82nd International Scientific Conference of the University of Latvia 2024

Advanced Composites and Applications

Book of Abstracts

February 13, 2024

UNIVERSITY OF LATVIA

82nd International Scientific Conference of the University of Latvia 2024

Tuesday, 13 February 2024
10:00-13:50, online

Programme

Chair: Assist. Prof. Tatjana Glaskova-Kuzmina		
10:00-10:05	**Tatjana Glaskova-Kuzmina** *University of Latvia, Riga, Latvia*	**Opening of the Conference special session**
10:05–10:20	**Andrejs Krauklis and Sotirios Grammatikos** *Norwegian University of Science and Technology, Gjøvik, Norway*	**Modular framework for modelling composite material-environment interactions**
10:20–10:35	**Anish Niranjan Kulkarni, Andrejs Pupurs, Olga Kononova, and Vladislavs Jevstigņejevs** *Riga Technical University, Riga, Latvia*	**Micro-damage evolution in novel composite-metal joints with textile mesostructure**
10:35–10:50	**Mostafa Sadeghian and Naginevičius Vytenis** *Kaunas University of Technology, Kaunas University of Applied Engineering Sciences, Kaunas, Lithuania*	**Static higher-order analysis of nanoplates using an analytical approach**
10:50–11:05	**Leons Stankevics, Jevgenijs Sevcenko, and Andrey Aniskevich** *University of Latvia, Riga, Latvia*	**Modelling of linear viscoelastic creep of 3D printed PETG samples**
11:05-11:20	**Mughees Shahid and Daiva Zelenkiene** *Kaunas University of Technology, Kaunas, Lithuania*	**Numerical investigation of different natural, synthetic or hybrid fiber-reinforced polymer composites for automotive applications**
11:20-11:35	**Sultan Ullah, Muhhamad Faizan Ali, Hassan Iftikhar, and Giedrius Janusas** *Kaunas University of Technology, Kaunas, Lithuania* *National Textile University, Faisalabad, Pakistan*	**Dibutyle phthalate (DBP) infusion: crafting mechanical excellence in polyester matrix composites**
11:35-11:50	**Gabriele Jovarauskaite, Gediminas Monastyreckis, and Daiva Zeleniakiene** *Kaunas University of Technology, Kaunas, Lithuania*	**Self-sensing sandwich composites with electrically conductive MXene nanoparticles**

11:50-12:20	**Coffee break**	
12:20-12:35	**Gytautas Rinkevicius and Daiva Zeleniakiene** *Kaunas University of Technology, Kaunas, Lithuania*	**Smart de-icing system for structural composites**
12:35-12:50	**Gopi Kompelli, Arunas Kleiva, and Rolanas Dauksevicius** *Kaunas University of Technology, Kaunas, Lithuania*	**3D printable lead-free piezoelectric polymer-ceramic composites manufactured using more environmentally responsible melt-based process**
12:50–13:05	**Monika Chomiak, Małgorzata Szymiczek, Iwona Gródek and Wojciech Danek** *Silesian University of Technology, Gliwice, Poland* *Symkom Sp. z o. o., Warsaw, Poland*	**Analysis of the progress of processing shrinkage of injection molded parts using the optical method**
13:05-13:20	**Angelika Jasinska and Piotr Zagulski** *Kielce University of Technology, Kielce, Poland*	**Influence of curing and post-curing processes on the service life of polymer matrix composite materials**
13:20-13:35	**Tatjana Glaskova-Kuzmina, Didzis Dejus, Jānis Jātnieks, Elīna Vīndedze, Irina Bute, Jevgenijs Sevcenko, Andrey Aniskevich, and Stanislav Stankevich** *Baltic3D.eu, Riga, Latvia,* *University of Latvia, Riga, Latvia*	**Evaluation of tensile, thermal and flame-retardant properties of 3D printed parts of polyetherimide and polyetherketoneketone**
13:35-13:50	**Concluding remarks**	

Contents

MODULAR FRAMEWORK FOR MODELLING Composite MATERIAL-ENVIRONMENT INTERACTIONS

Andrejs Krauklis and Sotirios Grammatikos

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Material-Environmental Interaction (MEI), such as environmental aging, profoundly affects composite materials' durability, undermining their inherent strength and stiffness, leading to uncertainty in predicting long-term performance. Predicting the desired service life under such conditions is pivotal, yet conventional validation through testing is highly costly and time-consuming, hindering innovation. Modeling emerges as an economically feasible alternative, complementing testing with simulation and accelerated testing methodologies based on fundamental physicochemical principles [1].

