FPCM - 10
10th International Conference on Flow Processes in Composite Materials

Book of Abstracts

July 11-15, 2010

Centro Stefano Franscini, Monte Verità
Ascona, Switzerland
www.fpcm10.ch

Foreword

The 10th International Conference on Flow Processes in Composite Materials will be held from July 11 to 15, 2010, at the Centro Stefano Franscini, Monte Verità in Ascona, Switzerland.

Hosted by EPFL and ETHZ, the conference in Ascona is focused on well-defined aspects related to flow processing, such as novel materials and manufacturing processes, simulation, sensing and flow control, design, optimization of moulds and processes. One of the main goals is to help bridging the gap between theory and practice. Set-up of standard techniques for permeability measurement will also be a focus of the conference. Lecturers from academia and industry will discuss the latest scientific results on flow processes and illustrate through specific examples applications of liquid moulding to the manufacturing of high performance composites.

This conference is the tenth of a series devoted to the manufacturing of polymer matrix composites and related topics. Previous meetings were held amongst others at the University of Auckland, New Zealand (2001), University of Delaware, USA (2004), École des Mines de Douai, France (2006) and École Polytechnique de Montréal, Canada (2008). Each of the previous conferences has set ever new standards in the field of LCM science and engineering.

VENUE

The Conference is held in cooperation with the **Centro Stefano Franscini** (CSF), the International conference centre of ETH Zurich, situated at Monte Verità, Ascona http://www.csf.ethz.ch .

LOCAL ORGANIZING COMMITTEE

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We acknowledge support from:

	Day 1: Monday, July 12, Morning
8h00-8h10	**Welcome and opening Remarks** **Chairs: Dr. V. Michaud, Dr. P.Ermanni**
8h10-8h55	**Keynote 1: Dr. Georg Reif, CEO, 3A Composites, CH** "Industrial aspects of composite materials" Chair: Dr. V. Michaud, EPFL
	Auditorium
9h00-10h20	**Applications I** Chair: Dr. V. Michaud EPFL
9h00	98-Industrialisation, optimisation of RTM process applying manufacturing process simulation, François Dumont and Christian Weimer, Eurocopter, Germany.
9h20	39-Manufacturing a Composite Gearbox for Rotorcraft Applications Jeffrey Lawrence, V system composites, USA.
9h40	6-Effects of groove configurations on fatigue resistance of infused sandwich panels Lars Massüger and Roman Gätzi, Alcan Airex AG, Switzerland
10h00	69-Injection of a Complex Preform by RTM. Process Parameters and Quality of the Part. Pierre Ouagne, Damien Soulat, Romain Agogué, Chung-Hae Park, Laurent Bizet, Joel Breard and Didier Zanelli, Polytech Orleans, and University Le Havre, France.

Note: the numbers on each contribution corresponds to the submission number and can be used to quickly find the corresponding article in the CD.

Keynote lecture 1:

Applications of composite materials

Georg Reif, CEO of 3A composites, Switzerland

3A Composites is the global market leader in core materials for sandwich constructions, particularly for use in wind farms. The company is also a leading player in other segments, such as composite panels for high-quality facades and display applications. Its best-known brands are Airex, Alucobond Baltek, Dibond, Forex, Gator, Kapa and Sintra. Mr Reif will share some of his views on the composite applications and potential for growth in Switzerland and globally.

98-Industrialisation, optimisation of RTM process applying manufacturing process simulation,

François Dumont and Christian Weimer,
Eurocopter, Germany.

Today's and future helicopter programs require an optimised development and industrialisation phase, fulfilling the "first-time-right" requirements. It demands a detailed understanding of the processes at a very early stage of the part design in order to speed up the feasibility study and to reduce prototype number and costs. Thus, Manufacturing Process Simulation (MPS) can be seen as a strong tool to master processes and to speed up development and industrialisation.

The paper gives an overview of the currently available and used manufacturing process simulation tools for the RTM process. Their applicability in development projects and during the industrialisation, ramp-up and serial production phases is described.
An actual case is explained more in detail concerning heating and curing modelling of a RTM part.

The case is presented through real applications of MPS for rotorcraft part out of composite materials. The different features will be explained in order to focus on industrial 'end-users' needs. The questions of the actual technical blocking points as well as the needs for a new design chain will be approached.

39-Manufacturing a Composite Gearbox for Rotorcraft Applications

Jeffrey Lawrence,
V system composites, USA.

Our current effort is to convert a metallic gearbox for rotorcraft applications to composite. The challenge in transmission components is being highly loaded, tend to be thick sectioned and of complex geometry. In addition to the structural challenges in designing such a part lies a manufacturing challenge. The complex layup and quantity of material used leads to an expensive part in both labor and materials. Therefore it is desirable to utilize virtual manufacturing to reduce risk in manufacturing. In this study a complex gearbox will be fabricated using Resin Transfer Molding. Flow simulation will be conducted to locate injection and vent holes, as well as estimate fill times. Permeability characterization is done on the fabric. Finally, during the infusion, in-process monitoring is used to track the progress of the resin into the mold. The resultant part will be examined for the existence of void-free regions, and the simulation will be compared to the experimentally collected data.

6-Effects of groove configurations on fatigue resistance of infused sandwich panels

Lars Massüger and Roman Gätzi,
Alcan Airex AG, Switzerland

A wide variety of parameters relevant for the vacuum infusion process have been investigated. The influence of the different configurations of grooves and perforations on the flow speed, wet-out, the resulting mechanical properties and weight of the produced panels were determined.

As many of the main applications of sandwich structures are subjected to high cycle fatigue loading, the connection is drawn between processing and fatigue performance. The results obtained on samples with plain cores are compared to such with different configurations of grooving to ensure homogeneous resin flow and wet-out are finally discussed.

69-Injection of a Complex Preform by RTM. Process Parameters and Quality of the Part.

Pierre Ouagne, Damien Soulat, Romain Agogué, Chung-Hae Park, Laurent Bizet, Joel Breard and Didier Zanelli,
Polytech Orleans, and University Le Havre, France.

This work concerns the manufacturing of a composite tube from a 3D particular preform arrangement using RTM process. During the preforming which is the first step of the RTM process, a woven ribbon is laid down and stacked on a mandrel so that reinforcement plies form conical shapes with a defined angle. A high ablation resistance is then conferred to the final composite part. Preforming cannot be performed by using a classical braiding machine [1] because of the specific and predefined orientation of the plies. Consequently, an innovative experimental preforming procedure has been developed and will be presented. The resin injection step which is the second stage of the RTM process has been studied both experimentally and numerically. A transparent cylindrical closed mould has been realised so that the outside flow front evolution can be followed during the injection of carbon fiber preform by silicon resin. The silicon resin can be injected under pressure or flow rate conditions at about 50° C [2].

The influence of processing parameters such as the injection pressure or the imposed flow rate upon the number, the position and the size of possible defects has been evaluated. Cartographies of the defects as a function of the processing parameters have been obtained on final parts. Possible displacements of the preform during the injection of resin have also been investigated by image analysis.

A numerical study has been conducted to model the flow of resin within the different areas of the complex preform. Within the preform, variation of angle between the yarns indicates that shear takes place. This suggests that the constituents of the permeability tensor are not constant in the preform especially along a radius of the part. Planar and through-the-thickness permeability studies were conducted experimentally as a function of the fibre volume fraction and the shear angle between the yarns following established methodologies [3, 4]. Then experimental data was used to model the filling of the preform by the resin. Simulation results presenting the evolution of the flow front within the preform for different injection cases will be presented, discussed and correlated to the experimental study results previously mentioned.

Références

[1] Potluri P, Rawal A, Rivaldi M, Porat I. Geometrical modelling and control of a triaxial braiding machine for producing 3D preforms. Composites: Part A 34 (2003) 481–492.
[2], Soulat D, Telmar A, Agogué R, Zanelli D. Étapes du procédé RTM pour pièces de protections thermiques. Comptes-rendus du 19ième Congrès Français de Mécanique. Marseille 24-28 Août 2009. (in french)
[3] Luce T, Advani S, Howard J, Parnas R. Permeability characterization Part 2: flow behaviour in multi-layer preforms. Polymer composites 1995; 16: 446-458.
[4] Ouagne P, Bréard J. Continuous transverse permeability of fibrous media. Composites: Part A (2009), doi:10.1016/j.compositesa.2009.07.008

	Auditorium
10h50-12h20	**Applications II** Chair: Dr. M. Henne, U.Applied Sciences Rapperswil, CH
10h50	80-Industrialisation of Liquid Resin Processes (LRI) considering to the stress transferred influences Henri-F. Perrin, Alain D'acunto and Patrick Martin Arts et Métiers Metz/ PPE, France
11h10	96-Polyurethane Composite Sandwich Structure Paul Trudeau and Edu Ruiz Ecole Polytechnique de Montréal, Canada
11h20	27-Relationship betwen process parameters and mechanical properties of laminated plates made by LRI. Alvine NJIONHOU KEPNANG, Florentin BERTHET and Bruno CASTANIE, Université de Toulouse, ICA / Mines Albi, France
11h40	48-Advanced Material and Tooling Concept for a RTM Helicopter Fitting Markus Henne, Manuel Müller, Gion Andrea Barandun, Paolo Ermanni and Markus Zogg, University of Applied Sciences Rapperswil/ ETHZ, Switzerland.

80-Industrialisation of Liquid Resin Processes (LRI) considering to the stress transferred influences

Henri-F. Perrin, Alain D'acunto and Patrick Martin
Arts et Métiers Metz/ PPE, France

High performance composite parts require high dimensional quality. During the manufacturing of composite material, the temperature has to be elevated to assure the highest resin properties. This temperature variation is partly responsible for the low dimensional fidelity between the tool shape and the part shape. Due to part-process-resources interactions, different deformation mechanisms can occur depending to part-process-resources characteristics. This work will study two deformation mechanisms in case of symmetric balanced thin laminate: the warpage and the spring-in. The warpage deformations result of stresses transferred into the part during the cure cycle by the different resources. The spring-in deformations are induced during the cure cycle because of the anisotropic properties oft the part. Investigations have showed the specific comportment of part manufactured by LRI processes for these both mechanisms like the strong influence of molding resources (resin distribution medium).

The optimization method of the resources parameters for minimize the shape distortion has to be specific because of the differences in the deformation mechanism in compare to part manufactured by prepreg-autoclave processes. Stresses transferred into the part during manufacturing by LRI processes cause important deformations and significant material properties reduction. Their industrialization has to consider these effects. This work will present methods to industrialize composite part to anticipate the influences of transferred stresses.

Models are proposed to predict the part shape considering the LRI process implementation. An experimental method and an experimental plan are proposed to characterize the model parameters. The equivalent cure and thermal shrinkages are experimentally determined for each cure cycle. The models predict the part shape with an acceptable accuracy. So it’s possible to anticipate the deformations and decide if they have to be neglected, minimized or if a tool correction is required. The minimization of the transferred stress level into the part is a key problem because of their influence on the end product material properties. Applied solutions are investigated to reduce the influence of their parameters on the part deformation. Results are satisfying in term of deformation but some difficulties appear. Specific experimental setups have been developed in order to identify the driver process and resource parameters in conventional configurations. As conclusion, method for their optimization is proposed.

96-Polyurethane Composite Sandwich Structure

Paul Trudeau and Edu Ruiz
Ecole Polytechnique de Montréal, Canada

This paper describes the process for manufacturing sandwich composites using polyurethane foam as core material, engineered fibreglass as reinforcement and thermoplastic skins. This new process is the result of a convergence of several processes: sheet thermoforming, preforming using ultraviolet cured adhesives, and polyurethane foam injection. It is greener than traditional sandwich composite processes, as no volatile organic compounds (VOC's) are emitted during manufacturing. The final products have a thermoplastic skin moulded in colour finish requiring no sanding or post painting. Depending on final use of the product, properties can be engineered for weather ability, chemical resistance, temperature resistance as well as colour and texture. The novelty of the process occurs when the liquid polyurethane resin is injected between two preformed thermoplastic sheets with fibreglass layers. The self skinning polyisocyanurate HFC blown foam[1] makes it possible to create the three-dimensional foam core, wet out the dry fibreglass and bond the thermoplastic surface skins during one processing step. This paper details the analysis of the polyurethane reaction that takes place during manufacturing. The foaming behaviour and wetting of the fibres were studied under different manufacturing conditions. Optimization of the composite laminate was finally carried out by improving the foaming conditions.

