the influence of stirring pin geometry, rotational speed, feed rate, and immersion depth on the joining quality. The resulting weld seams were characterized by microscopic analysis of the joining zone and quasi-static lap shear tensile tests according to ASTM D5868. Additionally, leak-tightness tests under media pressure exposure were conducted to evaluate the sealing performance of the joints. The obtained results confirm the industrial applicability of the PSW process. Optimized process parameters enabled shear tensile strengths of up to 35 MPa, representing up to seven times higher strength compared to adhesive bonding, while also achieving the required level of leak-tightness for the intended application. Furthermore, welding speeds of up to 1 m/min have already been achieved, underlining the scalability of the process for industrial production. The technology has already reached series production maturity for plastic/aluminum applications and is currently being implemented in ongoing projects involving additional material combinations such as plastic/wood and plastic/steel (see Figure 1(b)). These results highlight the strong potential of PSW as a scalable, sustainable, and resource-efficient joining technology for next-generation lightweight multi-material systems.

Figure 1. PSW tool (a) and overview of available material combinations (b).

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Sensing the Melt - Inline Process Monitoring in Medical 3D Printing

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Keywords: Additive Manufacturing 1; Pellet Extruder; Medical 3D printing, Inline Monitoring

Additive manufacturing has emerged as a potential approach for medical applications, encompassing patient-specific implants and resorbable devices, owing to its capacity to produce complex, tailored shapes. Several process families compete in this domain: powder bed fusion (PBF), vat photopolymerisation (VAT), and material extrusion (MEX), among others. Each is, nonetheless, constrained by its specified material palette. In MEX, medical applications are primarily confined to a limited number of authorised filaments, including PEEK. Pellet-based extrusion mitigates this limitation. Most medical-grade polymers come in small granules rather than filaments, so being able to print directly from these pellets greatly expands the choices of materials and eliminates an important processing step, making it easier to use new materials in medical applications. The manufacturer assures the quality of the granulate, but the printing process still primarily operates in an open-loop manner. This talk emphasises inline monitoring of the 3D printing process. A complete measurement system that tracks melt pressure, melt temperature, and motor current is built into the printer's software and works with G-code, allowing the printer to automatically record every measurement along with the command that created it. The initial results are promising: the measured melt pressure clearly changes with the commands to “extrude” or to “retract”, showing that the system accurately reflects real melt behaviour. As an independent check, motor current tracks the pressure signal closely (Pearson $r = 0.96$) to further validate the measured signal. Together with the synchronised process record, these findings establish a validated basis for in-process adjustments to extrusion speed and temperature, thus ensuring the quality of the printed components.

Towards in-line rheology for closed-loop plastics reprocessing

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Keywords: Closed-loop manufacturing; In-line rheology; Predictive modeling; Cross-WLF; PLA

Closed-loop plastics reprocessing has been often presented as one of the key enablers of the circular economy of plastics. However, its implementation in existing plastics processing operations faces important challenges that need to be assessed. One such challenge is polymer degradation occurring along the lifecycle of plastics. In several widely used polymers, exposure to the thermomechanical conditions of melt-processing under an uncontrolled atmosphere cumulatively leads to significant changes in molecular weight, viscosity, thermal and rheological properties. In turn, this brings uncertainty regarding material behavior and end-product properties, which can be a major barrier to the adoption of closed-loop processing. Thus, there is a need for solutions that allow manufacturers to efficiently predict the condition of feedstock plastics integrated into closed-loop processing scenarios. This work is aimed at contributing to such solutions by exploring the potential of rheological behavior modeling and measurements in-line with the extrusion process, at the benchtop scale. To that end, the rheological behavior of an extrusion poly(lactic acid) (PLA) grade was evaluated in a double capillary rheometer at apparent shear rates ranging from 12.2 to 6080.6 s^{-1} and at 180, 190, and 200 °C. This was carried out both on the virgin polymer pellets and after one and two consecutive processing cycles. Each processing cycle included extrusion, fused filament fabrication, and granulation. Data from the two most extreme tested temperatures were used to fit the Cross-WLF rheological model parameters. The resulting model was successfully used to predict behavior at the intermediate temperature ($0.952 < R^2 < 0.983$). In parallel, the prototype of an in-line rheometer has been conceptualized, manufactured, installed and tested on a single-screw benchtop extruder. It was possible to collect data from its pressure and temperature sensors which, along with averaged manual mass flowrate measurements, allowed calculating viscosity values at different temperatures. Despite a deviation from model predictions when tested with virgin PLA, the system was able to capture the expected reduction of viscosity with increasing temperatures. Regarding the first approach, its capability to translate material at untested conditions behavior was shown, which means it can reduce the need for more extensive testing. When combined with in-line measurements, targeted by the mentioned rheometer prototype, important possibilities for monitoring and control algorithms may be unlocked. Future work will focus on modifying extruder setup so screw speed can be actively controlled, monitored and correlated with flowrate. Furthermore, in-line rheometer geometry and sensors need to be revised to improve measurement accuracy and viscosity calculation. Gathering more in-process data will expand both the range and the predictive capabilities of algorithms developed for property prediction and material assessment.

Engineering Effect of Processing Conditions on Flow-Induced Morphology and Dimensional Stability in FFF-Printed Polypropylene

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Keywords: Polypropylene; Fused Filament Fabrication; Flow-Induced Morphology; Dimensional Accuracy; Additive Manufacturing

The use of polypropylene (PP) in fused filament fabrication (FFF) is still limited due to deformation induced by significant shrinkage during cooling. These effects are related to the fast crystallization kinetics and the complex thermal history experienced by the material upon the process. Understanding how printing conditions affect morphology and crystallization behavior is, therefore, essential for improving the dimensional accuracy and mechanical performance of FFF-printed PP parts. In this work, neat PP boxes were produced by FFF under different conditions (printing speed and flow rate) and characterized to assess the effects of processing parameters. Interlayer adhesion was evaluated by dynamic mechanical analysis, whereas optical microscopy and scanning electron microscopy (SEM) were used to characterize the developed morphology. Numerical simulations were performed to analyze the flow conditions during extrusion and correlate them with the experimentally observed microstructures. The results highlighted a clear relationship between processing parameters and microstructure developed within the printed layers. Optical microscopy under polarized light showed that higher printing speeds led to increased molecular orientation along the printing direction, consistent with the higher shear rates predicted by the simulations. SEM analysis revealed a complex heterogeneous morphology: oriented structures aligned along the printing direction were observed near the filament interfaces, whereas spherulitic structures developed in the bulk regions. Weld lines also acted as preferential nucleation sites for subsequently deposited layers. Overall, this work demonstrates that the dimensional stability and mechanical performances of FFF-printed PP are strongly controlled by the interplay between processing conditions, molecular orientation, and crystallization kinetics. The combined experimental and numerical framework proposed a useful guidelines for optimizing the processing of polyolefin-based materials in additive manufacturing.

Direct Extrusion Additive Manufacturing of Pellet-Based Feedstocks: A Bottom-Up Approach for Process Optimization by use of an Innovative Flow-Controlled printing head

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Keywords: Design-for-recycling; flexible films; multi-layer packaging; polyethylene; recycled materials; film blowing extrusion

Additive manufacturing (AM) is an emerging processing technique to produce polymeric and composite parts with a high degree of design freedom. Very popular are extrusion-based AM techniques such as fused filament fabrication (FFF) and pellet-based AM (PBAM). In the present work both techniques are compared, employing both detailed experimental analysis [1,2,3,4] and advanced modelling tools [1,5]. As reference materials polymers such as acrylonitrile-butadienestyrene (ABS) and poly(lactic acid) (PLA) are considered. It is demonstrated that the melting efficiency is affected by either the printing head (FFF) or screw design (PBAM), the selected processing parameters, and during deposition several strands are still modified by molecular diffusion upon the laying down of new layers. Globally a better qualitative interpretation of both rheological and mechanical content, surface roughness and characteristic behaviour in view of process and material stability control is highlighted. Novel trends for composites are also included such as direct extrusion additive manufacturing for technical composite and sensor applications, being able to be processed by use of an innovative flow-controlled printing head.