This work discusses the modular framework for composites, which covers the material aging mechanisms, including insights into the aging of the composite (micro-)constituents (matrix, reinforcement, sizing). Aging degradation rate is mainly influenced by chemical formulation, sizing quality, environmental and material composition, acidity, mechanical stresses and temperature. Utilizing a spectrum of modeling tools, from simplified correlations to advanced simulations, enables the prediction of environmental aging effects on the performance of composite materials. Service life is forecasted using degradation rate models, superposition principles, and parametrization techniques, offering valuable insights for both the industry and academia.

Moreover, the rising demand for bio-polymers and bio-composites adds further complexity in predicting lifetime, with implications ranging from advantageous degradation in bio-degradable plastics to detrimental effects in structural polymeric composites. The duality of the lifetime prediction is discussed [2]. The distinction lies in preserving material integrity versus simulating end-of-life scenarios. Consequently, similar aging phenomena and modeling methodologies apply, whether prioritizing "safety" or "decomposition".

Acknowledgements

Some elements described herein are the results and findings from the earlier project of A. E. Krauklis funded from the European Regional Development Fund within the Activity 1.1.1.2 "Post-doctoral Research Aid" of the Specific Aid Objective 1.1.1 of the Operational Programme "Growth and Employment" (Nr.1.1.1.2/VIAA/4/20/606).

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MICRO-DAMAGE EVOLUTION IN NOVEL COMPOSITE-METAL JOINTS WITH TEXTILE MESOSTRUCTURE

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In structures where composites and metallic materials are used together, the composite-metal joints act as stress concentration regions due to abrupt property change. In addition, mechanical fastening of composites using rivets or bolts creates irreversible fiber damage, leading to a drastic reduction in strength and ultimate failure strain. A novel composite-metal joining technique using hybrid composites with textile mesostructure is proposed to overcome such drawbacks.

The present work studied mechanical properties and microdamage accumulation under uniaxial tensile loading in hybrid carbon/steel fiber textile composites using experimental and numerical methods.

Plain-woven or plain weft-knitted fabrics were manufactured using T300 carbon-fiber yarns and S.Y. 11-1 stainless steel-fiber yarns on manual weaving and knitting machines. Hybrid composites were prepared by vacuum infusion of epoxy resin into various configurations of dry fabric stack-ups. Under uniaxial tensile loading, the initial elastic modulus before micro-damage initiation was measured. With the increase in applied strain, micro-damage in the form of delamination along yarn-matrix boundaries and transverse cracks inside weft yarns was observed using optical microscopy.

In the next step, see Fig. 1, which shows representative volume elements (RVEs) of the meso-structure of various configurations of hybrid composites generated in SolidWorks CAD software. The RVEs were calibrated by performing FE numerical simulations of elastic properties and comparing them with experimental values from tensile tests. Cohesive zone material (CZM) elements were applied at the interface between steel-fiber or carbon-fiber yarns and epoxy matrix, and maximum stress failure criterion was applied to find probable locations of delaminations and fiber damage under uniaxial tensile loading. The FEM results were compared with experimental stress-strain curves and damage observations in optical microscopy.