27-Relationship betwen process parameters and mechanical properties of laminated plates made by LRI.

Alvine NJIONHOU KEPNANG, Florentin BERTHET and Bruno CASTANIE,
Université de Toulouse, ICA / Mines Albi, France

It has been generally observed that preform reinforcement texture coupled with resin infusion process causes variability of mechanical properties of composites made by Liquid Resin Infusion (L.R.I). The L.R.I is a manufacturing process for composite structure where liquid resin infuses through the thickness of fiber fabrics. The aim of this study is to evaluate relationship between L.R.I process parameters and mechanical properties of quadri-axial carbon Non-Crimp-Fabric (NCF) composites, reinforces the epoxy RTM 6, using experimental plan approach methodology. Process parameters have been identified and classified [1]. Ultimate Tensile Strength (UTS) were performed. Statistical analysis showed effects of specimens location in the plate depending of the manufacturing process. UTS of composite vacuum side plate is lower than the UTS of composite resin injection side plate. This property is directly connected to an increase of fiber volume fraction (Vf) and a decrease of structure thickness for the same parameter. These two last properties, Vf and structure thickness, strongly depend on vacuum level achieved during resin infusion process, and also on the mould temperature, number of NCF layers and High Porous Media (HPM) layers used. The effects of process parameters on Ultimate Compressive Strength (UCS) and Interlaminar Shear Strength (ILSS) were investigated. Results show a decrease in UCS with a decrease of glass transition temperature obtained by Dynamic Mechanical Analysis (DMA). ILSS is strongly affected by the interaction between number of NCF layer and number of HPM layers. ILSS is higher for preform containing higher NCF layers using higher HPM layers. Scanning electron microscopy (SEM) observations are made to find a physical basis for macroscopic characterization results and to explain effects of process parameters found on void content, such as vacuum level, curing and mould temperature, and composite plate location.

48-Advanced Material and Tooling Concept for a RTM Helicopter Fitting

Markus Henne, Manuel Müller, Gion Andrea Barandun, Paolo Ermanni and Markus Zogg,
University of Applied Sciences Rapperswil/ ETHZ, Switzerland.

The VANTEX (Vanishing textile) project combined a new type of filament made of EMS MS Grilon Phenoxy to enhance laminate toughness with the manufacture of a potential RTM component (helicopter fitting), usually done as aluminium milled part. The component is riveted onto the ground and has two interfaces to load introductions with 20’000N and 2’000N, respectively.

In preforming, phenoxy filaments are applied in woven and non-crimped fabrics, as fleece or as sewing thread. Phenoxy replaces binder material and increases the toughness of the final part. Preform structure and injection process are optimized in terms of load introduction and complete wet-out. Due to the geometry of the component, an advanced tooling concept using a mould made of Invar and aluminium, combined with temperature controlled demoulding are applied.

The so manufactured components are evaluated in terms of toughness and maximum load introduction. Experimental results show, that the toughness increases thanks to the use of the Phenoxy filament. The required static loads are exceeded by a factor 4.

	Sala Balint
10h50-12h20	**Multiphase flow I** Chair: Dr. S. Lomov, KU Leuven, Belgium
10h50	1-Void Formation During Preform Impregnation in Liquid Composite Molding Processes Caleb DeValve and Ranga Pitchumani Virginia Tech, USA
11h10	45-Analysis of Macro/Micro Voids in the Resin Transfer Molding Process Chung Hae PARK, Aurélie LEBEL, Joël BREARD, Abdelghani SAOUAB and Woo Il LEE Université Le Havre, France/Soul National, Korea
11h20	20-On wetting of fiber with a resin by capillary force Yoshizumi Fukuhara and Ichiro Ueno Tokyo University of Science, Japan
11h40	38-Three-dimensional meso-scale mapping of the fluid content in partially impregnated reinforcement textiles using high resolution magnetic resonance imaging Andreas Endruweit, Paul Glover, Kay Head and Andrew C. Long, University of Nottingham, UK

1-Void Formation During Preform Impregnation in Liquid Composite Molding Processes

Caleb DeValve and Ranga Pitchumani
Virginia Tech, USA

It is well know that air entrapment during the mold filling stage of liquid composite molding processes leads to unwanted void formation in the resulting composite. This void formation results in discontinuous material properties and failure zones which need to be eliminated or reduced for robust composite manufacturing. While void formation is among the leading causes of quality-related defects in composite manufacturing via liquid molding, an accurate prediction of local air entrapment locations during processing is limited. This study presents a detailed numerical simulation of unsaturated flow at both the macro- and micro-scale levels, specifically the coupled effects of the macro-scale flow of the advancing resin flow front around individual fiber bundles combined with the simultaneous micro-scale flow through the fiber bundles in realistic perform geometries, including stochastic variations. The primary goal is to develop a predictive paradigm for spatial variation of the location and relative size of the resulting voids for better design of liquid molding process and the products fabricated using the process. The effects of processing and perform parameters on void formation and strategies for controlling them will be presented and discussed.

45-Analysis of Macro/Micro Voids in the Resin Transfer Molding Process

Chung Hae PARK, Aurélie LEBEL, Joël BREARD, Abdelghani SAOUAB and Woo Il LEE
Université Le Havre, France/Soul National, Korea

As the cost reduction becomes a main issue in aeronautic and automobile industries, a class of LCM (Liquid Composite Molding) processes such as the RTM (Resin Transfer Molding) process and the VARTM (Vacuum Assisted Resin Transfer Molding) process, are being widely employed for the fabrication of large and complex structures. In spite of their cost effectiveness, void type defects created during the LCM processes are a primary trouble to degenerate the mechanical performances of final products.

It has been well known that the main mechanism of void formation in the RTM process is mechanical air entrapment by a non-uniform resin flow at the flow front. This non-uniform flow advancement is caused by a difference of flow conductance in the heterogeneous micro-architecture of textile reinforcements. Many experimental observations have shown that the void formation can be correlated with the capillary number. Furthermore, it has been reported that air voids created at the flow front can be compressed or swept away along the resin flow, afterwards. Hence, it is of interest to develop a model and to perform an analysis to consider all the physics: bubble formation (competition between a capillary wicking and a viscous flow) at the flow front, bubble compression and bubble transport, etc.

We propose a model to predict void contents in the macro pore between fiber tows and in micro pores inside tows (warp and weft are considered separately) by considering the micro architecture of preform. Then, the bubble compression and migration is taken into account. Based on the model, a computer code is developed and some simulation results are presented.

To validate the present model, experimental results will be compared with numerical results. In particular, we propose a real time measurement of void contents, to consider the void compression and migration as well as the void formation. We place some sensors at pre-defined positions in the mold and inject electrically conductive liquid. Then, the voltage values measured are correlated with the void contents as a function of time, considering air bubbles as non-conducting material. The simulation and experimental results show that there still remain residual voids in the mold even after the resin is impregnated through the mold. In practices, vacuum application or bleeding is favorable to reduce the void contents. The present model and simulation is useful to optimize the processing conditions for minimal void content.

20-On wetting of fiber with a resin by capillary force

Yoshizumi Fukuhara and Ichiro Ueno
Tokyo University of Science, Japan

This study accumulates the knowledge of the making process of FRP (fiber reinforced plastics) on the viewpoint of the interfacial thermo-fluid dynamics. This research aims at the development of higher function and next generation composite materials. VARTM (Vacuum Assisted Resin Transfer Moldings) is a potential method to realize low-cost processing of the composite materials. In this method, the resin is driven by a pressure difference within fiber bundles. It is indispensable to realize quite-well wetting of fibers with resin to realize higher-quality materials. The objectives of this research are to comprehensive a wetting dynamic process in the vicinity of the solid-liquid-gas interface.

In the present system, wetting of glass fiber(s) of 25 μm in diameter on silicon substrate by epoxy resin in focused, after placing the fiber(s) on the substrate, a drop of resin in settled on the fiber. The leading edge of the resin in directed by observing high-speed CCD camera. Back lighting system in employed light source is a polarized laser light of 532 nm in wavelength. We see the effect of the gas distance between the fiber and the substrate. We are controlled by placing space between the fiber and the substrate. We also focus on effect of micro- and nano-meter-scale particles suspended in the resin on the wetting process.

Fluorescence particles of 1.0 μm in diameter are suspended on the resin. ‘Coffee stain problem’ takes place near the contact line of the advancing resin. That is, tiny particles stick the macroscopic contact line and drastically change the flow behavior around the fiber. Confined resin region realizes a ‘narrow path’ of the liquid to lead larger velocity of the fluid beyond the macroscopic contact line. In the case of two fibers, we vary the distance between the fibers, and drop a single droplet on the both simultaneously. The effects of the distance between the fibers and the one between the fiber and the substrate will be introduced.

38-Three-dimensional meso-scale mapping of the fluid content in partially impregnated reinforcement textiles using high resolution magnetic resonance imaging

Andreas Endruweit, Paul Glover, Kay Head and Andrew C. Long,
University of Nottingham, UK

The manufacture of composite components involves the impregnation of a fibrous reinforcement with a liquid resin system. Fabrics with a variety of geometrical structures produced from continuous fibres by processes such as weaving, knitting or braiding, are frequently used as reinforcements. The fabric impregnation behaviour is critical for the quality of the finished component and for optimisation of the process parameters. It is characterised by the reinforcement permeability, which is determined by the fibre arrangement in the fabric structure. The permeability can be measured at the macro-scale, based on tracking of the flow front propagation. However, this implies a homogenisation of meso- and micro-scale effects, which determine the flow behaviour. Since visualisation of the fabric impregnation at the meso- and micro-scale is generally not possible using conventional means, identification of the resin distribution is in practice based on micrographic analysis of moulded and cured specimens.

High resolution Magnetic Resonance Imaging (MRI) can be used for 3D mapping of the actual fluid content in partially saturated reinforcements during impregnation. Information on the meso- and micro-scale impregnation complements macro-scale permeability data acquired by more conventional means. This can help to better understand the influence of the fabric structure on impregnating flow and gives a unique insight into the coupling of flow phenomena at different length scales, which is not possible with other methods.

In this study, experimental methods and issues are presented, and results are discussed for fabrics with different architecture.

Day 1: Monday, July 12, Afternoon	
	Auditorium
16h00-17h30	**Applications III** Chair: Dr. Paul Trudeau, Ecole Polytechnique Montreal, Canada
	Auditorium
16h00	32-A study on the effect of Joule-heating during the liquid composite molding (LCM) process and on the curing of CFRP composite laminates Nikos Athanasopoulos and Vassilis Kostopoulos, University of Patras, Greece
16h20	51-In-Mould Gel-Coating (IMGC) for Resin Transfer Moulding John Summerscales, Christopher Hoppins, Paul Anstice, Nick Brooks, Dilruk Yahathugoda, Alan Harper, Charles Wood and Mark Cooper, Uni of Plymouth, PERA, Magnum Venus, W Ball and Sons, Scott Bader, UK.
16h40	52-In-Mould Gel-Coating for Resin Infusion Processes using a Flow Medium Bharaneedharan Muralidharan and John Summerscales, University of Plymouth, UK.
17h00	55-Observations from the filling and post-filling stages of axisymmetric liquid composite moulding with flexible Jamie Timms, Quentin Govignon, Simon Bickerton and Piaras Kelly, University of Auckland, New Zealand.