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Shear-Induced Carbon Nanotube Alignment in FFF-Printed ABS Composites for Smart Applications

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Keywords: Fused Filament Fabrication; Carbon Nanotubes; Rheological investigation; Shear-induced filler alignment; Smart properties

Fused Filament Fabrication (FFF) represents the most widely used additive manufacturing technique, yet achieving tailored functional properties requires a deep understanding of filler orientation during extrusion. This work explores the correlation between FFF processing conditions and the resulting morphological anisotropy in carbon nanotube (CNT) reinforced acrylonitrile butadiene styrene (ABS) composites. The investigation focuses on estimating shear stresses generated within the printing nozzle during extrusion, which acts as the primary driving force for filler orientation. Rheological tests are employed to study the flow behavior of nanocomposite material and predict the degree of nanotube alignment as a function of key printing variables, including flow rate and nozzle temperature. The induced filler organization is then correlated with the electrical performance of the 3D-printed samples. The results demonstrate that controlling the shear-induced CNTs alignment could impact on the electrical properties of the material without changing the filler concentration. Finally, filler orientation allows for tuning the smart functionalities of 3D printed components, such as Joule heating performance and self-sensing properties under mechanical strain.

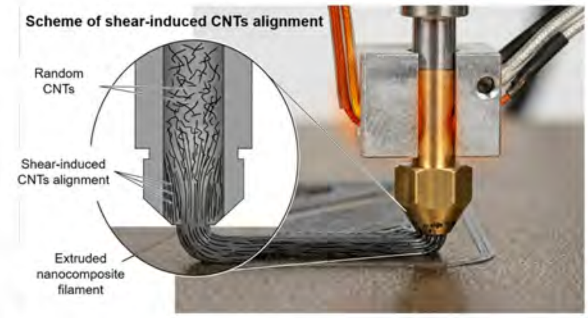

Figure 1. Scheme of shear-induced CNT alignment during the FFF process.

O24 | Oral Presentation | Session 5 – Additive Manufacturing

Performance of Hybrid Moulds using moulding blocks manufactured via different AM technologies: A comparative study

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Keywords: Injection Moulding, Hybrid Moulds, Additive Manufacturing, Fused Filament Fabrication, Selective Laser Melting, simulation

Additive Manufacturing (AM) offers new possibilities for the production of mould inserts for polymer injection moulding, especially where reduced tooling cost and short lead times are required. This study evaluates the feasibility and performance of AM inserts for hybrid moulds, with in particular a focus on Fused Filament Fabrication (FFF) and Powder Bed Fusion based Selective Laser Melting (SLM) technologies. While the literature review considers a broader range of AM processes, including VAT based photopolymerization, extrusion based AM, and powder based Fusion, the experimental work focuses on FFF inserts produced of ABS, PA, and carbon-fibre-filled PA, and SLM inserts manufactured from 18Ni maraging steel powder. The study combines experimental injection moulding trials, mechanical testing, process monitoring, and numerical simulation. Parts produced using the different additively manufactured inserts are compared with conventionally manufactured mould inserts. The evaluation is based on tensile and bending tests of the moulded parts, as well as the analysis of cavity pressure and temperature during the injection moulding process. In addition, the measured sensor data are compared with simulated values obtained from Moldex3D in order to support the identification of insert failure modes and the prediction of moulded part quality The results indicate that FFF inserts can provide a low-cost solution for very short production runs and prototype product design, although their performance is strongly influenced by the processing conditions, AM mould instert material, and part complexity. Among the selected FFF materials, carbon-fibre-filled PA is expected to provide the most promising results. SLM inserts demonstrate greater suitability for production volumes in the range of hundreds of parts, due to the improved mechanical and thermal properties of selected AM materials. The combined experimental and simulation approach provides guidance for selecting AM technologies and materials for hybrid mould applications.

Digital Polymer Science

CONTRIBUTIONS IN PROGRAMME ORDER

>>> Data-driven development & Process simulation

KEYNOTE | Ana Carina Lopes
Integrating advanced design techniques and additive manufacturing for the development of novel injection moulds

Thomas Lucyshyn
Using Moldflow simulation to estimate the energy consumption of the injection molding process

Targol Hashemi
Integrated Thermo-Mechanical Modeling for Warpage Prediction in Material Extrusion Additive Manufacturing (MEAM)

Ward Vandaele
The Viscous Circle: Correlating PVC gelation and rheology in slit die extrusion

Rasoul Varedi
Numerical Framework for Movable-Die Polymer Extrusion

>>> Data-driven development & real-time control

KEYNOTE | Davide Nocita
Extending the reach of rheological characterization. Bridging SAOS limitations through advanced measurement strategies

Ângela Rodrigues
DOE-Based Analysis of Friction and Adhesion at the Polymer-Mold Interface in the Injection Molding Process

Catarina Ribeiro
Development of a hot tensile testing system for Electromechanical characterization in hybrid In-Mould Electronics

Emad Izadi Vasafi
Multi-objective optimisation of injection moulding parameters for an In-Mould Electronics part: balancing defects, clamping force, and insert adhesion

Annika Lenger
Experimental Investigation and Numerical Simulation of Injection Overmolding of Film-Based Electronic Components

O25 | Keynote | Session 6 – Data-driven development & Process simulation

Integrating advanced design techniques and additive manufacturing for the development of novel injection moulds

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Keywords: Injection Moulding; Mould; Additive Manufacturing; Generative Design

Injection moulding (IM) is a conventional formative manufacturing technology that uses a mould structure to produce plastic components for a wide range of applications. Despite the great capabilities of conventional moulds, increasing demands for higher efficiency, improved part quality, and greater design flexibility have driven the need to rethink conventional mould design and manufacturing practices. Recent advances in digital manufacturing, such as additive manufacturing (AM), and in advanced design techniques, such as generative design (GD), have significantly expanded the possibilities for developing more efficient and innovative solutions in this field. Together, these approaches offer substantial potential to transform conventional design and manufacturing paradigms by enabling the creation of highly optimised, functionally integrated, and manufacturable geometries that would be difficult or impossible to achieve using traditional methods. This work proposes a methodological approach that leverages this promising combination to develop advanced mould concepts for IM. Based on an industrial case study, several alternative designs of a nonconventional injection mould were generated through generative design, using numerical data derived from IM process simulations as input parameters. After an iterative phase of design and prototyping, the most promising geometry was manufactured using powder bed fusion on a TruPrint 3000 system with tool steel 1.2709. Once produced, the mould was assembled and subsequently tested on an ENGEL e-victory 160 IM machine using real operating conditions. The results demonstrated that the developed mould exhibited an improved strength-to-weight ratio and a reduced number of components, while maintaining mechanical integrity, IM efficiency, and promising sustainability indicators. With such outcomes, this study highlights the potential of combining advanced design techniques and AM to transform and optimise traditional production scenarios within the IM context.

Using Moldflow simulation to estimate the energy consumption of the injection molding process

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Keywords: injection molding; energy consumption; simulation (List three to six keywords specific to the research topic)

Energy consumption and associated greenhouse-gas emissions are becoming central concerns in industrial processes. In injection molding, many factors-including mold design and materials, polymer properties, part geometry, process settings, and machine type-interact to determine the total energy required to produce a part. Because these parameters interact complexly, it is difficult to isolate their individual effects. Although commercial injection-molding simulation tools provide many insights into processing and part quality, they do not directly predict the total energy consumption for producing a part. This work develops a method that combines results exported from Autodesk Moldflow Insight with theoretical calculations to estimate energy consumption in distinct process phases. Time traces of filling pressure and melt volume-flow rate are exported and, using Python scripts, integrated to compute the injection and packing energy (injection work). The energy required to heat/plasticize the polymer is estimated from Moldflow-extracted pvT data, part volume, specific heat capacity, and the applied back pressure, with the calculation performed in a second Python script. The energy for mold motion (opening/closing) is calculated analytically from the mass of the moving mold half and its acceleration. A parameter study investigated the influence of melt temperature and injection speed on energy consumption. For the studied part geometry and material, heating/plasticizing dominated the energy demand. Increasing melt temperature reduced injection work by lowering melt viscosity, but this saving was far outweighed by the additional heating energy required. Mold kinetic energy was a negligible fraction of the total and can often be ignored. While the method does not provide exact absolute energy values, it yields useful insight into the relative importance of different process phases and quantifies how specific parameters affect energy consumption, enabling scenario comparisons. Current limitations include the lack of a suitable model for cooling-system energy, which depends on specific temperature-control unit characteristics, and incomplete treatment of mold heat losses to the environment; both are subjects of ongoing development, the latter using Moldflow heat-flux outputs of mold components.