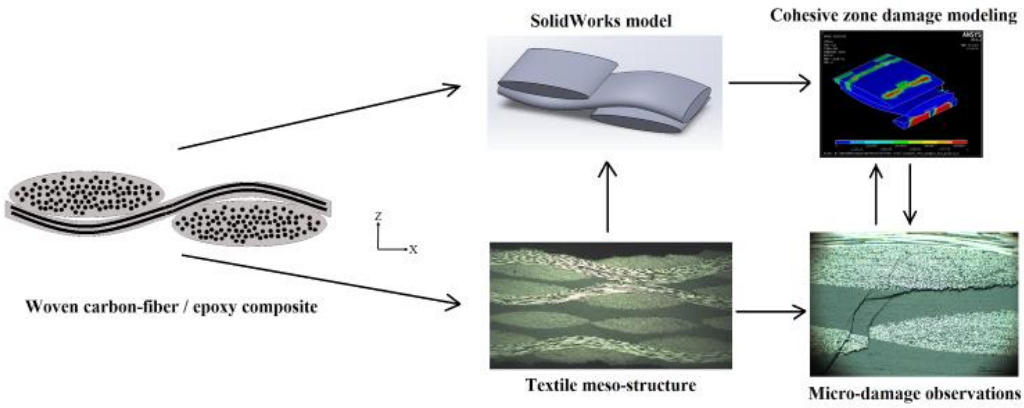

Fig. 1. Scheme for experimental and numerical study.

STATIC HIGHER-ORDER ANALYSIS OF NANOPLATES USING AN ANALYTICAL APPROACH

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Static analysis of nanoplates is crucial for determining their stability, load-bearing capacity, and deformation under applied forces. This information is fundamental in designing nanomaterials for structural applications, ensuring they can withstand various conditions without failure. Static analysis also guides engineers in developing reliable and durable nanoplate-based structures in engineering, construction, and materials science. Nonlocal strain gradient theory combines nonlocal and strain gradient effects to provide a more comprehensive understanding of material behavior, especially in small-scale structures. It considers both nonlocal effects, where material properties depend on the entire deformation field, and strain gradient effects, which account for variations in strain within the material. This theory is particularly relevant at the nanoscale, where traditional continuum mechanics may not accurately describe material behavior, and useful for analyzing and predicting the behavior of materials in advanced applications such as nanoelectromechanical systems and microelectromechanical systems. A higher-order theory in mechanics refers to an approach that includes higher-order derivatives of the deformation field or higher-order gradients of the displacement field. Unlike classical theories or first-order beam theory, higher-order theories provide a more detailed description of the mechanical behavior of structures.

This study applies the nonlocal strain gradient theory for analyzing the static analysis of nanoplates. The equilibrium equations regarding displacements and rotations are developed, accounting for the nonlocal strain gradient theory and higher-order deformation theory. An analytical method, which is simpler than other numerical techniques, is employed to solve the governing equations. The results are validated with other references, which show good accuracy. Studies are carried out to examine the effects of small-scale variables and different elastic bases and load levels. It can be noticed that small-scale characteristics significantly influence the static analysis of nanoplates.

MODELLING OF LINEAR VISCOELASTIC CREEP OF 3D PRINTED PETG SAMPLES

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Polyethylene terephthalate glycol (PETG), commonly used in 3D printing, like other polymers, has a noticeable creep, which can lead to the deterioration of printed parts. 3D printed constructions, due to the specific technology, have anisotropic structure. This research aimed to investigate experimentally and model the viscoelastic creep of PETG samples, taking their anisotropy into account.

Two sets of bar-shape samples were unidirectionally printed using Ultimaker S5 3D printer along the principal axis X and perpendicular Y, with the printer head moving only along the X axis. Samples were printed with a nozzle diameter of 0.4 mm, line width of 0.35 mm, layer height of 0.1 mm, and infill density of 100%. The strength of the tested earlier PETG samples was 50.43 and 22.48 MPa in the X and Y directions, respectively, and the elastic modulus was 2.33 and 2.19 GPa in the X and Y directions.

Two tests were performed with applied six stress levels from 25 to 93% of sample strength. The first set of tests kept samples under constant stress for 20 h. The second set of tests kept samples under constant stress for 5 h, then the stress was removed, and creep recovery was observed for 15 h. The tests were performed using Zwick 2.5 machine. Samples were loaded to the required stress levels within 1- to 1.7-second intervals. The intermediate stress loading and unloading states were not considered in the modelling.