32-A study on the effect of Joule-heating during the liquid composite molding (LCM) process and on the curing of CFRP composite laminates

Nikos Athanasopoulos and Vassilis Kostopoulos,
University of Patras, Greece

Manufacturing CFRP composite laminate using the liquid composite molding (LCM) process is a highly temperature-sensitive procedure. So far this problem was tackled using complex mould setups for resin heating and large ovens for laminate curing. All these procedures are costly and inefficient from an energy point of view. In the current work, a novel procedure for increasing overall efficiency of the LCM process is addressed. This novel procedure utilizes the material physical properties and one (1) simple physical phenomenon, carbon-fiber electrical conductivity and Joule-heating respectively. Being able to predict, quantify and control these parameters during the LCM process is highly beneficial.

The steps of the proposed procedure do not deviate from the classic LCM process. According to the LCM process a heat conductive mould is needed, the carbon fabric preforms are placed inside the mould and appropriate vacuum sealing materials are used. In order to increase the temperature of the preforms the whole mould has to be heated using energy expensive heating elements or large ovens. The novel approach of the current work omits the need of external mould heating as it uses the preform itself as the heating element.

Joule's first-law dictates that when electric current passes through a conductor heat is generated, this is known as Joule-effect or Joule-heating. Carbon fibers are electrically conductive with known resistivity behaviour. Applying electric current through the carbon preform makes it act as an ohmic resistor thus heat is generated. The generated heat and thus the preform temperature, is easy to control being affected only by the applied electric power. The available heat is used as the means of heating up and maintaining the liquid resin temperature, leading to reduced resin viscosity and thus promoting preform impregnation.

After the impregnation phase is completed the carbon-preform and thus the resulted composite remains electrically conductive, thus further exploitation of the Joule-effect can be obtained. Appropriate adjustment of the input parameters (electric power) leads in resin curing and post-curing procedure control. The material properties of the manufactured laminates are compared to ones conventionally manufactured. Finally, the advantages and disadvantages of the proposed procedure are addressed and further application of the procedure is discussed in the end of this work.

51-In-Mould Gel-Coating (IMGC) for Resin Transfer Moulding

John Summerscales, Christopher Hoppins, Paul Anstice, Nick Brooks, Dilruk Yahathugoda, Alan Harper, Charles Wood and Mark Cooper,
Uni of Plymouth, PERA, Magnum Venus, W Ball and Sons, Scott Bader, UK.

Fibre-reinforced polymer matrix composites find use in most transport applications, chemical plant, renewable energy systems, pipelines and a variety of other industries. Many of these applications require a separate surface finish for cosmetic and/or durability reasons. This coating, known as the gel-coat, is normally applied onto the mould tool before the structural laminate is moulded against the coating. The majority of the volatile organic components (VOC) in the coating will react during the polymer curing process, but the application process is such that some VOC will be emitted into the workplace and the environment.

A consortium funded by the UK Technology Strategy Board call Meeting the Challenge of the Zero Emission Enterprise is developing a proprietary system for In-Mould Gel Coating in the context of Resin Transfer Moulding and related processes. Gel-coated laminates have been manufactured using several process variations. The new in-mould gel-coating process has potential to improve workplace safety and reduce environmental impact during the manufacture of composite components.

The surface finish has been measured using both fractal dimension determined from digital images and Wavescan DOI. Z-direction tensile strength tests have been undertaken to establish the interfacial bond strengths.

52-In-Mould Gel-Coating for Resin Infusion Processes using a Flow Medium

Bharaneedharan Muralidharan and John Summerscales,
University of Plymouth, UK.

Fibre-reinforced polymer matrix composites find use in most transport applications, chemical plant, renewable energy systems, pipelines and a variety of other industries. Many of these applications require a separate surface finish for cosmetic and/or durability reasons. This coating, known as the gel-coat, is normally applied onto the mould tool before the structural laminate is moulded against the coating. The majority of the volatile organic components (VOC) in the coating will react during the polymer curing process, but the application process is such that some VOC will be emitted into the workplace and the environment.

A separate paper offered for this conference describes a project to develop an In-Mould Gel Coating process in the context of Resin Transfer Moulding. This paper will describe the use of the same novel concept (British Patent GB 2 432 336A) in the context of Resin Infusion under Flexible Tooling (RIFT) using a flow medium. Gel-coated laminates have been manufactured using several process variations. The new in-mould gel-coating process has potential to improve workplace safety and reduce environmental impact during the manufacture of composite components.

55-Observations from the filling and post-filling stages of axisymmetric liquid composite moulding with flexible

Jamie Timms, Quentin Govignon, Simon Bickerton and Piaras Kelly,
University of Auckland, New Zealand.

Mould rigidity is a principal point of distinction between the Liquid Composite Moulding (LCM) processes, allowing them to be placed on a spectrum extending from fully rigid moulds (Resin Transfer Moulding, Compression Resin Transfer Moulding) to fully flexible moulds (Resin Infusion, VARTM). Processes that use semi-rigid tooling, such as RTMLight, lie between the two extreme cases. Much of the additional difficulty of characterising and simulating LCM processes with partially or fully flexible tooling surfaces arises from the coupling of structural and flow behaviour caused by mould cavity thickness varying with both time and position. It is therefore essential to have an experimental setup which can monitor thickness in the spatial and temporal dimensions when characterising a process or verifying a simulation.

A stereophotogrammetry system developed at the University of Auckland uses image correlation of high frequency speckle patterns to generate full-field out of plane thickness measurements at acquisition rates up to 0.2 frames per second. This system has been used extensively in the characterisation and modelling of one dimensional rectilinear Resin Infusion as part of an experimental facility with fluid pressure, temperature and flow rate monitoring capabilities. The facility has since been expanded to cover 1D axisymmetric scenarios with partially and fully flexible upper mould components. This has been achieved with a circular mould with a rigid aluminium lower half. The upper mould half is either vacuum bagging or a polycarbonate plate depending on whether a Resin Infusion or RTMLight process is under consideration.

This paper presents the experimental observations during the filling and post-filling stages of axisymmetric Resin Infusion and RTMLight. A series of experiments using two in-plane isotropic reinforcements (chopped strand mat and continuous filament mat) and a mineral oil test fluid have been conducted with vacuum bagging and two polycarbonate plates of different stiffness as upper mould halves. Full-field thickness data is generated by the stereophotogrammetry system, along with point fluid pressure and thickness measurements. Radial and peripheral filling modes have been considered, allowing convergent and divergent flow front progressions to be compared. Although the peripheral fill mode is popular in industry because of its much faster fill times, observations from these experiments indicate that, upon the completion of filling, the part thicknesses take significantly longer to equilibrate than they do with radial filling. As such, the post-filling period is longer in peripheral filling and the differences in total cycle time are less pronounced.

Multiphase Flow 2 Chair: Dr. Gerhard Ziegmann, TU Clausthal, Germany
Sala Balint
21-Wetting process of fibrous porous media by resin in VARTM Yoshiaki Kisara and Ichiro Ueno, Tokyo University of Science, Japan
10-Microscale simulation of resin–air flow around single fibers Yasuhiro Inoue, Michihito Matsumoto, Masaki Hojo, Kazuki Ishida, Naoki Takada and Taiji Adachi Mitsubishi Electric/Tokyo University, Japan
58-Modeling Unsaturated Flow in Dual-Scale Fiber Mats of Liquid Composite Molding: Some Recent Developments Hua Tan and Krishna Pillai University of Wisconsin-Milwaukee, USA.
63-Analysis of the Saturation in Liquid Composite Molding Processes using an Essentially Non-Oscillatory (ENO) Technique Llanos Gascon, Juan A. Garcia, Francisco Chinesta, Edu Ruiz and Francois Trochu, UP Valencia, Spain/Poly Montreal, Canada.

21-Wetting process of fibrous porous media by resin in VARTM

Yoshiaki Kisara and Ichiro Ueno,
Tokyo University of Science, Japan

We study flow of resin in fibrous porous to use vacuum assisted resin transfer moldings (VARTM) system. VARTM system realize lower-cost process than other methods. We have inherent problem on VARTM, however, of the void formation in the hardened FRP. It is very important to have knowledge on wetting process in fibrous porous media to resolve the problems and to make stronger FRP with lower-cost. we focus on the flow of the resin in fibrous porous.
In the present VARTM system, fiber bundles (as a fibrous porous media) are placed on the grass mold. Peel cloth and mesh are settled on the bundles to realize a flow path of the resin. Two tubes on the plate as resin inlet and outlet. Vacuum-bag film is tightened on the whole system with sealant tape. Resin outlet is connected to vacuum pump through the resin pool. We employ epoxy resin JER 819, product of Japan Epoxy Resins Co.,Ltd, as the test fluid. A bundle of glass fiber of 50×40×0.4in length, wide, thickness, respectively, is used as a unit of fibrous porous. We examine several cases of porous media in the present study, (1)a layer of unit parallel to the mean flow direction (defined as 0°), (2)a layer of unit perpendicular to the mean flow direction(90°), (3) double layered of 0°-unit on 0°-unit, (4)double layered of 90°-unit on 0°-unit and, (5) 0°-unit on 90°-unit, and so on … Resin flows above/beneath the bundles are simultaneously observed unit two CCD camera. After each experimental view, post image processing is applied to the original image to detect the leading edge of the penetrating resin.

Brightness of the detected images observed from the bottom corresponds to the advancement of the resin penetration in the fiber bundle. Through the careful observation, it is confirmed that minimum brightness before transfering the resin corresponds to 'perfectly dried' state, and the maximum after transfering the resin corresponds to 'perfectly wet' state. In the present study, we assume a linear profile of the wet region in the direction of the bundle thickness corresponding to the relative brightness between the maximum and minimum values in the detected image. It is found that the resin does flow into the vacant region between the bundles because of the capillary effect. This results indicate that the resin would penetrate into the gap in the bundle regardless of the net direction of the pressure gradient. And it is also found that a counter flow against the direction of the net flow of the resin is always formed at the edge of the bundle. These flows result in encounter regions of the resin inside the bundle. This leads a formation of the voids in the composite material.

10-Microscale simulation of resin–air flow around single fibers

Yasuhiro Inoue, Michihito Matsumoto, Masaki Hojo, Kazuki Ishida, Naoki Takada and Taiji Adachi
Mitsubishi Electric/Tokyo University, Japan

Resin transfer molding (RTM) is anticipated to be utilized in manufacturing large scale composite parts owing to its economic viability. Since the formation of voids much reduces mechanical properties, the analysis of resin flow during RTM process is essential to assure structural integrity. Though Darcy’s law is employed with 3D permeability of fabric porous media in the present macroscopic analyses, it has been noted that woven and stitched fabrics inherently induce a dual-scale flow behavior: the inter-tow space gets rapidly saturated, while in the intra-tow micro-space, where individual fibers are bundled, saturation is more gradual.

Thus, the penetration of the resin–air interface into gaps between individual single fibers is slow enough for the capillary forces to be comparable to the pressure gradient. Therefore, the mechanism of microvoid formation is completely different from that of macrovoid formation and remains elusive.

In this study, we developed a numerical code of a multiphase fluid model that employs Navier–Stokes equation including the interfacial tension term and Cahn–Hilliard equation for capturing the resin–air interface. We performed preliminary numerical simulations of microscale resin–air flow around a regular-lattice array of four single fibers. To investigate effects of the resin–air interface on void formation, we numerically analyzed four cases in which the longitudinal (flow direction) gap between two individual fibers was the same or twice the transverse gap under two different magnitudes of interfacial tension coefficient.

From the analysis, we found that (1) Laplace pressure arisen from the finite curvature of the resin–air interface could drive a transverse flow (capillary-driven flow) penetrating into the longitudinal gap between the two fibers; (2) there was another dual time scale even at the microscale on the determination of flow patters: one was caused by the main flow, and the other by capillary driven transverse flow; (3) voids could be formed when the time scale of the main flow was shorter than that of capillary flow; (4) two modes of void formations were revealed numerically: longitudinal gaps fully capped by the resin–air interface leading to the void formation under a high interfacial tension coefficient; and a small bubble left at the back-step of the fiber under a relatively weak interfacial tension coefficient. These results give key factors for better understanding of microvoid formation and its control during molding processes.