Integrated Thermo-Mechanical Modeling for Warpage Prediction in Material Extrusion Additive Manufacturing (MEAM)

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Keywords: Material extrusion additive manufacturing, Warpage, P4MP, ABS, Crystallinity, Thermo-mechanical modeling

This study investigates the complex thermo-mechanical behavior of polymers during Material Extrusion Additive Manufacturing (MEAM), focusing on the interplay between process parameters, mechanical performances, and geometrical accuracy. Two representative thermoplastics: Acrylonitrile Butadiene Styrene (ABS) and Poly(4-methyl-1-pentene) (P4MP) were analyzed to understand how MEAM conditions influence deformation, warpage, and interlayer adhesion. A 3D printer equipped with a pellet extruder and a localized temperature-control system (Fire-cup) enabled precise regulation of the temperature deposition environment, allowing for detailed assessment of chamber conditions on part accuracy. A model for the description of temperature and stress evolution during cooling was developed and implemented in LabVIEW to simulate the deposition process. In the model, deposition was accounted for by considering the activation of each element at different times, reflecting the printing speed adopted during the MEAM process. The model was validated by comparing predictions with experimental temperature recordings and the deformation of produced parts. The temperature field and flow rates were found to be the key factors in determining the final deformation of the part. In the case of ABS, increasing the temperature of both the chamber (fire-cup) and the deposition plate decreased deformation. For P4MP, a crystallization model was introduced. The evolution of crystallinity was found to be the key factor in determining the part's final deformation. Overall, the integrated modeling and experimental approach provides insight into mitigating warpage and optimizing MEAM process parameters for both amorphous and semicrystalline polymers, advancing the manufacturing of dimensionally stable and mechanically robust parts.

The Viscous Circle: Correlating PVC gelation and rheology in slit die extrusion

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Keywords: rheology, PVC gelation, process simulation

This study concerns the characterization of the transient nature of PVC rheology using slit die extrusion trials. Melt rheology is vital in process simulations, which help to identify optimal process conditions and mould design. Simulation of rigid PVC (PVC-U) processing remains challenging because PVC compounds exhibit not only wall slip but also inconsistent flow behaviour across different flow paths. This behaviour, which remains to be fully quantified, originates from the process history-dependent microstructure. Since PVC microstructure undergoes a transformation in the presence of thermal and mechanical stress, in which the granules and primary crystallites are broken down, the flow will change from a particle plug flow to a more viscous behaviour. This aspect poses a challenge in modelling PVC rheology, as gelation and rheology cannot be identified separately. By performing dual slit die extrusion experiments, an attempt is made to map this spectrum of material states and flow properties. The use of a dual slit die, with 2 parallel exit channels, has proven necessary to decouple the mass flow from the extruder settings, which would result in a confounding of shear rate and gelation. By adapting the length of the secondary purge slit instead, mass flow is changed while keeping extruder settings constant. For a single material, samples were taken at different extrusion settings and mass flow distributions. Three slit geometries were included to quantify the presence of slip and account for shear thinning behaviour. Samples were analysed using Differential Scanning Calorimetry (DSC) to determine the fusion grade, which indicates gelation. Samples taken at various points in the flow path should indicate the rate of change in the material. The resulting data effectively demonstrate the transient nature of PVC-U rheology and give way to an improved approach to modelling PVC flow behaviour. Furthermore, a major conclusion from this study is that gelation is not limited to the extruder itself; a significant share takes place within the measurement slit as well. In that sense, a single measurement does not represent a unique state of the material, but rather a combined effect from a range of states (Figure 1). This dataset provides a starting point to incorporate PVC gelation into a rheological model for further application in process simulations. To this extent, a coupled flow-thermal simulation approach has been prepared for validation.

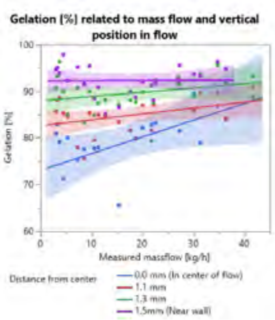

Figure 1. Effect of mass flow (x-axis) and location through the die height (colors) on gelation (y-axis).

O29 | Oral Presentation | Session 6 – Data-driven development & Process simulation

Numerical Framework for Movable-Die Polymer Extrusion

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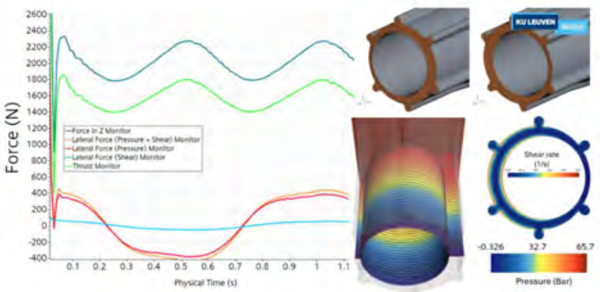
Keywords: Movable die extrusion; Adaptive extrusion tooling; CFD simulation; Mesh morphing; Polymer melt flow

Polymer extrusion is widely used for producing continuous profiles because of its high productivity, material efficiency, and low tooling cost. However, conventional extrusion is inherently limited to products with a constant cross section, which restricts its use for components requiring local geometrical variation along their length. Enabling controlled cross-sectional changes during extrusion would significantly expand the range of products that could benefit from the economic advantages of extrusion. Although variable-geometry extrusion dies have been proposed as a promising solution, they are still not widely implemented in industrial manufacturing, and further research is required to understand their process limits, flow behaviour, and mechanical design requirements. This study presents a computational framework for analysing movable-die polymer extrusion, in which the die opening changes dynamically during processing. A representative movable-die geometry is investigated using computational fluid dynamics (CFD), with the polymer melt described by a shear-thinning Carreau-Yasuda viscosity model. The die motion is introduced through a prescribed sinusoidal displacement of the movable wall, combined with mesh morphing to capture the transient deformation of the flow domain. Within this forward simulation workflow, the extrudate profile is predicted while key process responses are evaluated, including pressure drop, shear-rate distribution, and hydraulic loads acting on the movable die. These loads include the lateral force generated by pressure and viscous shear contributions, as well as the axial thrust force. The predicted profile is then compared with the desired target geometry, and an inverse optimization loop is proposed to adjust key design and process variables, including die motion frequency, melt flow rate, and die geometry parameters. This iterative procedure continues until the predicted profile remains within the required tolerance, leading to an optimized combination of processing conditions and geometrical parameters. For the investigated operating condition, with a mass flow inlet of 0.01 kg/s, a 21 mm movable-die diameter, a 17 mm inner flow opening, and an active movable-die length of 20 mm, the transient force response was evaluated during the prescribed die motion. The 4 mm diametral difference between the movable die and the inner opening defines the deformation/flow gap considered in the model. The combined lateral force, including both pressure and viscous shear contributions, reaches a peak value of approximately 400 N. The pressure contribution dominates the lateral load, while the shear contribution remains comparatively small. In addition, the axial thrust load is predicted to be approximately 1.8 kN, providing important input for actuator selection, structural sizing, and mechanical design of the movable extrusion tooling. The proposed framework supports the digital design of movable extrusion dies and contributes to the development of adaptive polymer extrusion processes capable of producing variable cross-section profiles with improved design flexibility.



Extending the reach of rheological characterization. Bridging SAOS limitations through advanced measurement strategies

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Keywords: Rheology; Viscoelasticity; DOSY NMR; Polymer Dynamics; Diffusion

Small amplitude oscillatory shear (SAOS) rheology is a cornerstone technique for probing polymer dynamics, yet its applicability is often limited when dealing with complex fluids or low molecular weight systems exhibiting weak elastic responses. In this keynote, we present strategies to overcome these limitations through methodological refinement and integration with complementary techniques. First, we demonstrate robust rheological characterization of highly complex fluids, focusing on gel polymer electrolytes in the sol state. Reliable data acquisition is achieved via the combined use of solvent traps, temperature ramps, short time sweeps, and frequency sweeps employing a logarithmic increase in acquisition time to match the logarithmic decrease in angular frequency. Using this approach, we show that the Cox Merz rule is satisfied for formulations containing lithium salts, while significant deviations are observed in simple PVdF based electrolyte sols, highlighting the role of ionic interactions in governing viscoelastic behaviour. In the second part, we establish connections between diffusion-ordered spectroscopy (DOSY) NMR and conventional SAOS rheology. For low molar mass polymers within the Rouse regime, relaxation times derived from diffusion coefficients show good agreement with viscosity based estimates via the Stokes Einstein relation. At higher molar masses, diffusion derived relaxation times correlate more closely with the shortest relaxation times obtained from discrete relaxation spectra in SAOS measurements. These findings demonstrate that DOSY and rheology, despite probing dynamics on different length and time scales, can provide consistent insight into polymer motion. Crucially, DOSY offers a powerful alternative for systems where traditional rheology is heavily limited, particularly low molecular weight or weakly elastic materials that exhibit near Newtonian behaviour. This work helps linking Diffusive and Viscoelastic Dynamics, effectively overcoming SAOS limitations in complex polymer systems.