It was assumed that the deformation of samples could be described with a linear viscoelastic model (1) using Boltzmann-Volterra theory:

$$\epsilon(t) = \frac{\sigma(t)}{E} + \sum_{i=1}^{k} \frac{A_i}{E\cdot\eta_i} \int_0^t \sigma(\tau) e^{-\frac{t-\tau}{\eta_i}} d\tau, \tag{1}$$

where ϵ is strain, σ is stress. A combination of times of relaxation η_i and amplitudes A_i is commonly called a material relaxation spectrum. Simplifying (1) for a case of constant stress applied at a time $0<t<t_0$ and then taken away at a time t_0:

$$\epsilon(t) = \frac{\sigma}{E}\left[1 + \sum_{i=1}^{k} \mathrm{A_i} \cdot \left(1 - e^{-\frac{t}{\eta_i}}\right)\right], t < t_0, \tag{2}$$

$$\epsilon(t) = \frac{\sigma}{E} \sum_{i=1}^{k} \mathrm{A_i} \cdot \left(-\mathrm{e}^{-\frac{\mathrm{t}}{\eta_i}} + \mathrm{e}^{\frac{t_0-\mathrm{t}}{\eta_i}}\right), \mathrm{t} > t_0. \tag{3}$$

Relaxation spectrum amplitudes for the relaxation time equal to or less than η_i = 10000 s were in the range *A* = 0.5-4, but for η_i = 100000 s or 28 h, the amplitude was 30 for X and 18 for Y directions. Though conclusive analysis was not made with modelled recovery, the calculated data were close to the experimental. Isochrones of experimental and theoretical data for the creep stage were constructed. They showed that theoretical data for stress less than approximately 70% of sample strength, or 35 MPa for X and 16 MPa for Y printing directions, adequately described experimental data. In comparison, samples subjected to a stress of more than 70% were not as successful. Further attempts at describing creep with a non-linear viscoelastic model will be performed.

NUMERICAL INVESTIGATION OF DIFFERENT NATURAL, SYNTHETIC, OR HYBRID FIBER-REINFORCED POLYMER COMPOSITES FOR AUTOMOTIVE APPLICATIONS

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Composite materials have gained attention in the automotive industry for their potential to reduce weight and improve mechanical properties, leading to increased fuel efficiency and lower CO_2 emissions. Recent research has focused on developing eco-friendly polymer composites with low environmental impact and sufficient mechanical properties [1-3]. In this research work, numerical investigations were performed to find out the best suitable plastic composite with better structural integrity in response to the applied load, its behavior to sustain impact energy, impact absorption, and its safety for automotive applications using different natural, synthetic, and hybrid fiber-reinforced polymer composites. Natural fibers (kenaf, hemp), synthetic fibers (carbon, glass), reinforced thermoplastic polymers (polypropylene, polyetherimide), and thermoset polymer epoxy were investigated. Static structural analyses were performed on Ansys Workbench 22.0. Total deformation, equivalent elastic strain, and stress results were gathered. Maximum deformation was observed for the kenaf-reinforced polypropylene composite, which is 5.84 mm, and minimum deformation was observed for the hemp/glass fiber-reinforced epoxy hybrid $4.48x10^{-01}$ mm composite. Maximum and minimum equivalent stresses were found for glass fiber-reinforced epoxy composite 5.59 MPa and kenaf/glass fibre-reinforced epoxy hybrid composite 5.52 MPa. Maximum and minimum equivalent strain values were recorded for the kenaf-reinforced polypropylene composite 1.28×10^{-3}, and the hemp/glass fiber-reinforced epoxy hybrid composite 9.58×10^{-5}. Hemp/glass fiber-reinforced epoxy hybrid composite perfomed better as it absorbed less impact energy, had better impact absorption, and had a lower chance of failure overall. Moreover, by incorporating natural fibre hybrid composites in automobile applications, possible advantages such as a reduction in weight, an increment in fuel efficiency, and a reduction in carbon footprints will be achieved.