58-Modeling Unsaturated Flow in Dual-Scale Fiber Mats of Liquid Composite Molding: Some Recent Developments

Hua Tan and Krishna Pillai
University of Wisconsin-Milwaukee, USA.

Liquid composite molding (LCM) including resin transfer molding (RTM) and vacuum-assisted RTM is a set of technologies to produce net-shaped parts from polymer-matrix composites. Unsaturated flow, characterized by a partially-saturated region behind a moving resin-front, is often witnessed during mold-filling in LCM molds when parts are made from woven or stitched (dual-scale) fiber-mats.

In this paper, the unsaturated flow is modeled as a coupled, two-scale flow at the gap (inter-tow) and tow (intra-tow) levels. The simulation is based on the macroscopic flow model proposed earlier by Pillai et al. using the rigorous volume-averaging method and is marked by sink and source terms in the gap-level mass, temperature and cure equations. The simpler, isothermal mold-filling is tackled using two different approaches: 1) A faster, 'lumped' algorithm is proposed to estimate the mass sink term using a sink function developed from the tow impregnation simulation in a unit cell. 2) A more accurate, multiscale algorithm is proposed to couple the gap-level flow with the microscopic, tow-level flow. (A coarse global mesh is used to solve the global gap flow over the entire domain, and a fine local mesh in form of the unit-cell of periodic fabrics is employed to solve the local tow-impregnation so as to compute sink terms required for solving the gap flow.) The algorithms are implemented in our in-house code PORE-FLOW©, a simulation tool for the mold-filling type flows. The inlet-pressure history, and the partially-saturated regions predicted by the proposed models are compared with the experimental measurements for 1-D flow. Fairly good comparisons between predictions of the two models and experiments are achieved without the use of any fitting parameters. Later the multiscale algorithm is extended to solve the unsaturated flow under non-isothermal, reactive conditions and an example of LCM mold-filling simulation is presented.

63-Analysis of the Saturation in Liquid Composite Molding Processes using an Essentially Non-Oscillatory (ENO) Technique

Llanos Gascon, Juan A. Garcia, Francisco Chinesta, Edu Ruiz and Francois Trochu,
UP Valencia, Spain/Poly Montreal, Canada

In the manufacturing of composite parts by Liquid Composite Molding process (LCM), complete saturation of the fibrous reinforcement is key. Incomplete saturation leads to voids within the fibers which cause failure of the final product. Thus, understanding of the formation of voids is necessary for proper molding. In order to analyze the formation of voids during the resin impregnation process, a one-dimensional solution based on two-phase flow through a porous medium, is proposed. This model leads to the introduction of relative permeability as a function of saturation and a modified equation for the saturation as a non-linear advection-diffusion equation with viscous and capillary phenomena, which depends on a number of factors. A detailed analysis is performed to assess the relative significance of the various input parameters on the saturation profiles. In order to numerically solve the modified saturation equation for the LCM process a high order essentially non-oscillatory (ENO) technique is proposed. The implemented algorithm allows a numerical optimization of the injected flow rate, which minimizes the micro/macroscopic void formation during mold filling. Some numerical results are presented and compared with the results taken from literature in order to validate the proposed mathematical model and the numerical scheme.

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17h45-18h45	**Applications IV** Chair: Dr. C. Fischer, Alcan Innovation Cell, CH
17h45	89- Characterization, analysis and computer aided process design for resin transfer molding, Edouardo Ruiz, Vincent Achim and Francois LeBel Ecole Polytechnique de Montreal Canada
18h05	3-A comparison between numerical simulation and experimental study for a plate infusion test carried out by Liquid Resin Infusion process under industrial conditions Peng Wang, Sylvain Drapier, Jérôme Molimard, Alain Vautrin and Jean-Christophe Minni, Ecole des Mines de St Etienne/Hexcel corporation, France
18h25	90-Experimental analysis of flexible injection for curved composite parts Philippe Causse, Edu Ruiz and François Trochu École Polytechnique de Montréal, Canada

89- Characterization, analysis and computer aided process design for resin transfer molding,

Edouardo Ruiz, Vincent Achim and Francois LeBel

Ecole Polytechnique de Montreal Canada

Resin Transfer Molding (RTM) is a widely used manufacturing technique of composite parts. It involves several complex phenomena such as resin flow, fiber impregnation, resin cure, thermal and rheological variations, etc. The combination of these phenomena makes RTM manufacturing very sensitive to the processing parameters, often leading to non-optimal and sometimes inappropriate definitions of processing parameters. Selecting adequate manufacturing conditions (i.e., injection temperature and pressure or resin formulation) becomes then a tricky decision based more on user's knowledge and experience rather than on a systematic and rigorous procedure. In this study, a numerical approach is proposed for assisting process engineers in selecting proper molding parameters. The software intends to support manufacturing specialists in reducing process development time while improving the robustness of composite manufacturing. The software is also combined with a new data acquisition system allowing quick identification of key material properties. The data acquisition unit developed on this work is controlled on-line through web based software allowing remote characterization of cure and thermal conductivity of the resin, fibers and mold. To demonstrate the capabilities of the proposed approach, an application example is implemented for an industrial part.

3-A comparison between numerical simulation and experimental study for a plate infusion test carried out by Liquid Resin Infusion process under industrial conditions

Peng Wang, Sylvain Drapier, Jérôme Molimard, Alain Vautrin and Jean-Christophe Minni,

Ecole des Mines de St Etienne/Hexcel corporation, France

Liquid Resin Infusion (LRI) processes are promising manufacturing routes to produce large, thick or complex structural parts. They are based on the resin flow induced across its thickness by pressure applied onto a preform / resin stacking. However, both thickness and fibre volume fraction of the final piece are not well controlled since they result from complex mechanisms which drive the transient mechanical equilibria leading to the final geometrical configuration. In order to optimize both design and manufacturing parameters, but also to monitor the LRI process, an isothermal numerical model has been developed which describes the mechanical interaction between the deformations of the porous medium and the resin flow during infusion [1,2]. With this 3D numerical model, it is possible to investigate the LRI process with classical industrial piece shapes. To validate the numerical model, first in 2D, and to improve the knowledge of the LRI process, the present study details a comparison between numerical simulations and an experimental study of a plate infusion test carried out by LRI process under industrial conditions. From the numerical prediction, the filling time, the resin mass and the thickness of the preform can be determined. On another hand, the resin flow and the preform response can be monitored by experimental methods during the filling stage. One key issue of this research work is to highlight the major process parameters changes during the resin infusion stage, such as the preform and resin temperature, the variations of both thickness and fiber volume fraction of the preform. Moreover, these two approaches are both good ways to explore and improve our knowledge on the resin infusion processes, and finally, to develop simulation tools for the design of advanced composite parts.

90-Experimental analysis of flexible injection for curved composite parts

Philippe Causse, Edu Ruiz and François Trochu
École Polytechnique de Montréal, Canada

Flexible Injection (FI) is a new Liquid Composite Molding (LCM) process for the manufacture of high performance composites, which consists of injecting a thermosetting resin through a fibrous reinforcement contained in the lower chamber of a double cavity mold. Resin is injected in the lower cavity, which is sealed by a membrane, after which a compaction fluid is injected in the upper chamber to compress the reinforcement. This new composite manufacturing technique, which allows a limited and controlled deformation of the membrane during processing, was shown to be very effective in reducing filling times in the case of planar or slightly curved geometries. In the present study, flexible injection is applied to strongly curved parts, namely here a composite rectangular panel with two 90 degrees corners. After setting up an experimental procedure to produce the stair-shaped components out of fiberglass and vinylester resin, the analysis of longitudinal cross-sections of the parts have shown that the curvature significantly changes the lay-up quality. While flat sections consolidate adequately to nearly uniform thickness, corners of the parts are likely to exhibit manufacturing defaults. Actually two types of defects have been observed: firstly, resin-rich zones are created when the fibrous preform does not match perfectly the shape of the tool. In addition, the corners of the part may exhibit thickness gradients. Preliminary results indicate that such defects could be reduced by an appropriate preforming strategy. Finally, the study demonstrates the key role of preforming to ensure successful manufacturing by flexible injection of complex composite structures.

17h45-18h45	**Advanced measuring methods** Chair: Dr J. Summerscales, University of Plymouth
17h45	18-Comparing flow-front propagation sensed by FBGs with PAM-RTM simulation Johannes Balvers, Harald Bersee and Adriaan Beukers, TU Delft, Netherlands
18h05	97-Vacuum infusion processing of composites with integrated damping elements Véronique Michaud, Antoine Sigg, Rui de Oliveira, and Jan-Anders E. Månson Ecole Polytechnique Fédérale de Lausanne, Switzerland
18h25	76-X-ray microtomography and pull-out test to characterise fibre-fibre contacts in short fibre-reinforced composites during their processing Olivier Guiraud, Laurent Orgéas, Pierre Dumont and Denis Favier University of Grenoble, France

18-Comparing flow-front propagation sensed by FBGs with PAM-RTM simulation

Johannes Balvers, Harald Bersee and Adriaan Beukers,
TU Delft, Netherlands

This study is part of a larger project, in which the potential of fibre Bragg grating sensors for monitoring liquid composite moulding processes is deeper investigated. In an earlier study, experimental data was obtained for preform compaction and flow-front propagation [1]. By then, the question arose whether Bragg response could be related to process parameters such as pressure. In that sense, a study was started that had the main objective to relate the Bragg response to simulation results from PAM-RTM. As an intermediate step, the Bragg responses were compared to the local change in preform thickness measured by a three-dimensional contactless and full-field measuring technique. Process points such as resin arrival, increase in pressure, and inlet closing were identified. Establishing a relation was however difficult. For the simulations, it turned out that, although several models were developed describing material characteristics, a 'dry-wet compressibility model' was certainly needed to address the lubrication effect causing compaction of the preform just after resin arrival. This part was therefore left for future work.

1. J.M. Balvers, H.E.N. Bersee, A. Beukers, "Integration of Fiber Bragg Gratings in Woven Fabrics: Influences of Preform Compaction and Flow-Front Propagation", Proc. of the 9th International Conference on Flow Processes in Composite Materials (FPCM-9), Montreal, Canada, 2008

97-Vacuum infusion processing of composites with integrated damping elements

Véronique Michaud, Antoine Sigg, Rui de Oliveira, and Jan-Anders E. Månson

Ecole Polytechnique Fédérale de Lausanne, Switzerland

NiTi alloy wires were embedded during the infusion processing of woven carbon fibre reinforced plastic (CFRP) composite plates with the purpose to passively increase their damping. Two types of NiTi wires, having the same diameter of 203 μm, were considered, a superelastic at room temperature, the other one martensitic. For the first wire type, a martensitic transformation was induced by applying a pre-strain of 2.5% before embedding the wires. A metallic mould with a frame was designed for shape memory alloys (SMA) wire placement and pre-straining during infusion process. The internal stress build-up during cure and post-cure of composite and the impact on the cure progress of the presence of SMA wires was evaluated using optical fibre Bragg gratings (FBG) sensors.

76-X-ray microtomography and pull-out test to characterise fibre-fibre contacts in short fibre-reinforced composites during their processing

Olivier Guiraud, Laurent Orgéas, Pierre Dumont and Denis Favier

University of Grenoble, France

Polymeric composite materials reinforced by short glass fibres such as the Sheet Moulding Compounds (SMC) and the Glass Mat Thermoplastics (GMT) are widely used by the automotive industry. Their fibre content (volume fraction comprised between 5% and 20%) is so high that each fibre or each fibre bundle has multiple contact points with its neighbours. During the processing of these materials, often carried out by compression moulding, the interaction mechanisms at the contact points have a very large influence on the rheological behaviour of such kind of very concentrated fibrous suspensions. They are accounted for by most of the rheological models based on a micromechanical approach [1-5]. In order to investigate the micro-mechanisms of the fibre-fibre or bundle-bundle contacts, several authors performed pull-out tests of fibres or bundles in the cases of GMT's [2] or Carbon Mat Thermoplastics (CMT) [6]. These studies were quite comprehensive, but the set of tested fibrous microstructures was limited due to the industrial origins of the tested fibrous reinforcement mats. Furthermore, the influence of a confining stress, which is nonetheless applied on the suspensions during their processing, was not studied. Finally, strong assumptions were a priori made on the fibrous microstructure in order to establish the micro-mechanical models of contacts.
Thus, the objective of this study is to complete previous rheological studies [2,6] using model fibrous concentrated polymeric suspensions. Their microstructures are controlled and mimic that of industrial composites: the fibrous reinforcement is a network where fibres are highly connected. An analysis of the considered microstructures was performed by using X-ray microtomography volumes, showing (i) that corresponding fibrous networks exhibited planar orientation and (ii) that the number of fibre-fibre contacts per fibre was well predicted by the statistical tube model. Pull-out tests were performed in order to emphasise the strong influence of the volume fraction of fibres, the extraction velocity and length, as well as the confining stress on the pull-out forces. Obtained results by these two techniques allow a fibre-fibre interaction model to be established.