DOE-Based Analysis of Friction and Adhesion at the Polymer-Mold Interface in the Injection Molding Process

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Keywords: injection moulding, coefficient of friction, coefficient of adhesion, processing conditions

Friction and adhesion at the polymer-mould interface play a decisive role in demoulding forces, surface quality, and cycle time in injection moulding, as consistently highlighted in the tribological and polymer-processing literature. Prior studies have reported that interfacial behaviour is strongly governed by thermal conditions, contact pressure, and surface topography, with temperature-dependent softening of the polymer and micro-scale mechanical interlocking frequently identified as dominant mechanisms. However, the combined and potentially nonlinear interactions between these factors remain insufficiently quantified, particularly for engineering polymers and industrial mould materials. In this context, this study applies a Design of Experiments (DOE) methodology to evaluate the influence of demoulding temperature, contact force, and mould surface roughness on the coefficients of friction (CoF) and adhesion (CoA) for three polymer-metal pairs: PP-steel, PP-aluminium, and PC-steel. For the PP-steel interface, results show that CoF show that CoF decreases with increasing extraction temperature and contact force, while roughness shows no linear trend; the CoA follows the same behaviour and remains nearly unaffected by roughness. For PP-aluminium, the CoF decreased with temperature, force, and roughness, whereas the CoA decreased with temperature and force but increased with roughness. For PC-steel, the CoF decreased slightly with temperature, and both force and roughness presented nonlinear effects; the CoA decreased with temperature and force, with roughness again showing no linear influence. Overall, the DOE approach revealed that the demoulding temperature and contact force were the dominant factors across all material combinations, whereas the surface roughness exhibited material-dependent and often nonlinear contributions. These insights support the optimisation of mould surface engineering and processing conditions to reduce demoulding resistance and enhance injection moulding performance.

Development of a hot tensile testing system for Electromechanical characterization in hybrid In-Mould Electronics

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Keywords: Hybridization; In Moul Eletronics; Hot tensile test, Fused Filament Fabrication, Thermoforming

Uniaxial hot tensile testing is an essential method for characterizing the deformation behavior of thermoplastic materials. However, conventional systems present limitations such as sample slippage, restricted flexibility, limited access, and high costs. These constraints are particularly relevant for In-Mould Electronics (IME), where printed electrical circuits must remain functional. Standard environmental chambers are not easily adapted for simultaneous mechanical deformation, thermal control, and electrical monitoring, reducing their suitability for evaluating thermoformable electronic structures. This work presents the development, validation, and application of a custom-built open heating system coupled to a universal tensile testing machine. The system integrates ceramic infrared heaters for controlled heating and infrared thermography for real-time monitoring of specimen surface temperature. The setup was developed as a flexible, low-cost alternative to commercial environmental chambers. Its open architecture allows direct access to the specimen and enables monitoring methods, including real-time electrical resistance acquisition. A temperature calibration procedure was performed to validate infrared thermography as a reliable monitoring technique and to define repeatable heating conditions. The results confirmed that the system can generate controlled and reproducible thermal profiles suitable for uniaxial hot tensile testing. The validation also demonstrated that the setup can reproduce relevant thermoforming conditions while maintaining the flexibility required for conventional thermoplastic specimens and multifunctional hybrid structures. To demonstrate its applicability to IME-related studies, a case study involving hybrid structures was carried out. These structures combined additive manufacturing with conductive polymer tracks, providing an alternative to printed electronics based on silver conductive inks, which often exhibit limited stretchability and may fail during forming. Proto-Pasta conductive PLA was selected as the functional material because of its commercial availability and established use in conductive Fused Filament Fabrication (FFF). High-impact polystyrene (HIPS) was selected as both the substrate foil and overlay material. The substrate consisted of a 1000 µm thick HIPS sheet supplied by Intraplás S.A. (Guimarães, Portugal), while the HIPS overlay filament was obtained from Orbi-Tech. Since direct adhesion between the conductive filament and HIPS foil was limited, HIPS overlays were printed around the tracks to improve adhesion, facilitate handling, and enhance integrity during thermoforming and hot tensile deformation. The hybrid structures were produced using a Raise E2CF FFF printer equipped with dual independent printheads. A 0.8 mm nozzle was used for the conductive Proto-Pasta PLA filament, whereas a 0.4 mm nozzle was employed for the HIPS overlays. Three overlay configurations, designated Sides, Partial, and Total, were compared to assess their influence on adhesion, deformation behaviour, and electrical performance. Electrical resistance was measured before and after testing using a two-probe method with an Owon XDM1241 multimeter. During hot tensile testing, the multimeter was connected to a computer for real-time resistance acquisition. The relative resistance variation, $\Delta R/R0$, was calculated for selected regions and correlated with strain. The electromechanical results showed that the $\Delta R/R0$-strain curves exhibited a discretized progression, attributed to the acquisition system sampling rate during high-speed deformation. Nevertheless, the conductive tracks remained functional up to at least 300 % strain, demonstrating potential for large-deformation electronics. The strong overlap between piezoresistive curves for the different overlay configurations indicates that the response is governed mainly by the intrinsic gauge factor of the conductive PLA core rather than by the surrounding HIPS geometry. Thus, the proposed HIPS overlay strategies improve physical integration and structural stability without compromising sensor sensitivity.

Multi-objective optimisation of injection moulding parameters for an In-Mould Electronics part: balancing defects, clamping force, and insert adhesion

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Keywords: in-mould electronics; injection moulding; film insert; numerical simulation; design of experiments

In-Mould Electronics (IME) is a manufacturing technology in which a thermoformed, printed-electronics film insert is placed in an injection mould and encapsulated within the polymer matrix during injection moulding, producing structurally integrated electronic components. Compared with injection moulding of conventional parts, the embedded electronic insert locally modifies melt flow, heat transfer and pressure distribution, influencing the formation of sink marks, warpage and non-uniform shrinkage, and requiring a sufficient fraction of the insert thickness to exceed its glass-transition temperature during filling, enabling polymer interdiffusion and reliable bonding with the surrounding polymer. This study aimed to identify processing conditions that minimise moulding defects, maintain clamping force within the safe operating range of the production machine, and maximise the fraction of the insert thickness remelted at the end of filling, used as a proxy indicator of interfacial bonding potential. A polycarbonate IME front panel (Makrolon 2207, Covestro) containing a polycarbonate electronic insert (Makrolon 2205, Covestro) was simulated in Autodesk Moldflow Insight, using a three-dimensional tetrahedral mesh and an industrial mould configuration with a hybrid runner system and four valve gates. A full-factorial Design of Experiments was performed over melt temperature (295-315 °C), coolant inlet temperature (70- 90 °C) and packing pressure (70-110 % of filling pressure), at three levels each, yielding twenty-seven simulation runs. Multi-objective optimisation in OriginLab was conducted under two scenarios. The first considered four part-related criteria (insert remelting, sink mark depth, Z-warpage range, volumetric shrinkage uniformity, quantified by the root mean square (RMS) of volumetric shrinkage, and identified an optimum at 295 °C melt, 110 % packing pressure and 90 °C coolant, with 45.9 % of the insert thickness above the glass-transition temperature (Tg ≈ 150 °C), sink mark depth of 0.014 mm, Z-direction warpage from -2.40 mm to +2.60 mm and shrinkage RMS of 1.12 %; the predicted clamping force, however, reached the machine maximum. The second scenario added peak clamping force as a fifth criterion, shifting the optimum to 315 °C melt while retaining the packing pressure and coolant temperature, raising the insert remelted fraction to 49.7 % and reducing clamping force by approximately 25 % to within the safe operating range, at the cost of moderately increased sink marks (0.024 mm), Z-direction warpage from -3.16 mm to +4.08 mm and shrinkage RMS (1.51 %). The study demonstrates the trade-offs between dimensional quality, interfacial bonding potential, and clamping-force requirements, supporting process-condition selection for IME injection moulding.