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DIBUTYL PHTHALATE (DBP) INFUSION: CRAFTING MECHANICAL EXCELLENCE IN POLYESTER MATRIX COMPOSITES

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In this research, we investigate the mechanical properties of fiber-reinforced hybrid polymeric composites comprising unsaturated polyester resin (UPR) and dibutyl phthalate (DBP) as a novel short-chain plasticizer. Addressing the brittleness and low resistance to crack propagation inherent in UPR, various DBP and UPR mixing ratios were employed as matrices for woven glass fabric composites via compression moulding. The process flowchart for blend and composite fabrication is shown in Figure 1. Tensile, flexural, delamination and Charpy impact tests were conducted to evaluate the mechanical performance. The results indicate that incorporating 4% DBP and 96% UPR in the matrix yields composites with significantly improved mechanical properties compared to pure UPR matrices.

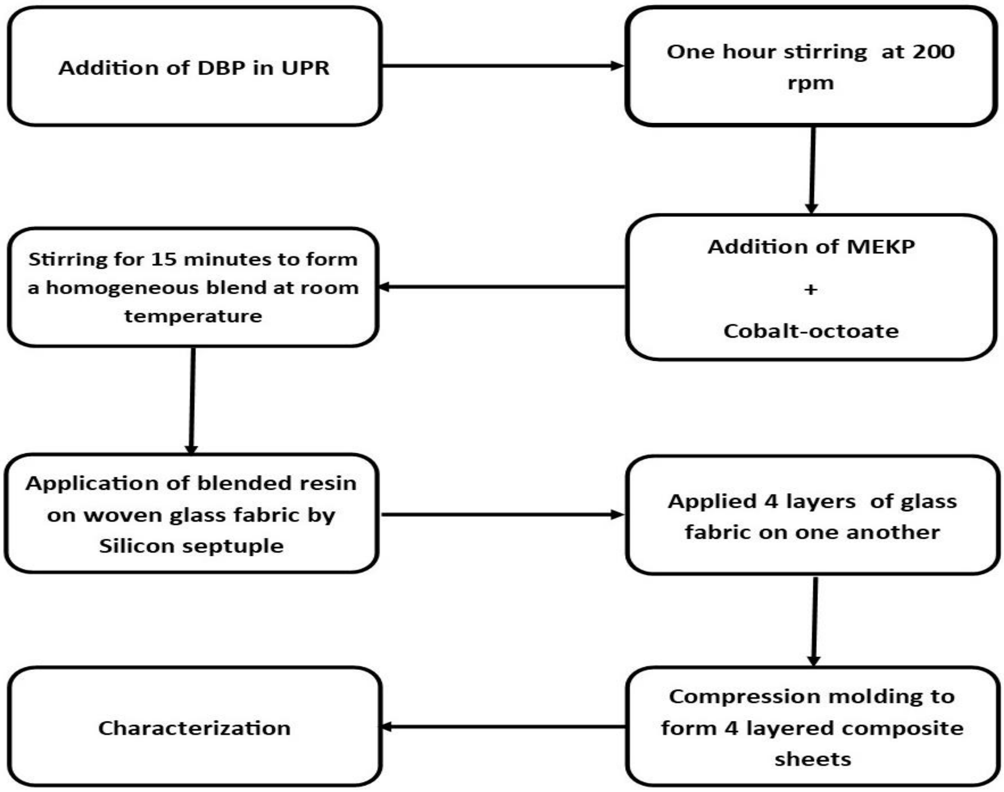

Fig.1. Process flowchart for blend and composite fabrication.