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	Day 2: Tuesday, July 13, Morning
8h00-8h10	***Announcements of Day 2***
8h10-8h55	**Keynote lecture 2, Dr. Andrew Long, University of Nottingham, UK** "Prediction, measurement and significance of reinforcement permeability" Chair: Dr P. Ermanni, ETHZ, CH
	Auditorium
9h00-10h30	**Permeability measurement I** Chair: Dr P. Ermanni, ETHZ, CH
9h00	59-A Reference Porous Medium made by Rapid Prototyping as a Calibration Tool for Permeability Measuring Devices Reza Masoodi, Andrew Vechart and Krishna Pillai University of Wisconsin-Milwaukee, USA
9h20	71-Evaluation of Resin Impregnation Process in Textile Fabrics Asami Nakai, Yuki Kadoma and Shinji Ogihara, Kyoto Institute of Technology/Tokyo University of Science, Japan
9h40	84-An Optically Based Inverse Method to Measure In-plane Permeability Fields, Simon Bickerton, Jia Ming Gan, Fan Zhang, Benoit B. Cosson, Sebastien Comas-Cardona and Christophe Binetruy, Ecole des Mines de Douai, France/University of Auckland, New Zealand.
10h	86-Experimental and numerical analysis of the deformation of a woven composite reinforcement. Consequences on the permeability Quang-Thanh Nguyen, Emmanuelle Vidal-Salle, Philippe Boisse, Joel Bréard and Bertrand Laine, INSA Lyon/Université du Havre/ONERA, France

Keynote lecture 2:

Prediction, measurement and significance of reinforcement permeability

Prof Andrew Long Associate Dean for Research Faculty of Engineering University of Nottingham

Reinforcement permeability data are critical for accurate simulation of liquid moulding processes. Extensive studies have addressed experimental measurement over the last 25 years, and over a similar period models of increasing sophistication and predictive capability have been proposed for a range of material forms. Despite these extensive, collective efforts, today there are no accepted standard techniques for measurement of reinforcement permeability, with data from different laboratories varying significantly for the same material. Models are able to predict trends in permeability data – effects of fibre volume fraction, compaction, shear for example, but generally predicted values are not particularly close to experimental data. These two issues are almost certainly related: modelers cannot be sure that they have valid experimental data for validation, whilst the validity of assumptions inherent in models (uniform textile geometry, idealized flow conditions etc) may indicate some of the difficulties in obtaining reliable experimental data. Variability in both measured (repeated experiments) and predicted (stochastic analysis) data have recently been recognized as key issues, promising the ability to predict manufacturing process variations, probability of defects and hence optimal process parameters. In this presentation recent efforts related to permeability prediction and measurement will be described, and their significance to real manufacturing processes will be discussed.

59-A Reference Porous Medium made by Rapid Prototyping as a Calibration Tool for Permeability Measuring Devices

Reza Masoodi, Andrew Vechart and Krishna Pillai
University of Wisconsin-Milwaukee, USA

Permeability is a very important parameter for mold-filling simulation of liquid composite molding (LCM) processes including resin transfer molding (RTM) and vacuum-assisted RTM. A lack of proper calibration of permeability measuring devices leads to a great uncertainty about the accuracy of reported permeability measurements—often different permeability values for the same fiber mat are reported by different research groups as well as different devices. This problem can be mitigated to some extent if a reference medium, a porous material of known permeability, can be used in the permeability measuring setups for their calibration.

In this presentation, a reference porous medium made from the rapid prototyping method for use in both the 1-D and radial flow based permeability measurement setups was evaluated. A numerical simulation in the unit-cell of the reference medium using Fluent established the theoretical permeability of the medium along the two in-plane directions. Steady-state as well as transient experiments were conducted to evaluate the performance of the reference medium where the principal permeabilities of the reference medium were measured. A good match of the measured and theoretical permeability values, achieved for both the 1-D and radial flow setups, testified to the usefulness of the reference medium for calibration.

71-Evaluation of Resin Impregnation Process in Textile Fabrics

Asami Nakai, Yuki Kadoma and Shinji Ogihara,
Kyoto Institute of Technology/Tokyo University of Science, Japan

Currently, the improvement of the molding process of Fiber reinforced plastic (FRP) and low-cost molding technology are investigated. There is a process which curing after thermoset resin impregnate to dry fabric. This process is called Liquid composite molding (LCM). The permeability is important parameters used especially in the LCM processes such as Resin Transfer Molding (RTM). The permeability is changed by materials, surface treatment and structure. Therefore, it is important that measure the permeability under many condition. In this study, some different condition that materials, surface treatment and structure were investigated.

For material, carbon fiber, glass fiber and natural fiber were used. These fibers were based for textile fabrics in generally. For surface treatment, glass woven fabrics with different silane coupling agent were used. One is the acryl silane agent and the other one is epoxy silane agent. For structure, three types of fabrics were used such as woven fabric, multi axial warp knitted fabric and three dimensional hollow knitted fabric.

A multi axial warp knit fabric, a kind of textile that is knit to fix unidirectional fiber bundles that are aligned at some angle by warp-knitting technology. These fiber bundles perform better mechanically than do the no-climp fiber bundles of general textile composites. The fabric can be treated as one layer, reducing stacking and hence fabrication costs. Moreover, hybrid composites can be fabricated by introducing two or more reinforcements. In this study, natural fiber and grass fiber were used for reinforcement.
Three-dimensional hollow knitted fabric is consisted of two surface knitted fabrics, which are knitted simultaneously. And at the same time two knitted fabric are conected by the pile yarn. Therefore, three-dimensional hollow structure in which the top and bottom skin layers are interconnected is achieved.
The purpose is to measure the permeability using these materials.

84-An Optically Based Inverse Method to Measure In-plane Permeability Fields,

Simon Bickerton, Jia Ming Gan, Fan Zhang, Benoit B. Cosson, Sebastien Comas-Cardona and Christophe Binetruy,
Ecole des Mines de Douai, France/University of Auckland, New Zealand.

The manufacturing of composite materials is influenced by variability in the constituent materials. Processing methods involving significant resin flow through the fibre reinforcement, for example the Liquid Composite Moulding techniques, are affected strongly by variability in the reinforcement structure. Local variations in fibre content and orientation lead to variation in permeability and through-thickness compaction response. Significant in-plane variability has been shown to exist within a single reinforcement layer, and the influence of this variability can possibly be amplified as multiple layer preforms are assembled. The effects of these property variations are then demonstrated by increased spread in mould filling times, part thickness, and forces exerted on tooling.

This paper is focused on variability within a single layer of reinforcement, considering physical realisations of the areal weight and permeability fields. A major goal of this research is to develop efficient techniques to experimentally quantify these fields, which are coupled, and require independent measurements. A technique has been developed to experimentally measure the areal weight field within samples of an isotropic chopped strand mat. This procedure utilises optical images of light transmission through a sample of reinforcement. Constant flow rate radial injection is carried out within the characterised samples, with detailed flow front information being recorded via image data acquisition. Recorded injection pressure and flow front data are employed within a numerically based inverse method, which solves for the unknown in-plane permeability field. The current work is focused on isotropic materials, but the method will be adapted to anisotropic media. The major advantage of these techniques will be fast acquisition of statistical data on reinforcement variability, which can be utilised in stochastic based process simulations.

86-Experimental and numerical analysis of the deformation of a woven composite reinforcement. Consequences on the permeability

Quang-Thanh Nguyen, Emmanuelle Vidal-Salle, Philippe Boisse, Joel Bréard and Bertrand Laine,
INSA Lyon/Université du Havre/ONERA, France

The trend in the industry nowadays is to produce larger and larger as well as more and more geometrically complex composite parts. Introduction of the resin in the fibrous reinforcement by LCM (Liquid Composite Moulding) techniques is increasingly used. The simulation of this injection step is of prime importance in order to ensure the quality of the so-produced part. To do so, it is necessary to take into account the influence of local deformations (shear, compression and nesting) of the fibrous reinforcement on its permeability in the simulation. This work presents a numerical tool which has been developed in order to predict the influence of each individual deformation on reinforcement permeability. Our tool uses 3D REV (Representative Elementary Volume) description which is eventually deformed and meshed. Stokes and Brinkman equations are then solved on this mesh together with adequate boundary conditions in order to determine the permeability by classical homogenization techniques. An analytical model based on weaving parameters is proposed and shows very good correlation with 3D model. This model takes into account shearing, nesting and compression effects to a certain extend. Influence of shear, compression and nesting has been assessed for two woven fabrics as well as the influence of the geometrical model used. These models allow to reduce the quantity of experiments needed to fully characterize a fibrous reinforcement.

	Auditorium
10h50-12h20	**Permeability measurement II** Chair: Dr C. Binetruy, Ecole des Mines de Douai (F)
10h50	2-Validation of flexible permeability characterization methods in numerical simulation of resin Infusion processes Enrique Díaz, Concha Sanz and Juan Antonio García, AIMPLAS/UP Valencia, Spain
11h10	23-Correlation of permeability values with flow channel diameters determined by 3D-image analysis of a woven textile Gunnar Rieber and Peter Mitschang, University of Kaiserslautern, Germany
11h20	34-Comparison and Evaluation of Two Different Permeability Measurement Methods for Fibre Reinforcement Materials Mathias Wietgrefe, Véronique Michaud ,Jose Pariona Lartiga, Konstantin Schubert and Michael Sinapius DLR, Germany/EPFL, Switzerland
11h40	57-Gerd Morren, Hugo Sol and Sven Bossuyt. Permeability measurement of a reference specimen using an inverse method VLB, Belgium/Uni Helsinki, Finland

2-Validation of flexible permeability characterization methods in numerical simulation of resin Infusion processes

Enrique Díaz, Concha Sanz and Juan Antonio García,
AIMPLAS/UP Valencia, Spain

Day by day, Liquid Composite Moulding (LCM) processes are gaining importance in the composites industry. In particular, Infusion processes, in which the resin impregnates the reinforcement due to a gradient of pressure between the vacuum in the cavity and the resin outside the mould, have found a wide range of application in the production of large parts, such as hulks and windmill blades. In this type of process, the development of a virtual prototype of the mould is the most cost – effective approach in order to optimize the design and setting up of the process for a new serial manufacturing(1) . In the present work, a specific method for permeability measurement of reinforcement and sandwich laminates generally employed in the infusion process is detailed. The method explained shows advantages compared to the traditional ones(2). On one hand, the permeability is determined in similar conditions to the infusion process, so a pseudo-permeability or flexible permeability(3) is obtained, which can be used directly in finite element methods to describe the flow of the resin inside the flexible mould without other considerations, such as the variation of the porosity of the reinforcement due to the variation of thickness of the cavity of the mould(4). On the other hand, the experimental set up allows the characterization of flexible permeability for different radius of the mould, what permits to relate the effect of such deformation of the reinforcement to the flexible permeability. Finally, several simulations of the filling stage of an Infusion mould are carried out in this work. By means of them is possible to analyse the accuracy of the presented solution, comparing the simulated flow pattern of the resin, versus its real behaviour.