Experimental Investigation and Numerical Simulation of Injection Overmolding of Film-Based Electronic Components

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Keywords: in-mold electronics, overmolding, injection molding, simulation, Moldflow

Integrating electronic functions directly into injection-molded plastic parts offers a promising route towards producing lightweight, durable parts with a high degree of design freedom. Electronic components such as LEDs or piezoelectric sensors can be incorporated into polymer films with printed conductive tracks. The films are subsequently thermoformed into the desired three-dimensional geometry. The resulting film stack is then placed into a mold and overmolded with a polymer to create a rigid functional component, for example, a human-machine interface. Manufacturing such in-mold electronics (IME) remains challenging due to the complex interaction of material compatibility, thermomechanical loading, and dimensional stability throughout the different manufacturing steps. During thermoforming and overmolding, the film stack and integrated electronic components are subjected to deformation, elevated temperatures, pressure, and shear stresses. In particular, the thermal and mechanical loads generated during overmolding can induce film deformation and compromise the integrity of the embedded electronic components.

This study investigates the influence of processing conditions and component positioning on the overmolding behavior of IME structures by combining experimental trials with numerical injection molding simulations. Film stacks consisting of a PC layer with a graphical layer, printed conductive tracks, and mounted electronic components were overmolded using PC or TPU. The effects of melt temperature and the position of electronic components relative to the gate were examined. The resulting parts were evaluated visually, and the experimental observations were compared with the corresponding numerical simulations to assess relationships between local processing conditions and the observed behavior of the film and electronic components.

The results demonstrate that increasing the melt temperature reduced the observed film distortion. Furthermore, small changes in the position of an electronic component relative to the gate resulted in pronounced differences in the simulated thermal load experienced during overmolding. These results indicate that both processing conditions and component placement strongly influence the local thermomechanical conditions during IME manufacturing. The combined experimental and numerical approach therefore provides a basis for optimizing component positioning and process parameters to reduce film deformation and thermal loading during overmolding.

PART II

POSTER PRESENTATIONS

Poster contributions are listed and reproduced in programme order.

Poster Presentations

CONTRIBUTIONS IN PROGRAMME ORDER

>>> Poster Presentation

Florian Arbeiter
A semi-empirical/semi-simulation-based approach towards predicting the fatigue lifetime of extrusion based additive manufacturing

Vincent Berthé
Whole spirulina cell-based biomaterials for material extrusion and shape-debind-sinter processing

Michael Huszar
Inclusion detection via Nanoindentation

Uwe Klaeger
Large-Scale Printer for Wood-Plastic Composites for the Sustainable Manufacture of Parts

Nina Krempl
System Analysis of Recycled PLA for Material Extrusion Additive Manufacturing

Carina Maurer
Influence of different amounts and qualities of Post-Consumer-Recyclates on the mechanical lifetime of Polypropylene

Daria Shestakova
Linking Polymerization Kinetics to Viscoelastic Response through Kinetic Monte Carlo Modelling

Edda Valentina Veracierta Rodriguez
Influence of processing conditions on the properties of recycled PET: A comparison of flakes and pelletized material

Kaat Vastesaegher
Hidden variability in monostream recycling: Impact of color-dependent formulations and processing conditions on recycled pipette tip racks

Christoph Waly
Lithosphere-Inspired Polymeric Architectures: Lab-Scale Manufacturing and Structure-Property Relationships

Daniel Zach
Mechanical Performance and Fracture Behavior of Polypropylene Compounds Containing Modelled Post-Consumer Recyclates

Jing Li
Asymmetric Fiber Double-Electrode Triboelectric Nanogenerator Design for Energy Harvesting and Multidirectional Motion Sensing

A semi-empirical/semi-simulation-based approach towards predicting the fatigue lifetime of extrusion based additive manufacturing

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Keywords: lifetime estimation, fatigue, extrusion based additive manufacturing

This work presents an end-to-end methodology to predict the fatigue lifetime of components produced by extrusion-based additive manufacturing (AM). The approach addresses two dominant drivers of fatigue in AM parts-strand orientation and, critically, the weld strength between deposited strands and layers-by linking process-induced thermal histories to local mechanical properties within a simulation chain suitable for early design stages. Material characterization begins with determining key matrix properties (thermal conductivity, heat capacity, coefficients of thermal expansion) and establishing a processing-structure-property link via controlled printing experiments. Single-strand walls are printed at varied nozzle temperatures while in situ temperatures are recorded; these thermal histories are reduced to an equivalent welding time teq using time-temperature superposition (activation energy from cone-plate rheometry, following Seppala et al. [1]). Specimens cut along and across the deposition direction provide strength and fatigue data to build a calibration curve relating teq to weld strength and fatigue behavior, capturing the full thermal history in a single value. Process simulation then reconstructs the transient temperature field by activating elements according to the part's G-code, reproducing strand-by-strand deposition order. The nodal temperature histories are converted to teq and mapped to local strength and fatigue properties via the calibration curve, enabling spatially resolved property assignment across the component. Structural and fatigue assessment proceeds by computing local stresses with ABAQUS and comparing them to the mapped local fatigue properties using FEMFAT, yielding cycles-to-failure at each node and identifying critical regions with minimal safety margins or expected lifetime. Validation through four-point bending fatigue tests on printed components shows reasonable agreement between measured and simulated lifetimes, with deviations attributed to AM-induced scatter and modeling simplifications. Overall, the methodology effectively couples processing conditions, anisotropic and weld-governed material behavior, and structural loading to deliver practical lifetime predictions for fiber-reinforced AM parts.

Literature: [1] Seppala, J. E., Han, S. H., Hillgartner, K. E., Davis, C. S., & Migler, K. B. (2017). Weld formation during material extrusion additive manufacturing. Soft Matter, 13(38), 6761-6769. doi.org Acknowledgement: This research was performed within the project eFAM4Ind (877409) which is funded by the Austrian funding agency association (FFG) and the federal ministry of climate action, environment, energy, mobility innovation and technology (BMK).

Whole spirulina cell-based biomaterials for material extrusion and shape-debind-sinter processing

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Keywords: Spirulina; regolith; material extrusion, shape-debind-sinter process

As space exploration advances, long-duration missions will rely on closed-loop systems, as external resupply is severely constrained. In this context, materials directly produced from whole-cell biomass offer the advantage of avoiding complex extraction and purification processes [1]. Spirulina (a cyanobacterium) represents a particularly attractive resource because it can be rapidly photosynthetically cultivated in controlled environments using limited resources. Already investigated as a food supplement, oxygen source, and contributor to wastewater recycling, spirulina is considered a promising building block for sustainable space habitats [2 - 4]. In this presentation, we introduce a novel spirulina-based material developed for extrusion additive manufacturing and shape-debind-sinter (SDS) processing. Unfractionated spirulina biomass was melt-blended with glycerol and water through twin-screw extrusion to produce printable pellets and filaments. An end-to-end laboratory-scale process was established, including compounding, filament production, material extrusion (MEX) 3D printing, thermal debinding, and high-temperature sintering. In addition, regolith simulant powders were incorporated as mineral fillers to evaluate the feasibility of manufacturing sintered ceramic components through SDS processing. This approach enables the combination of biologically produced binders with locally available mineral resources for potential in-situ resource utilization applications. Following formulation optimization, the spirulina-based materials demonstrated good printability, recyclability, and intrinsic self-extinguishing behavior. Ceramic mechanical properties are also reported as a function of binder humidity, plasticizer content, and processing conditions. These promising properties, combined with scalable processing and the replacement of conventional fossil-based binders commonly used in ceramic additive manufacturing, position spirulina-based biomaterials as promising candidates for sustainable manufacturing applications. [1] Campbell, I. R.et al. Ann. Rev. Mater. Res. 2023, 53, 81. [2] Fredricks, J.L. et al. J. Polym. Sc. 2021, 59, 2878. [3] Zeller, M.A. et al. Appl. Polym. Sci. 2013, 130, 3263. [4] Iyer, H. et al. Cells. Adv. Funct. Mat. 2023, 33, 2302067.