SELF-SENSING SANDWICH COMPOSITES WITH ELECTRICALLY CONDUCTIVE MXENE NANOPARTICLES

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Due to their great weight and strength ratio, composites are used in different areas of the aircraft. Despite the significant advantages of composites, they are sensitive to defects such as cracks, debonding, delamination, and fibre breakage. After numerous flight cycles, unnoticed weaknesses can lead to structural integrity failure, ultimately affecting aircraft safety. It is crucial to identify these defects early to prevent such failures. The condition of the aircraft structure is periodically checked during maintenance with the help of non-destructive or structural health monitoring (SHM) methods using sensors such as strain gages and optical fibres. However, these methods are limited by time and resources. Another SHM technique is based on self-sensing composites. They include electrically conductive additives, which create a piezo-resistive effect and can indicate potential structure damage. Therefore, such composites are a viable solution for aircraft structures where early-stage damage monitoring is necessary.

This study is aimed to develop a self-sensing sandwich-structured composite. The composite consisted of an electrically conductive honeycomb dip-coated with MXenes, a CNT spray-coated glass-fibre interlayer and a unidirectional carbon fibre interlayer was investigated. Firstly, each layer's electrical parameters were characterized depending on the preparation procedures. Then, the piezo-resistive response was obtained by performing separate indentation tests. Lastly, damage sensing characteristics of the composite were measured depending on the position and size of indentations through local electrical resistance variations. This study showed that sandwich-structured composites with different nanoparticle modification techniques unlock the ability for complex damage sensing, including core buckling, fibre cracking and interlaminar debonding, making it practically suitable for in-flight aircraft condition diagnostics.

Acknowledgements

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SMART DE-ICING SYSTEM FOR STRUCTURAL COMPOSITES

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One of the main problem in the aeronautics and wind turbine sectors is icing. An ice layer on the aircraft can lead to bad control of the aircraft, reduced lift, and increased drag [1]. On wind turbines, icing can lead to reduced efficiency, cause stresses on the turbine and damage the entire structure [2]. All traditional solutions, such as heating or pneumatic systems, integration requires a lot of energy or complicated structures. An excellent solution to this problem is a heating and self-sensing composite system, which can identify whether the ice layer is on the surface and heat the entire surface. The ice layer can be identified by the change in electrical resistance, which is sensitive to the temperature. Heating is based on the "Joule heating "law, which states that the power of heating generated by an electrical conductor equals the product of its resistance and the square of the current [3].

This investigation aims to develop a self-detecting and heating composite structure which could identify and remove the ice layer from the surface. In this work, an epoxy matrix modified with 1 mg/mL CNT and an epoxy matrix modified with 1 mg/mL MXene were tested, and their electrical properties were compared and created a smart de-icing system structure and its working principle. Structures were made from epoxy resin and a coating of MXene or carbon nanotubes. The structure used an "Arduino Uno "microcontroller, electrical components and wires. Temperature was measured using a thermopore. For the heating measurement, a voltage of 100 V was used, and the measurement was taken after 1, 2 and 3 minutes of heating.

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3D PRINTABLE LEAD-FREE PIEZOELECTRIC POLYMER-CERAMIC COMPOSITES MANUFACTURED USING MORE ENVIRONMENTALLY RESPONSIBLE MELT-BASED PROCESS

Gopi Kompelli[1], Arunas Kleiva[2], Rolanas Dauksevicius[3]

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This work presents melt-based manufacturing of more eco-friendly lead-free 3D printable piezo composites with higher filler content for sensing and energy harvesting applications. The piezocomposites are fabricated using polyvinylidene fluoride-co-hexafluoropropylene (PVDF-HFP) granules as the matrix phase and potassium sodium niobate (KNN) microparticles as the lead-free piezoceramic filler. The research addresses the imperative to avoid using hazardous solvents detrimental to human health and the environment in compliance with European REACH legislation. The aim is to develop a cleaner and industrially scalable solvent-free manufacturing process based on a multi-stage hot melt extrusion to enhance dispersion homogeneity for larger filler content (wt%) in the thermoplastic matrix to enhance the quality and printability of the filaments. The workflow (Fig. 1) consists of mechanically dry mixing PVDF-HFP with KNN in lower wt% and then extruding with a conventional extruder, followed by pelletization of the composite extrudate. The extrusion-pelletization cycle is repeated several times by incrementally increasing filler content until the intended wt% is achieved (e.g. >60 wt%) in the final filament (diameter is 1.75 ± 0.15 mm). Fused filament fabrication (FFF) technology is used to 3D print thin samples for contact-type electrical poling. It is performed for 2 hrs using up to 12 kV voltage, and the highest piezocoefficient (d_{33}) value, 9.8 pC/N is achieved with the 60 wt% KNN in PVDF-HFP. Increasing the filler content is found to improve d_{33}. The conducted research work aligns with the priorities of The Advanced Materials 2030 Initiative, which emphasizes the pivotal role of advanced materials in additive manufacturing in health applications and the development of efficient sensors and energy harvesters.