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23-Correlation of permeability values with flow channel diameters determined by 3D-image analysis of a woven textile

Gunnar Rieber and Peter Mitschang, Oliver Wirjadi
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Attempts to model and to better understand permeability by studying the build-up of textiles are widespread [1-3]. Yet, textile structure data are rarely based on quantitative analysis of high resolution 3D-images of the composite structure at multiple fiber volume fractions.

Within the present study, micro-computer tomography (μCT) images of glass twill weave reinforced epoxy are analyzed. After subtracting the fibers from the images, the geometry of the matrix space, below-named pore space, is analyzed by a process called spherical granulometry. It was possible to directly calculate the permeability with theses pore diameters using a combination of the Darcy and Hagen-Poiseuille formulae: the permeability value K is proportional to the squared diameter ($d^2/96$) of the flow channel. As permeability-dominating pore diameters the 10 %-, 25 %- and 40 %-quantiles of the cumulative pore volume have been determined for fiber volume fractions from 40 % to 56 %. The calculated results are in accordance with global permeability values determined by 2D and 3D permeability measurements.

34-Comparison and Evaluation of Two Different Permeability Measurement Methods for Fibre Reinforcement Materials

Mathias Wietgrefe, Véronique Michaud ,Jose Pariona Lartiga, Konstantin Schubert and Michael Sinapius
DLR, Germany/EPFL, Switzerland

The permeability of fibre reinforcement materials is one of the main material input parameter for macroscopic flow simulation in Liquid Composite Moulding. In spite of the importance of this property there is no standardized measurement method. A previous permeability benchmark has shown a high dispersion between the measurements, even though all measurements are based on Darcy´s Law which describes the flow of a fluid through a porous medium. The study presented in the paper compares two different test setups with (i) 1-D resin flow and (ii) 2-D resin flow to point out the boundary conditions that have to be respected for a reliable and reproducible permeability measurement. The viscosity of the test fluid is a possible major source of error which is minimized by using a viscosity standard fluid for the measurements. Further boundary conditions are fibre volume content, temperature, textile lay-up, volume flow, and injection pressure respectively. This study describes difficulties and limitations of each type of measurement and wishes to contribute to a normalization process.

57-Gerd Morren, Hugo Sol and Sven Bossuyt. Permeability measurement of a reference specimen using an inverse method
VLB, Belgium/Uni Helsinki, Finland

The simulation of a resin flow through a porous medium by FE models has become a very important aspect for the design of a high-performance RTM produced composite part. The key parameters to perform RTM flow simulations are the permeability values of the fibre reinforcement. The measurement of this material parameter is still not standardized and many different set-ups have been proposed. This paper presents a textile-like solid specimen with anisotropic permeability that is produced with a stereolithography technique. It is designed as a reference for calibration and comparison of permeability measurement set-ups and for validation of numerical permeability computation software [1, 2]. Unlike real textiles, the permeability properties of such reference specimens do not vary from test to test. Excellent repeatability of the experiments is achieved. When used for benchmarking, any discrepancy between different measurements on this specimen must be attributed to the set-up and data processing.

This article also describes an inverse method for permeability identification. The proposed method is a so-called mixed numerical/experimental technique (MNET) for material property identification. In this iterative inverse technique an experimental observation on a highly automated central injection rig, called “PIERS set-up” (Permeability Identification using Electrical Resistance Sensors), is compared with a computed observation using a numerical model that simulates exactly the same experiment. In this model the permeability values will appear as parameters which will be iteratively tuned in such a way that the computed observation matches the experiment [3].

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[3] Morren G, Bossuyt S, Sol H. 2D permeability tensor identification of fibrous reinforcements for RTM using an inverse method. Composites Part A 2008; 39A(9): 1530-1536.

	Sala Balint
10h50-12h20	**Textile compaction** Chair: Dr. K.Pillai, University of Wisconsin, USA
10h50	81-Fast X-Ray microtomography for the in situ analysis of the compression of a saturated fibre bundle, Pierre LATIL, Laurent ORGEAS, Christian GEINDREAU, Sabine ROLLAND DU ROSCOAT and Pierre DUMONT Université de Grenoble, France
11h10	40-Deviation from Darcy's Law during the Post-filling Stage of Resin Infusion Quentin Govignon, Jamie Timms, Simon Bickerton and Piaras A. Kelly University of Auckland, New Zealand
11h20	79-Jonathan Cheng, Piaras Kelly and Simon Bickerton. A Thermomechanical Constitutive Model for the Compaction Response of Fibrous Reinforcements University of Auckland, New Zealand
11h40	47-Influence of the Compaction Speed on the Transverse Continuous Permeability Pierre Ouagne and Joel Breard, Polytech Orléans/Université du Havre, France

81-Fast X-Ray microtomography for the in situ analysis of the compression of a saturated fibre bundle,

Pierre LATIL, Laurent ORGEAS, Christian GEINDREAU, Sabine ROLLAND DU ROSCOAT and Pierre DUMONT
Université de Grenoble, France

Many fibrous reinforcements which are used in polymer composites are made up of continuous or discontinuous fibre bundles. During the processing of these materials, fibre bundles are usually subjected to very high deformations that arise at the mesoscopic/bundle scale (e.g. the shearing of a woven textile during its stamping, or the bending of the short fibre bundles during the compression of GMT's or SMC's), but also at the microscopic/fibre scale (e.g. the relative motions and the bending of fibres within a bundle during its deformation). Such deformation mechanisms drastically affect the rheological behaviour of the composites during processing (e.g. by modifying the permeability and the anisotropy of the fibrous reinforcements), but also the final physical and mechanical properties of produced parts. Unfortunately, they are often complex and still not very well understood. For example, if deformations mechanisms at the bundle scale have already been studied experimentally for various fibrous reinforcements and various processing routes, much less is known on the micro-deformation mechanisms within a fibre bundle during a given mechanical loading.

Within this context, this study provides original experimental data concerning the evolution of the fibrous microstructure during the deformation of a saturated fibre bundle. For that purpose, a model fibre bundle was processed. It consisted of approximately 100 aligned fibres (diameter 150 μm, length 15 mm), which were extracted from a fluorocarbon fishing wire. The fibres were saturated with olive oil, which behaves as a Newtonian fluid at room temperature and which is solid at 5°C (allowing the freezing of the processed fibrous microstructure and thus an easy sample manipulation before mechanical testing at room temperature). The model fibre bundle was subjected to a simple compression at a low strain rate. This was achieved with a specially designed micro-compression machine (maximum axial load 500N) which was mounted on the ID19 beam line of the European Synchrotron Radiation Facilities (ESRF). Hence, 3D images of the evolving fibrous microstructure could be obtained during the compression by performing X-ray microtomography. In order to limit the scanning time and to perform quasi in situ observations, the Fast X-Ray microtomography was used, allowing a very fast scanning times below 2 minutes. After suitable filtering operations, results first show that the bundle was subjected to a consolidation which was accompanied with liquid phase migration, such a deformation mechanism being increased as stress levels were increased. Secondly, (i) the position, the mean orientation, the motion and the deformation of each fibre together with (ii) the position and the evolution of each fibre-fibre contact could be captured during the compression. The evolution of these microstructure descriptors permit a better analysis of consolidation mechanisms and provide useful informations for theoretical or numerical models dedicated to the micro-mechanics of fibre bundles during the processing fibre bundle reinforced polymer composites.

40-Deviation from Darcy's Law during the Post-filling Stage of Resin Infusion

Quentin Govignon, Jamie Timms, Simon Bickerton and Piaras A. Kelly
University of Auckland, New Zealand

In 1856, Henry Darcy published 'Les Fontaines Publiques de la Ville de Dijon' dealing with the creation of a pressurised drinking water distribution system in the town of Dijon (France). In this book appeared what was to be known as Darcy's law, which described the flow of water through layers of sand. The equation relates the flow rate to the pressure gradient using the fluid viscosity and the permeability of the porous media. This empirical law was then extended to other fluids and porous media and was later theoretically derived from the Stokes equations. Darcy's law has been proven to be only valid for flow with a low Reynolds number and for Newtonian fluids. In other situations, modifications to the relation need to be applied.

The Liquid Composite Moulding (LCM) family of processes involve the saturating flow of a liquid resin through a porous media formed by fibre reinforcements. With regards numerical modelling of LCM processes, given the properties of the resin and reinforcements employed, as well as the processing parameters, Darcy's law is usually employed to calculate the flow of resin through a mould cavity. However, during recent experimental studies of the resin infusion process (a.k.a. VARTM), two phenomenon were observed deviating from the expected flow predicted by Darcy's law.

Firstly, the decay of local resin pressures and laminate thicknesses observed during the post-filling stage were slower than one would expect using a Darcy’s law based simulation considering only in-plane flow. A proposed explanation could be the existence of a significant through-thickness flow caused by the compaction of the saturated porous reinforcement. As through-thickness permeability of fibrous reinforcement is typically an order of magnitude lower than in-plane values, a requirement for through-thickness flow could therefore explain the slower than expected decay in pressure and laminate thickness. An experimental investigation into the existence of through-thickness flow during the post-filling stage of a rectilinear infusion will be presented in this paper.

It was also noted that a resin pressure gradient from inlet to vent remains at the end of the process when effectively all flow has ceased. The existence of a pressure gradient in the absence of flow is contradicting Darcy's law and would imply that there is a lower limit (with regards local flow rate) to the domain of application of Darcy's law. In this paper, a modified version of Darcy's law introducing a threshold pressure gradient will be presented. Experimental determination of this threshold pressure gradient as a function of the permeability of the porous medium and of the fluid viscosity will also be presented.
This paper focuses on presenting experimental evidence of these two effects, and their interaction. A range of fluids and reinforcements will be used to determine the magnitude of these effects and their implication on the development of simulations for the resin infusion process.

79-Jonathan Cheng, Piaras Kelly and Simon Bickerton. A Thermomechanical Constitutive Model for the Compaction Response of Fibrous Reinforcements
University of Auckland, New Zealand

The through-thickness compaction of a fibrous reinforcement preform, typically present within Liquid Composite Moulding processes, is considered. Liquid Composite Moulding (LCM) processes involve the impregnation of a porous reinforcement preform, typically composed of glass, carbon or aramid fibres, with a polymeric resin. A common theme among these processes is that the preform is subjected to load that is transferred through a mold, before resin is forced through the preform. An important precursor to accurate simulation of LCM processes is an accurate model for the constitutive response of fibrous reinforcements. In rigid mold processes, such as Resin Transfer Molding (RTM), knowledge of the constitutive behaviour of the fibrous reinforcement is critical in the prediction of tooling forces on which process parameter choices and tooling designs may be based. In LCM processes which utilise flexible molds, such as RTM-Light or Vacuum Assisted Resin Infusion, the preform and mold deformation are intrinsically coupled to the compaction stress and neither can be determined accurately without knowledge of the constitutive response of the fibrous preform. The constitutive behaviour of the preform greatly affects the tolerances achievable with flexible mold processes and hence their viability as cost-effective alternatives to rigid mold processes. Significant mold and preform deformations still occur after the initial compaction, as a result of resin flow and the inelastic behaviour of the preform. Resin flow initially relieves the preform of compaction stress, but the preform may become reloaded as the resin continues to flow during the post-filling time. For this reason one requires constitutive models which account for several cycles of loading and not simply the initial compaction. A constitutive model for the response of fibrous reinforcements to compaction, developed using a thermomechanical approach, is presented. The model employs two internal variables to produce the inelastic compaction response with rate-independent and rate-dependent components that is characteristic of fibrous preforms. In particular, significant inelastic deformation remains after a compaction cycle and the material exhibits a softened response with successive loads, with a significant dependence on the compaction rate and time between successive cycles.