Inclusion detection via Nanoindentation

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Keywords: Nanoindentation; Material heterogeneity; Recycled polymers

Recycled polymer materials are increasingly used in engineering applications. However, they often have an unknown distribution of material heterogeneities, such as foreign polymer particles, inorganic contaminants, or filler agglomerates. These inclusions may act as local stress concentrators and can affect stiffness, creep behavior, crack initiation, and long-term performance. Understanding the influence of such defects on local mechanical performance can help develop suitable methods for their detection and serve as a basis for further simulations and lifetime estimations. One widely used tool for obtaining mechanical information at the micro-scale is Nanoindentation. [1,2] With small adjustments, it is also suitable for soft, time-dependent materials. [3] Using a load-controlled approach, it is possible to obtain local Young's Modulus, hardness, and creep behavior in a single experiment with the appropriate load schedule. [4] Given its high lateral resolution, this kind of experiment is a good choice for further characterizing inhomogeneous materials, such as metals with inclusions or different phases, and recycled polymers with foreign polymer inclusions. [5] Indentation is sensitive to variations in the material's stiffness beneath the indenter, which can be caused by inclusions that impede elastic and plastic deformation. This sensitivity allows detection of inclusions below the surface, but adequate pretesting is required. Therefore, a polypropylene sample containing glass balls (250 µm in diameter) was produced, and measurements were taken on the polished surface near visible glass inclusions using a cono-spherical tip (10 µm in diameter). This enables visualization of changes in the loading curve and helps determine the volume suitable for inclusion detection.

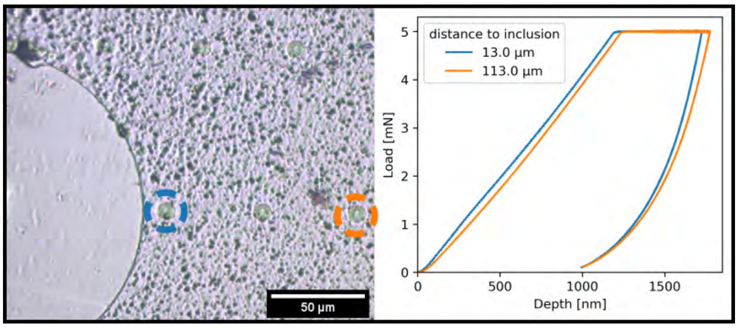

Figure 1. Indentation sites near the glass inclusion with the corresponding load-displacement curves.

Literature [1] Oliver, W. C. and Pharr, G. M.: Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology. J. Mater. Res., vol. 19 (2004), doi: 10.1557/jmr.2004.19.1.3. [2] Oliver, W. C. and Pharr, G. M.: An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments," J. Mater. Res., vol. 7 (1992), doi: 10.1557/JMR.1992.1564. [3] Arevalo, S. E., Ebenstein, D. M. u. Pruitt, L. A.: A methodological framework for nano-mechanical characterization of soft biomaterials and polymers. J. Mech. Behav. Bio-med. Mater. 134 (2022) 105384 [4] Yang, S., Zhang, Y.-W. u. Zeng, K.: Analysis of nanoindentation creep for polymeric materials. J. Appl. Phys. 95 (2004) 7, 3655-3666 [5] Trost, C., Žák, S., Schaffer, S., Walch, L., Zitz, J., Klünsner, T., Leitner, H., Exl, L. u. Cor-dill, M. J.: Explainable machine learning and feature engineering applied to nanoindentation data. Mater. Des. 253 (2025), 113897

Large-Scale Printer for Wood-Plastic Composites for the Sustainable Manufacture of Parts

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Keywords: additive manufacturing systems, green manufacturing, biomaterials and composites, simulation and optimization of manufacturing processes

3D printing processes (additive manufacturing) are steadily gaining importance in industry. Build space limitations and high production times because of additional process steps usually make the manufacture of parts larger than 1,000 mm impossible or unprofitable. A new innovative system and material design overcomes these deficits by taking advantage of the benefits of additive manufacturing to produce large-size building and facade elements. A significantly enlarged build space paired with high build rates and the additive processing of biogenic wood-plastic composites (WPC) being used for the first time are key features of this technological approach. Printed parts, such as facade elements measuring 6,000 mm × 6,000 mm × 200 mm, weigh as much as 3,000 kg. A special extrusion system that directly processes WPC granules was developed for the system to build continuously. This replaces petroleum-based and costlier materials still in use. The extruder unit was designed for high build rates of up to 20 kg/h. Control system development is an important component in the project. The advanced controller design is comprised of component control, motion planning and machine monitoring. Key activities include coupling the simulation with the machine controller (PLC and extruder controller through a real-time interface) and developing safety specifications that prevent collisions in workspaces. A simulation tool developed by the Fraunhofer IFF is being used to help develop the controller for complex manufacturing operations. This new integrative approach to motion planning and event simulation makes it possible to test geometry and function even before the building of the system begins. This enables developing and optimizing system components and the controller as well as assemblies and media concurrently. This 3D printing technology can be used with the biobased material developed to manufacture totally new products that previously defied cost-effective manufacture because of their complexity. Among others, these include load-bearing components with high thermal transmittance used to build or clad buildings, deck elements, and prefabricated parts for house-building and furniture. The controller designed by the Fraunhofer IFF and modified precisely for the products manufactured facilitates rapid part building, significantly reducing production times by as much as twenty percent.

Figure 1(a). Extruder for automated feeding of the granules.

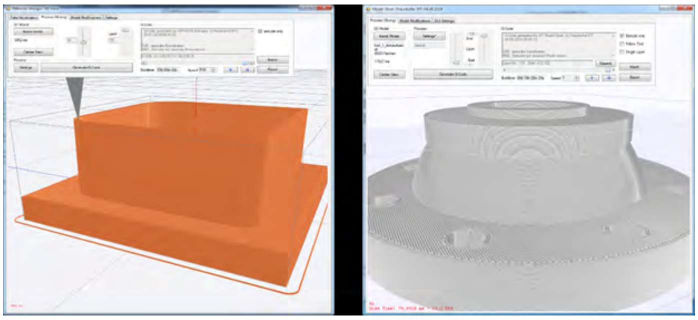

Figure 1(b). Deposition-path generation and G-code export with Slicer+.

P05 | Poster Presentation | Poster Presentation

System Analysis of Recycled PLA for Material Extrusion Additive Manufacturing

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Keywords: Recycled PLA; Material Extrusion; Circular Economy; Rheology; Design from Recycling

The transition to a circular economy requires polymer recycling strategies for additive manufacturing. Polylactic acid (PLA) is widely used in Material Extrusion (MEX). However, repeated recycling degrades the polymer and changes its processing behavior. This study evaluates how repeated recycling affects PLA and assesses its suitability for continued use in MEX. The study started with a virgin PLA filament as the reference material in a closed-loop recycling process, including shredding, filament extrusion, and repeated processing. Recycling was repeated five times under identical processing conditions. After the fifth recycling cycle a significant decrease in viscosity defined the endpoint of the study. The virgin filament and the recycled filament from the fifth cycle were then characterized by rheological measurements, which confirmed the observations and revealed a viscosity reduction of approximately 30 %, indicating polymer degradation. Printing trials showed that stable processing was maintained by adjusting the nozzle temperature and extrusion settings, while the printed structures exhibited only minor visual differences compared with those produced from virgin PLA. These findings indicate that recycled PLA remains suitable for Material Extrusion when the process parameters are adapted accordingly. In addition, replacing virgin PLA with recycled material has the potential to reduce greenhouse gas emissions by an estimated 40-50 %. Future work will investigate the mechanical properties of printed specimens after repeated recycling. If required, component geometries will be adapted to compensate for material degradation. This Design from Recycling approach supports the long-term use of recycled polymers in sustainable additive manufacturing.