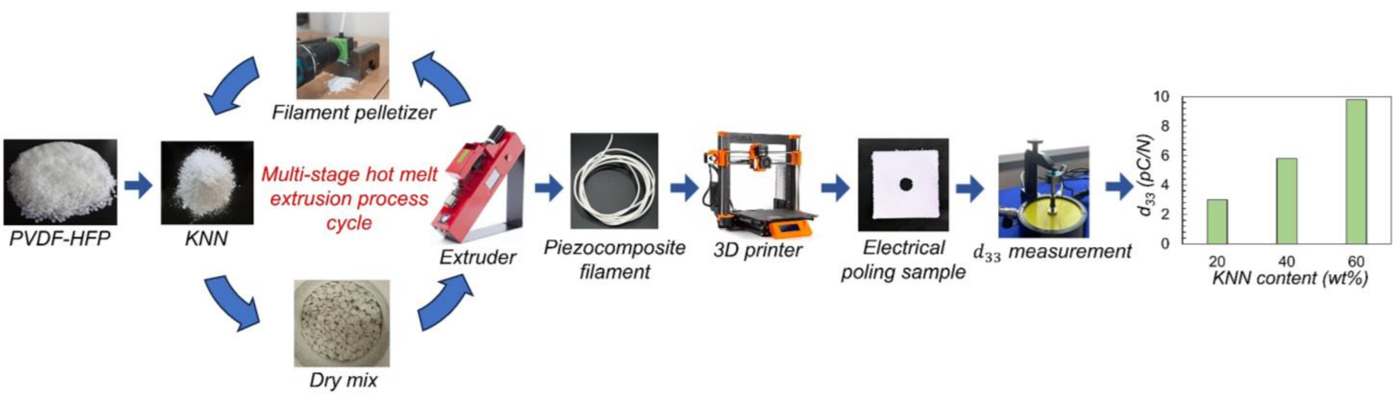

Fig.1 Schematic of the process used to fabricate and test the lead-free piezoelectric composites.

ANALYSIS OF THE PROGRESS OF PROCESSING SHRINKAGE OF INJECTION MOLDED PARTS USING THE OPTICAL METHOD

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In the design of injection moulded details, as well as the tools in which the detail is created, the knowledge of the time course of the processing shrinkage of the moulded parts is of great importance, because it allows you to save time related to the modification of tools at the stage of starting the production process, as well as to avoid a large number of products with incorrect dimensions. The work presents an analysis of the influence of selected technological parameters of the injection process on the value and course of processing shrinkage. As part of the work, injection mould cavities were measured with a 3D scanner. Two types of plastics were selected for testing, namely partially crystalline polypropylene MOPLEN HP500N from LyondellBasell Industries Holdings, B.V. and amorphous polystyrene PS GP 525 from Synthos Limited. Appropriate ranges of injection process parameters were determined for selected materials. Test samples were produced using injection molding technology. A systematic measurement (with an accuracy of 0.01 mm) of the geometric dimensions of the moulded parts was carried out, i.e. length and width, which are important due to the occurrence of processing shrinkage. For this purpose, an optical measurement system for spatial mapping of objects based on the Raspberry Pi minicomputer was used. Time series analysis allowed to determine the characteristics of changes in geometric dimensions of the tested injection samples. Charts of the dependence of injection shrinkage on injection pressure, clamping pressure, mold temperature and plasticization temperature were developed. It was found that low mold temperature, long cooling time of molded parts in the mold and high value of clamping pressure are the factors that determine the reduction of secondary shrinkage. Further lowering the mold temperature (below 20ºC) and extending the cooling time (above 50 s) of the molded parts could lead to an even greater reduction in shrinkage, but at the same time it would worsen the economic indicators of the injection process.