47-Influence of the Compaction Speed on the Transverse Continuous Permeability

Pierre Ouagne and Joel Breard,
Polytech Orléans/Université du Havre, France

The manufacturing of large composite parts in the field of aeronautics is increasingly important. LCM processes (Liquid Composite Molding) such as Resin Film Infusion RFI are currently used. During the RFI process, the resin flows through the fibrous medium under the stress created by a flexible membrane in the transverse direction of the reinforcement's plane. The compaction of the preforms and the flow of resin through the fibrous network take place simultaneously. There is, therefore, a coupled loading of the porous reinforcements. In order to better control this process, it is necessary to optimize resin pressure and fabric compression by using the appropriate simulating tools. The transverse permeability of the fabric is a key parameter to model the process and it has to be evaluated experimentally. By using a device set up to impose transverse Hydro-Mechanical loadings to fibrous preforms, Ouagne and Bréard [1] showed that a continuous technique to measure the transverse permeability in a single experiment could be used if a slow compression speed (0.5 mm/min) is applied. A time reduction of about 8-10 is observed in comparison to the "classical method". In processes such as RFI, the compression speed of the reinforcement is not constant. Ouagne et al. [2] showed that the expected compression speed of the glass satin weave fabric submitted to an applied transverse load is situated in a range 12-0.15 mm/min. Under such compression speeds, the transverse permeability values of the fabrics differ to the one measured under low compression speed. For a glass satin weave, a decrease in continuous transverse permeability is observed as a function of the increasing compression speed in the range 0.5- 5 mm/min. This work proposes to experimentally show the influence of the compression speed on the transverse continuous permeability values for a panel of different architecture reinforcement materials with the goal to improve the accuracy of the values used in such conditions to model processes such as RFI.

[1] Ouagne P, Bréard J. Continuous transverse permeability of fibrous media. Composites: Part A (2009), doi:10.1016/j.compositesa.2009.07.008

[2] Ouagne, P. Bréard, J. Ouahbi, T. Park, C.H. Saouab, A. Chatel, S. Hydromechanical loading and compressibility of fibrous reinforcements. The 10th International ESAFORM Conference on Material Forming, Lyon, France, April 2008.

	Day 2: Tuesday July 13, afternoon
	Auditorium
15h00-16h00	**Round Table on permeability measurement** Chair: Dr B.Laine, ONERA, F Co-chairs: S. Lomov, KULeuven, B, and Dr E. Ruiz, Poly Montreal, Ca 87-Experimental determination of textile permeability: a benchmark exercise, Rene Arbter, Jean-Marc Béraud, Christophe Binetruy, Demaria, Paolo Errmani, Frank Gommer, Senad Hasanovic, Bertrand Laine, Andrew Long, Stepan V. Lomov, Véronique Michaud, Gerd Morren, Romain Nunez, Laurent Bizet, Joel Breard, Eduardo Ruiz, Hugo Sol, François Trochu, Bart Verleye, Julien Verrey and Matthias Wietgrefe.

EXPERIMENTAL DETERMINATION OF TEXTILE PERMEABILITY: A BENCHMARK EXERCISE

B. Laine[1], R. Arbter[2], C. Binetruy[3], L. Bizet[4], J. Bréard[4], J.M. Beraud[5], C. Demaria[6], A. Endruweit[7], P. Ermanni[2], F. Gommer[8], S. Hasanovic[9], F. Klunker[10], S. Lavachy[11], A. Long[7], S.V. Lomov[8], V. Michaud[11], G. Morren[12], P. Henrat[5], E. Ruiz[6], H. Sol[12], F. Trochu[6], B. Verleye[8], M. Wietgrefe[9], G. Ziegmann[10], A. Vautrin[13], W. Wu[10], P. Beauchene[1]

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The design of an optimal liquid composite mould is a difficult and time consuming process. To optimize the mould without too much trial and error, the production process is simulated for different mould models. An important input parameter for these simulations is the permeability of the preform permeability. The permeability can be obtained experimentally, or also by CFD simulations. In this paper we concentrate on the experimental process, and we compare different set-ups and their results.
The paper examines the existing methods of measurement of permeability of textile preforms. It compares values of permeability of the same glass non-crimp and carbon woven fabrics, measured in the benchmarking exercise in ten laboratories employing different methods, e.g. saturated and non saturated permeability, radial and unidirectional flow. It is demonstrated that many methods yield a dispersion of different orders of magnitude of permeability values for the same textile. This results highlights the need of normalisation of measurements of permeability.

16h00-18h00	**Permeability Modelling** Chair: Dr. S.Bickerton, U. Auckland, New Zealand
16h00	26-Permeability prediction for a REV of a fibrous media with a monolithic finite element method Gregory Puaux, Luisa Silva, Patrice Laure and Michel Vincent CEMEF/Université de Nice, France
16h20	65-Permeability of woven fabrics: analytical and numerical predictions Bertrand Laine, Martin Hirsekorn, Philippe Boisse and Fabrice Boust INSA Lyon, ONERA, Polytech Orléans, France/KUL, Belgium
16h40	72-Development of a Multigrid Finite Difference Solver for Benchmark Permeability Analysis Richard Loendersloot, Remko Akkerman and Wouter Grouve University of Twente, Netherlands
17h00	92-A simplified computational treatment for Non-Isotropic Permeability Flow Models based on Flow Pattern Configuration Nicolas Montes, Fernando Sanchez and Nuno Correia INEGI, Portugal/Valencia, Spain
17h20	85-Alteration of permeability caused by transversal flow-induced deformation of fibres during composites manufacturing Vilnis Frishfelds, Gunnar Hellström and Staffan Lundström Lulea University of Technology, Sweden
17h40	28-Numerical simulation of coupled Stokes-Darcy flows: application to LCM at the mesoscopic scale Luisa Silva, Puaux Gregory, Patrice Laure and Philippe Boisse CEMEF/Université de Nice/INSA Lyon, France

26-Permeability prediction for a REV of a fibrous media with a monolithic finite element method

Gregory Puaux, Luisa Silva, Patrice Laure and Michel Vincent
CEMEF/Université de Nice, France

Permeability is a first order parameter in modelling impregnation of fiber reinforcements used in Liquid Composite Molding processes, at the mesoscopic and macroscopic scales (tow or fabric scale). In this paper, we use a stabilised finite element method for numerical computation of the multiphase flows occuring at fiber (microscopic) scale. To compute permeability of the REV, velocity and pressure fields are averaged on the volume. In our eulerian approach, interfaces between differents materials are represented using level-set functions. The solid parts are taken into account by penalisation, using a large viscosity difference between the fluid and the solid domain. The main characteristic of the monolithic approach is that we solve flow equations in all the computational domain, including the solid part. The results given by using this monolithic approach are in good agreement with analytical results found in the litterature, and will be presented, as well as a sensitivity analysis to parameters like the mesh size or REV architecture.

65-Permeability of woven fabrics: analytical and numerical predictions

Bertrand Laine, Martin Hirsekorn, Philippe Boisse and Fabrice Boust
INSA Lyon, ONERA, Polytech Orléans, France/KUL, Belgium

The permeability of a composite reinforcement depends on the geometry of the fibre network. This is often complex because of the weaving of the fibres but also because of the deformation due to the preforming stage. These strains are very important when the composite part is double curved. The objective of the present work is to propose a numerical analysis of the deformation of the unit woven cell of the fibrous reinforcement (mesoscopic scale). Then the resin flow within this strained unit cell is simulated and thus the textile permeability is determined.
Textile composite reinforcements are made up of fibers. Consequently their mechanical behavior is very specific considering the possible sliding and the interactions between the fibers. During the preforming stage, these fabrics are submitted to large strains, in particular large in-plane shear in case of double curved shapes and transverse compression strains. In the present communication, the textile reinforcement deformation analysis is based on a mesoscopic analysis. The yarn is modelled using an hypoelastic behaviour specific to materials made of fibers. The objective derivative of this law is defined from the fiber rotation, which guarantees a correct stress update during the simulation. The transverse mechanical behaviour separates the spherical part of the transverse strains (density change) and the deviatoric part (shape change).

A set of simulations of large deformations of textile composite reinforcements at mesoscopic scale will be presented, especially in plane shear and transverse compression. The numerical analyses are validated by X-ray tomography experiments.
The CelPer2 software uses deformed 3D REV description. The yarns and their complement are meshed and the Stokes and Brinkman equations are solved in order to determine the permeability.

[1] P. Badel, E. Vidal-Salle, E. Maire, P. Boisse, Simulation and tomography analyzis of textile composite reinforcement deformation at the mesoscopic scale, Composites Science and Technology 68 (2008) 2433–2440

[2] P. Badel; S. Gauthier, E. Vidal-Salle; P. Boisse; Rate constitutive equations for computational analyses of textile composite reinforcement mechanical behaviour during forming, Composites: Part A 40 (2009) 997–1007

72-Development of a Multigrid Finite Difference Solver for Benchmark Permeability Analysis

Richard Loendersloot, Remko Akkerman and Wouter Grouve
University of Twente, Netherlands

A finite difference based multigrid solver is currently being developed to analyse the permeability of a textile reinforcement numerically. The objective is to increase the performance of currently available fluid dynamics solvers in terms of computational requirements and level of detail included in the geometrical description of the fabric. The bottleneck for most permeability predicting flow solvers is the internal geometry of a textile reinforcement. This problem intensified over the past years driven by the higher demands on the accuracy of the permeability prediction due to the application of LCM production processes for more complex and structural components of high fibre content.

Finite difference solvers use structured meshes, in contrast to finite element or finite volume solvers which can also use non-structured meshes, but perform less on fluid flow problems. The FD solver's performance is determined by the grid resolution, which depends on the number of elements required in the narrowest fluid gaps between the bundles, for example the location where bundles cross over each other. This results in a relatively large amount of elements, affecting the overall performance in terms of CPU requirements negatively. A solution is the application of a multigrid algorithm.

The multigrid algorithm assures that the convergence rate does not decrease after a number of relaxation steps, as is the case for conventional finite difference schemes. The finest grid resolution should be sufficiently accurate to describe all occurring flow phenomena in the fluid domain in between the bundles, whereas relaxations on coarser grids guarantee a fast convergence. The basic idea, which has already been proven, is that a coarse and inaccurate description of the geometry provides a good starting point for the flow calculations on a finer grid. Errors introduced by the inaccuracies of the geometrical description, are smoothed easily and an acccurate solution is reached within an acceptable time.

However, the resolution of the coarsest grid is still determined by a minimum number of elements in the narrowest fluid regions. The coarser the initial grid, the higher the convergence rate will be in the initial steps and the lower the overall CPU requirements. An approximate analytical solution of the flow between plates (Hagen-Poiseuille flow) is used to solve the pressure and fluid velocities in the narrow regions, allowing a coarser grid to be used in the entire domain. The first studies on 2D models show a decrease of 50% in calculation time to reach an accurate solution when applying this method. A more pronounced reduction of computation time is expected for three dimensional problems, as a grid coarsening reduces the number of elements by a factor eight rather than four.

The solver is currently being implemented for testing of the benchmark reference geometry. It will support the measurements that are carried out in the benchmark project, but it will also set a reference for permeability analysis models, as it is sufficiently fast to incorporate detailed geometrical features of the textile reinforcements.

92-A simplified computational treatment for Non-Isotropic Permeability Flow Models based on Flow Pattern Configuration

Nicolas Montes, Fernando Sanchez and Nuno Correia
INEGI, Portugal/Valencia, Spain

The use of Flow Pattern Configuration Spaces (FPCS) has been previously demonstrated [1] as a simplified computational treatment when compared to standard FE/CV for Darcy flow (e.g. Liquid Composite Moulding (LCM) processes). The most salient aspect of FPCS is that it provides a geometric formulation for modelling LCM flow front geometries. In [1], we proposed a 2D-FPCS consisting of a discretized mould mesh in which the angle between a point of interest, such as nozzle or vent, and the relevant location in the mould were fixed. We then proceeded to study and demonstrate the applicability of FPCS to different analysis of LCM flow.