Influence of different amounts and qualities of Post-Consumer-Recyclates on the mechanical lifetime of Polypropylene

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Keywords: Post-Consumer-Recyclates; Polypropylene; fracture mechanics; long-term properties

In recent years, there has been a growing trend toward processing more recycled materials and producing blends with virgin materials for new products. Recyclates' properties depend on the feedstock, the treatment, and subsequent processing. Each additional processing step not only raises costs but also increases the thermal and/or mechanical stress on the materials. When the focus is on materials used in the building and construction sector, the requirements for the applications are significantly higher, because these materials typically have a lifetime of at least 50 years or more. In the case of pipe applications, especially non-pressure pipes, the usage of mechanical recyclates is increasing. Wherever technical standards allow the incorporation of recycled polyolefins, it needs to be guaranteed that performance requirements are met to ensure reliability and a long service life. This can bring challenges due to batch-to-batch differences in recycled feedstock. Therefore, additional tests are necessary, which were investigated in this study. For this, one defined virgin heterophasic Polypropylene were blended with two different post-consumer recyclates (PCRs) to have a wide range of different materials. Mechanical parameters such as tensile testing, charpy impact testing, melt flow rate, and rheological measurements were performed on the materials. However, the long-term properties must be investigated for the intended applications, which are analyzed on the basis of fatigue crack growth. The aim is to use fracture mechanics, crack resistance/slow crack growth, to investigate which factors have a greater influence on the results and, more importantly, on the lifetime of pipes. The study investigated whether blends with different proportions of PCRs show significantly different results, or whether the quality of the PCRs used has a stronger influence on the outcomes.

Linking Polymerization Kinetics to Viscoelastic Response through Kinetic Monte Carlo Modelling

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Keywords: small-amplitude oscillatory shear; rheology; kinetic Monte Carlo, linear polystyrene

Rheological properties govern the flow behavior of polymers during melt processing and are highly sensitive to structural characteristics such as molar mass, molar mass distribution, tacticity, and branching. As these characteristics are determined during polymerization, understanding the relationship between polymerization kinetics, polymer microstructure, and resulting material properties is essential for improving polymer performance. To address this challenge, a kinetic Monte Carlo (kMC) model based on Gillespie's stochastic simulation algorithm was developed. The kMC model explicitly tracks stochastic reaction events and enables monitoring of the composition of individual polymer chains during polymerization. This provides detailed information on chain-level microstructural characteristics and their evolution over time. The developed kMC framework was used to describe the polymerization of polystyrene synthesized via free-radical polymerization and reversible addition-fragmentation chain transfer polymerization. Polymerization conditions were varied to obtain three sets of polystyrene samples differing in molar mass, while variations in chain livingness within each set resulted in different molar mass dispersities. Experimentally obtained conversion data and size exclusion chromatography traces were used to adjust model parameters and reproduce polymerization behavior. Based on the obtained microstructural information, the developed framework is employed to predict the frequency-dependent rheological response, including viscosity, and the storage and loss moduli. Comparison with the corresponding experimental small-amplitude oscillatory shear data will be used to validate whether the model correctly links polymerization kinetics and polymer microstructure to the observed viscoelastic behavior.

P08 | Poster Presentation | Poster Presentation

Influence of processing conditions on the properties of recycled PET: A comparison of flakes and pelletized material

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Keywords: PET; mechanical recycling; injection moulding; degradation; mold temperature

One of the most relevant issues that society currently faces is the continuously increasing amount of waste generated by human activities, particularly plastic waste, reaching 430.9 million tons (Mt) in 2024 [1]. Polyethylene terephthalate (PET) is considered a major source of environmental concern due to its large-scale global production (26.72 Mt in 2024) and its rapid consumption, driven by its widespread use in beverage containers, food packaging and textiles [1-3]. As a result, increasing attention has been placed on PET recycling, with focus on optimizing processing parameters. According to the European Commission, the goal is to achieve 30 % recycled content in PET single-use plastic beverage bottles by 2030, aiming to 65 % by 2040 [4]. In order to mechanically recycle PET, typically four main steps are taken into account: collection and sorting, shredding, washing and drying, and reprocessing [5,6]. Following this route, recycled PET (rPET) flakes are produced in this work through and in-house mechanical recycling process using post-consumer PET bottles. Due to the inevitable deterioration of the mechanical properties over successive recycling cycles [3], the comparison between direct processing of rPET flakes and the pelletized material is of particular interest, as it allows to study the influence of the reprocessing (pelletizing) step. To optimize processing, three mold temperatures are investigated during injection moulding, providing further insight into the level of degradation of the recycled material. To obtain information about the application scale of the injection moulded dog-bones, mechanical properties are determined by tensile and Charpy impact testing and color measurements are also performed. On the meso-scale, thermal properties and stability are analyzed by TGA and DSC. The aim of this study is to adopt a multiscale analytical approach, determining the meso- and macroscale properties of rPET processed under different conditions, as well as assessing the extent to which pelletization, as an additional reprocessing step, further contributes to material degradation

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Hidden variability in monostream recycling: Impact of color-dependent formulations and processing conditions on recycled pipette tip racks

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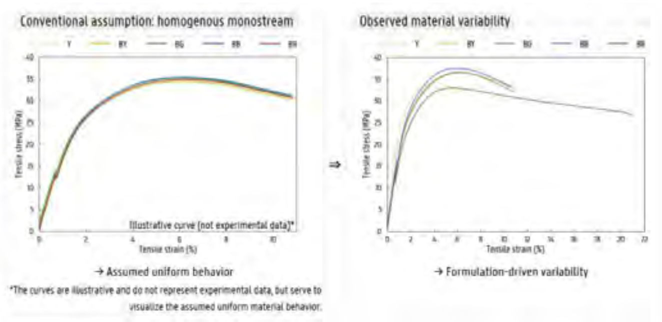
Keywords: polypropylene recycling; pipette tip racks; formulation variability; mechanical properties; processing conditions; injection molding

Single-use plastics are essential in biotechnology laboratories to ensure sterility, but they generate a disproportionate waste stream, with laboratories producing an estimated 5.5 million tons of plastic annually [1], [2]. Among these, polypropylene (PP) pipette tip racks represent a relatively clean and well-defined waste stream, making them a promising candidate for high-quality mechanical recycling [3]. These materials are often treated as a homogeneous monostream, despite the potential presence of formulation differences. As pipette tip racks are produced in different colors, this study investigates whether color-related differences in pigment and additive formulations affect the properties of mechanically recycled PP. Post-consumer PP pipette tip racks were sorted into five color fractions (yellow (Y), bright yellow (BY), bright green (BG), bright blue (BB), and bright red (BR)) and mechanically recycled via shredding and injection molding under two distinct processing conditions: (1) hot mold/high injection speed and (2) cold mold/low injection speed. Molecular and structural characterization (FTIR, DSC, TGA, SEM, POM) was combined with mechanical testing (tensile, flexural, and impact) to evaluate the origin of property variations. Clear differences in mechanical performance were observed between color fractions, particularly in stiffness and ductility. These variations could be directly linked to formulation differences, including the presence of inorganic fillers and changes in crystalline structure. In contrast, variations in processing conditions led to measurable morphological differences such as changes in skin-core structure, but resulted in only limited and non-systematic changes in mechanical properties. The results demonstrate that even within a single product stream, material variability can be substantial and primarily originates from formulation differences rather than processing conditions. This highlights the need to account for such hidden variability when evaluating the quality and consistency of recycled materials, particularly for applications with defined performance requirements.



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Lithosphere-Inspired Polymeric Architectures: Lab-Scale Manufacturing and Structure-Property Relationships

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Keywords: Lithomimetics; Lithomer; Fracture testing; multi-material manufacturing