Keywords: injection shrinkage, processing shrinkage, amorphous plastics, semi-crystalline plastics

Acknowledgements

This project has received funding from competition for Project-Based Learning (PBL), under the Excellence Initiative - Research University programme

INFLUENCE OF CURING AND POST-CURING PROCESSES ON THE SERVICE LIFE OF POLYMER MATRIX COMPOSITE MATERIALS

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This paper presents part of a study that presents the effect of temperature on the strength characteristics of a sandwich composite. Based on the contents of ISO 527, a comparison was made of the strength properties of a four-layer polymer matrix glass composite. When the curing processes were completed, the samples were subjected to a further post-curing process.

The research could be of significant importance to the industry in demonstrating the capabilities and nature of epoxy and determining the optimum annealing time for components. These will be directly reflected in reduced production costs or improved properties by the customer after purchase.

Based on the results obtained, it can be concluded that the post-curing process positively improves the strength properties of the layered composites.

EVALUATION OF TENSILE, THERMAL AND FLAME-RETARDANT PROPERTIES OF 3D PRINTED PARTS OF POLYETHERIMIDE AND POLYETHERKETONEKETONE

Tatjana Glaskova-Kuzmina[1,2], Didzis Dejus[1], Jānis Jātnieks[1], Elīna Vīndedze[1], Irina Bute[2], Jevgenijs Sevcenko[2], Andrey Aniskevich[2], and Stanislav Stankevich[2]

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In high-fire-risk applications like aviation interior components, polymer materials are increasingly prevalent. This study compares the tensile, thermal, and flame-retardant properties of test samples produced through fused filament fabrication (FFF) using ultra-performance materials, specifically polyetherimide (PEI) and polyetherketoneketone (PEKK). Tensile tests were conducted at various raster angles (0, 45, and 90°), while thermomechanical tests were performed in axial, perpendicular, and through-thickness directions. Vertical burn tests explored the impact of printing parameters on flame retardancy, considering specimen thicknesses and printing directions.

It was experimentally confirmed that the tensile characteristics (including elastic modulus and tensile strength) of PEKK surpass those of PEI, particularly at raster angles of 45 and 90°. Minimal differences in tensile characteristics were observed at a raster angle of 0° and with virgin filaments, suggesting a potential variation in void distribution within PEI at different filament orientations. In the case of PEKK, no significant impact of raster angle on tensile properties was discerned. Thermomechanical analysis revealed that PEI exhibited a higher softening temperature (140 °C and 160 °C for PEKK and PEI, respectively), indicating greater thermal stability in PEI compared to PEKK. Both materials displayed notable thermal deformation in measurement direction 1 compared to other directions. Burn length results indicated that PEI exhibited superior fire resistance compared to PEKK at various thicknesses and infill percentages. PEKK, however, demonstrated better isotropic behaviour than PEI in terms of mechanical performance, thermal expansion, and fire-resistant properties.

Isotropy in these properties among 3D printing materials is crucial for fabricating intricately shaped products, offering advantages over traditional machining methods, such as accelerated production, reduced material wastage, and lower energy consumption. Despite these differences, both materials, even at low infill percentages, met the flammability aviation requirements according to EASA CS 25 for use in aircraft interior compartments and cargo or baggage compartments. Consequently, these materials and Fused Filament Fabrication (FFF) are deemed suitable for aircraft interior applications. Low infill density in 3D printed structures can reduce overall aircraft weight, fuel consumption, and CO_2 emissions.

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