The incorporation of one or multiple compliant straight interlayers (IL) into a stiff polymeric matrix material can significantly enhance the damage tolerance when an appropriate layer architecture is selected. This improvement is primarily attributed to the material inhomogeneity effect, which locally alters the crack-driving force and thereby influences crack propagation behavior. Although this bio-inspired approach has shown considerable potential, it is often associated with reduced overall stiffness of the multilayer system. This decrease primarily arises from stress decoupling between adjacent layers and may adversely affect structural performance in stiffness-critical applications. To mitigate this drawback, the present work investigates the incorporation of wavy soft ILs instead of conventional straight ones. Owing to their geometrical configuration, these wavy structures generate a more complex stress state during mechanical loading, resulting in an additional stiffening effect of the overall system by simultaneously maintaining damage tolerance. This design concept, inspired by the non-living matter, the Earth's lithosphere, is not only of high interest from a fracture mechanics perspective but also presents substantial challenges and opportunities in terms of processing technology. While the manufacturing of conventional multilayer polymeric systems containing predominantly straight ILs is well established through extrusion-based technologies such as co-extrusion, the controlled fabrication of embedded wavy IL architectures remains challenging. Consequently, the realization of such structures on an industrial scale requires either substantial modifications of existing processes or entirely novel manufacturing concepts. In contrast, laboratory-scale fabrication provides greater flexibility for investigating lithosphere-inspired architectures and their structure-property relationships. Therefore, two experimental processing approaches were investigated in this study. The first approach was based on inkjet 3D printing and enabled the controlled embedding of wavy TangoBlackPlus ILs into a stiff VeroWhitePlus matrix. The second approach involved the development of a rotational mixing process designed to mimic lithosphere formation mechanisms. Since natural lithospheric structures evolve under elevated temperatures, high pressures, and relative movement caused by plate tectonics, these conditions were transferred to polymer processing using a custom-designed rotational mixer operating similarly to plate-plate rheometry. Within this rotational mixing concept, two different feed states were investigated. In the first series, Polycyclohexylendimethylenterephthalat (PCTG) and thermoplastic copolyester (TPC) granulates were processed under predefined thermomechanical conditions. In the second series, compression-molded plates of the same materials were stacked prior to rotational mixing. Independent of the initial feed state, both approaches generated distinct lithosphere-like patterns. Mechanical characterization revealed that the inkjet-printed structures exhibited an increase in fracture toughness of approximately 8000 % compared to the pure matrix material, while the associated stiffness reduction was approximately 30 % lower than that observed for structures containing straight compliant ILs. For the rotational mixing approach, only the plate-based route resulted in improved damage tolerance combined with a comparatively low stiffness reduction. In contrast, the granulate-based route did not yield beneficial mechanical behavior, which was attributed to the absence of a continuous compliant IL required for effective crack-arrest mechanisms. Overall, the results demonstrate that wavy IL architectures can substantially reduce the stiffness penalty typically associated with damage-tolerant multilayer systems. Inkjet 3D printing proved to be a powerful tool for the controlled reproduction of lithosphere-inspired patterns and for systematically studying geometry-property relationships. However, a deeper understanding of these structures requires processing conditions that more closely resemble those present in the Earth's lithosphere. For this reason, the rotational mixing process was developed and implemented. Initial findings reveal extraordinary internal structures closely resembling natural lithospheric patterns and highlight the strong influence of both material selection and initial feed state. More broadly, the emerging field of "Lithomeres" offers considerable potential for advancing both material design and polymer processing technologies.

Mechanical Performance and Fracture Behavior of Polypropylene Compounds Containing Modelled Post-Consumer Recyclates

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Keywords: Post-consumer Recyclate (PCR); Polypropylene (PP) compounds; Slow crack growth (CRB); Fracture mechanics

The use of post-consumer recyclates (PCR) in polymer compounds is becoming increasingly important in the context of sustainable material development. Despite continuous improvements in waste processing technologies, recyclates, particularly those derived from mixed plastic waste streams, still exhibit considerable variability in quality due to the presence of organic and inorganic contaminants as well as foreign particles. These fluctuations can adversely affect the processing behavior and overall performance of compounds based on blends of recyclates and virgin materials. In this study, different polypropylene (PP) grades were combined with small amounts of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) to create a model recyclate representing the typical composition of a real mixed-stream PCR. In order to systematically investigate the effects of controlled PCR addition on the short- and long-term behavior of the resulting compounds, the model recyclate was subsequently blended with a virgin PP extrusion grade in varying proportions. Furthermore, the presence of foreign particles, impurities, and defect-like structures commonly found in PCR materials was replicated through the controlled incorporation of uncoated glass inclusions with spherical and platelet-like geometries. Mechanical and rheological characterization was used to evaluate the short-term behavior of the compounds as a function of increasing recyclate content. In addition, long-term performance and the resistance to slow crack growth propagation were investigated using the Cracked Round Bar (CRB) method. The obtained results contribute to an improved understanding of the influence of PCR-related compositional variations and particulate inclusions as well as their influence on both the short-term and long-term performance of PP compounds.

Asymmetric Fiber Double-Electrode Triboelectric Nanogenerator Design for Energy Harvesting and Multidirectional Motion Sensing

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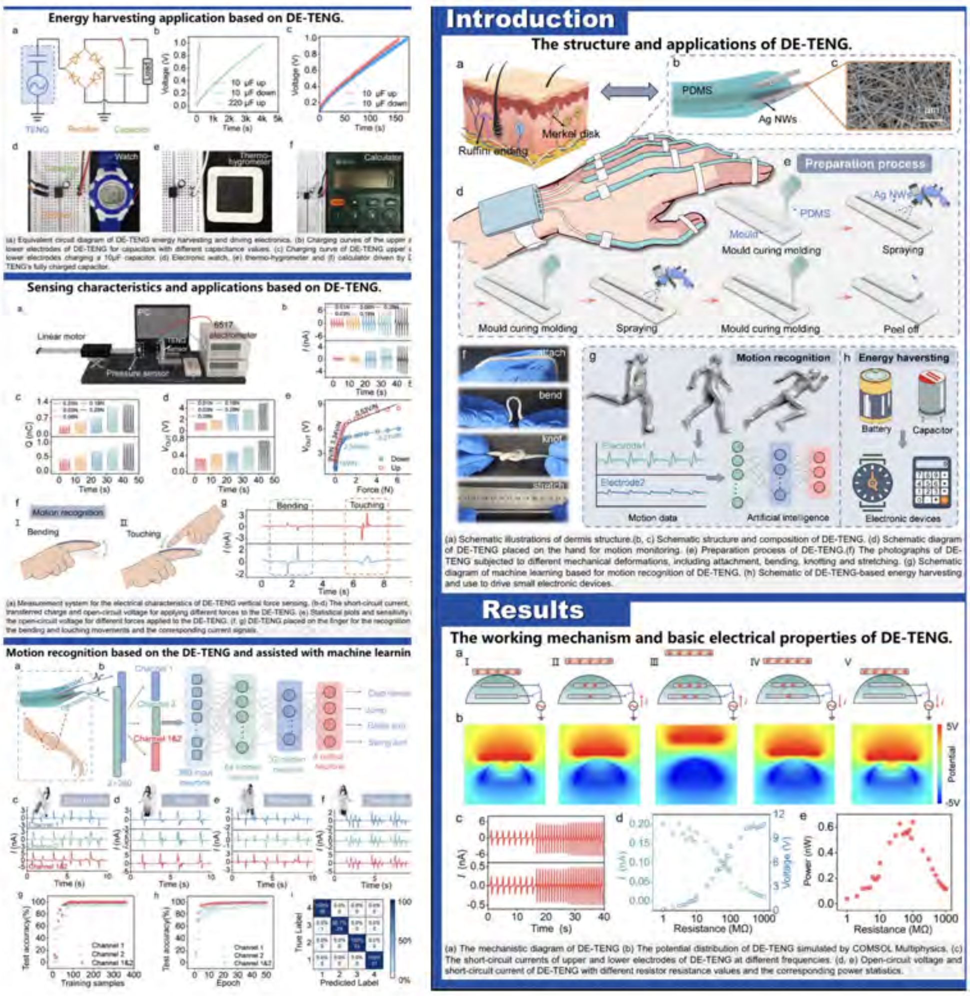
Triboelectric nanogenerator (TENG) devices have promising applications in the fields of wearable power technology, motion monitoring, physiological monitoring, and human-computer interaction. A challenge is making TENG devices according to scalable techniques enabling multidirectional action with high sensitivity and accuracy. Herein, we present a scalable nanotechnology, delivering a dual-electrode semi-cylindrical fiber TENG (DE-TENG), resembling a combination of Merkel disks and Ruffini endings skin elements responding to different tactile stimuli. The upper and lower silver nanowire-based (Ag NWs) electrodes are encapsulated in polydimethylsiloxane (PDMS) to form single-electrode modes in a DE-TENG configuration with asymmetric responsivity for both electrodes. For energy harvesting applications, a long-term stable output results, and the instantaneous output power of the upper electrode reaches a maximum value of 0.64 µW at an external load resistance of 100 MΩ, with the output power of the lower electrode being four times smaller. Moreover, for motion recognition with low forces (below 0.15 N), a very high sensitivity is realized in the state of the art, with the upper and lower electrode layers of the DE-TENG material providing 9 V/N and 15 V/N. In this context, the DE-TENG material was mounted onto a finger to accurately identify a bending or touching motion, benefiting from a strong signal at least by one of the electrodes, and further exploited in a multi-channel wearable e-fabric with stimulus-dependent position recognition. In combination with deep learning, coupling of multi-channel signals from such dual-electrode TENG can improve the accuracy of motion recognition up to 99.84%, further extending the applications of TENGs in wearable sensors.



Energy harvesting application based on DE-TENG.

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