The first FPCS proposed in [1] was based on the node to node distance criterion. We called this analysis Flow Pattern Distance Space (FPDS), of which we show an example in Fig.1. The second analysis incorporated node filling time: through Finite Element simulation, the normalized filling time is used as a criterion for the FPCS development. The resulting space was called Flow Pattern Time Space (FPTS). When we apply the normalized unidirectional flow equations to different filling strategies (e.g. constant flow rate or pressure) the flow patterns that arose were the same as we modelled in the FPTS (an example is shown in Fig.2). Both spaces therefore reduce the dimensionality of the problem to 2D or 1D allowing a simpler setting for LCM optimization and control of problems for isotropic models.

In this paper we propose a new configuration space, called Flow Pattern Permeability Space (FPkS) that allows us to extend the FPCS methodology to non-isotropic media. This space was obtained by applying the standard normalization scheme used in classic formulation of anisotropic Darcy flow [2] where elliptic flow is normalized to a circular flow by scaling of the cartesian space.
Then, it is possible to scale the geometry in order to translate the non isotropic model into an isotropic model where the Euclidean distance can be used as a distance measurement (e.g. Fig.3). This methodology can also be used if the principal permeability axes are rotated (Fig.4). The applications of this spaces in LCM processes are similar than the spaces proposed in [1], that is optimization and control algorithms. At the end of this paper, some example applications are shown.

85-Alteration of permeability caused by transversal flow-induced deformation of fibres during composites manufacturing

Vilnis Frishfelds, Gunnar Hellström and Staffan Lundström
Lulea University of Technology, Sweden

When a viscous fluid penetrates a porous medium consisting of fibres, each fibre is subjected to a force. The fibres may then redistribute changing as well the detailed flow field as the overall permeability. This can become important in composites manufacturing especially when very high pressure gradient drives the viscous fluid flow. In this case the Stokes drag force is balanced with the elasticity of the fibres and different friction forces at, for instance, fibre-fibre, fibre-stitching and fibre-mould wall interfaces. In general, detailed estimations of such natural processes in a randomised porous material are still insufficient despite a large number of investigations about the fluid flow through them. Hence, we here consider transversal and strictly two-dimensional flow of a viscous fluid through densely packed fibre bundles. Since the systems should include 1000 fibres as a minimum, we apply a combined approach where the system is discretized using modified Voronoi diagrams and the solutions of the Navier-Stokes equations are applied for each part of the division [1]. Then these small parts are combined into a complete system using the fact that the distribution of velocity obeys the principle of minimal dissipation rate of energy, i.e., by minimising the dissipation rate of energy we obtain a linear system of equations with respect to the stream function. Afterwards, the local change of the stream function gives the required stresses for each sector of a fibre and thus the total force and momentum given to a fibre assuming non-slip boundary condition at its interface. This will lead to redistribution of the fibres and a new structure. From a theoretical point of view the deformations can both increase the permeability by widening fractures and defects in porous material or also decrease it because of clogging or blocking as smaller fibres infiltrate into the spaces between larger ones. A first analysis revealed the expected result that increasing the flow rate causes increase in permeability if the fibres are assumed to be randomly packed as initial condition [1]. However, the rate of increase in permeability becomes slower if the size of the fibres significantly differs. More complicated scenarios are possible for other initial arrangements of the fibres. Even small deformations of the positions of the fibres in the bundle can cause significant change in permeability for bundles with low porosity. Applying the results to a Non-crimp fabric shows that the elastic properties of the fibre bundle particularly depend on the stitching positions of the bundle and whether the fibres can slide through the place of stitching during deformation. Depending on fibre diameter either stretching or bending energy of fibre deformation dominates.

[1] J.G.I. Hellström, V. Frishfelds & T.S. Lundström. ”Mechanisms of flow induced deformation of porous media.” J. Fluid Mech. (in review) (2009).

28-Numerical simulation of coupled Stokes-Darcy flows: application to LCM at the mesoscopic scale

Luisa Silva, Puaux Gregory, Patrice Laure and Philippe Boisse
CEMEF/Université de Nice/INSA Lyon, France

In order to understand the different phenomena that occur during the forming phase in LCM (Liquid Composite Moulding) processes, a multi-phase/multiphysics analysis must be undertaken. Three observation scales may be considered: macroscopic (process), mesoscopic (fluid/yarn), microscopic (fluid/fiber). At the macroscopic level, injection simulations require the determination of the permeability tensor. This tensor may be affected by the pre-forming step of the dry fabric. In this paper, a numerical study on the permeability determination is performed at the mesoscopic scale, on a 3D elementary cell, of the resin flow through this cell, when the fabric is considered has having been predeformed. A monolithic approach is coupled to an immersed volume technique: in an eulerian framework, the computational domain (corresponding to the elementary cell) is composed of one single mesh, where the interface between yarns composing the deformed fabric and fluid is captured through a level set approach. Resolution of a coupled Stokes (in the fluid)-Darcy (in the yarn) flow is necessary and is performed using a mixed finite element technique, providing a single system of equations. Stabilization of the Darcy flow is attained using the P1+/P1 element that has a bubble enriched degree of freedom on the velocity field. Results on elementary cells with fabric pre-deformation obtained also by simulation will illustrate the methodology followed.

16h00-18h00	**Thermoplastics** Chair: Dr. P. Mitschang, IVW Gmbh Kaiserslautern, Germany
16h00	11-Interfacial properties of carbon fiber reinforced thermoplastic composites Hajime Nakamura, Yoshitaka Tanaka, Asami Nakai, Satoshi Kobayashi and Nobuo Ikuta Kyoto Institute of Technology/ Tokyo Metropolitan University/Shonan Institute of Technology, Japan
16h20	22-Investigation on the reaction kinetics of adiabatic polymerization of anionic polyamide-6 Julie Teuwen and Harald Bersee TU Delft, Netherlands
16h40	31-Modeling of short fiber composites strength with use of failure indicators Dariusz Bednarowski and Łukasz Malinowski ABB Corporate research, Poland
17h00	61-Effect of Dispersed Phase Particle Dispersion on the Thermal Stability of Recycled Poly(ethylene terephthalate)/Polypropylene Blend Yew Wei Leong, Hiroyuki Inoya, Supaphorn Thumsorn and Hiroyuki Hamada Yasuda Sangyo-ko/Tokyo Institute of Technology, Japan
17h20	36-Glass/CBT Laminate Processing and Quality Aspects Prabhakaran R.T. Durai, Tom Løgstrup Andersen and Aage Lystrup Risoe, Danemark
17h40	70-Design methodology of braided fabric as the reinforcement for pultrusion thermoplastic composite and its mechanical properties Yoshitaka Tanaka, Akio Ohtani and Asami Nakai Japan Aerospace Exploration Agency/Tokyo Institute of Technology, Japan

11-Interfacial properties of carbon fiber reinforced thermoplastic composites

Hajime Nakamura, Yoshitaka Tanaka, Asami Nakai, Satoshi Kobayashi and Nobuo Ikuta
Kyoto Institute of Technology/ Tokyo Metropolitan University/Shonan Institute of Technology, Japan

Fiber reinforced theromoplastic resin composites have number of advantage such as high fracture toughness, recyclability and possibility to re-melt and reprocess compared with thermo-setting composites. Especially carbon fiber reinforced thermoplastic composite; CFRTP has high specific stiffness and strength. in these composites. Therefore, the CFRTP is very keen under global environmental issue in which natural resources are effectively used.

In our previous study, PP was applied for fiber reinforced composites. Thermoplastics as matrices have high melt viscosity so that it is difficult to impregnate resin into reinforcing fiber. To overcome this problem, CF/PP Micro-braided yarn was fabricated by Japanese traditional braiding technique. Micro-braided yarn is fabricated by braiding resin fibers alongside reinforcement fiber. Since resin fibers are located close to reinforcement fiber bundle, impregnation performance of thermoplastics is excellent. Moreover, the Micro-braided yarn could be applied for textile technique. The unidirectional composites were fabricated by the Micro-braided yarn and the mechanical properties were investigated. However, CF/PP composites had a problem as lower interfacial properties. Sizing agents was applied on the carbon fiber to improve handling ability of the carbon fiber and typical sizing agent which is used on the carbon fibers is bisphenol A type. Bisphenol A type sizing agents enhance the adhesion between fiber and epoxy resin, but interrupt the adhesion between fiber and thermoplastic resin. The interfacial adhesion between reinforcement and matrix is very important for mechanical properties of composites materials. A weaker interface reduces the efficiency of stress transfer from the matrix to the fiber and consequently the strength and stiffness are not high.

Therefore, various sizing agents was applied on the CF/PP and the interfacial properties were investigated by Micro-Droplet test and Micro-Indentation test. Micro-Droplet test is one of the experimental methods for assessing the interface. A small droplet of resin is applied to the fiber and the resin droplet is pulled by the knife edges. The maximum load F measered before detachment of the fiber from the matrix is related to the fiber-matrix shear strength ;τ. While the Micro-Indentation test was also the assessing method of interface. The interfacial shear strength was measured by the pushing out the fiber from the matricx resin. In this study, effects of the sizing agents on the interfacial properties and mechanical properties were investgated. Moreover, effects of interfacial properties on impregnation performance of resin and dispersion of carbon fiber were investigated.

22-Investigation on the reaction kinetics of adiabatic polymerization of anionic polyamide-6

Julie Teuwen and Harald Bersee
TU Delft, Netherlands

In order to produce thicker and bigger thermoplastic composite parts for use in offshore wind turbine blades the traditional melt processing technique, which requires high temperatures and pressures, has to be substituted with a vacuum infusion process. To overcome the high resin viscosity of thermoplastic resins, a reactive resin system was used for the vacuum infusion of glass fibre reinforced anionic polyamide-6 (APA-6) composites. The high molecular weight APA-6 is obtained, after a high temperature infusion process, through ring-opening polymerisation.

Previous work showed that the processing temperature is the most important parameter in the infusion of APA-6 composites. The processing temperature results from the sum of the external heat (heating device) and the internal heat (exothermic reaction of the resin). The effect of the temperature is thought to be significant for every stage in the infusion process. Since the infusion of thick-walled, large wind turbine blades, requires long residence times for the reactive resin, a deeper insight in the effect of this critical parameter is needed to find optimal infusion strategies that do not compromise the properties of the final part. In this paper, the reaction kinetics of the resin system will be described and the effect of the pot life (time and temperature) on the reaction/reactivity of the resin and the increment of its viscosity will be investigated.
Testing and modeling the reaction kinetics of the resin is the first step to understand the reaction itself. For this purpose, adiabatic reaction tests were performed in which the temperature of the reaction was recorded and was used to define the semi-empirical equations for the simulation of the APA-6 reaction kinetics. It was concluded that the reaction could be described by the autocatalytic expression, as reported extensively in literature on the reaction kinetics of the polymerization of caprolactam. The main difference however is the long induction time before the resin starts to react.

Afterwards, the effect of the residence time and the temperature of the reactive resin in the buffer vessel (before infusion) on the resin properties and the resin viscosity were investigated. The initial temperature and time of the reactive mixture were varied within the tests, simulating the temperature of the buffer vessel and the residence time of the reactive resin inside. The mixture was then subjected to either adiabatic temperature measurements or viscosity measurements in a mould heated to the cure temperature.

To investigate the effect on the reaction kinetics, the temperature measurements were compared with those corresponding to the reaction kinetics of the resin without any residence time in the buffer vessel. The baseline used for the viscosity measurements was the viscosity versus time of a mixture poured into the mould immediately after mixing. It could be concluded that the longer the residence time and the higher the initial buffer vessel temperature, the higher the initial viscosity and the faster the reaction, hence, complicating the infusion of large products.

31-Modeling of short fiber composites strength with use of failure indicators

Dariusz Bednarowski and Łukasz Malinowski
ABB Corporate research, Poland

Presented work is focusing on numerical simulation of short glass fibers reinforced thermoplastic composites produced with injection molding technology. A combination of commercial software packages for: injection molding analysis (two leading systems), material modeling (Digimat) and structural analyses (Abaqus) enables computer simulations of mechanical behavior incorporating information on fibers distribution. Such approach allows prediction of mechanical response much closer to reality and with the use of failure indicators a critical load could be estimated. A series of tensile tests on injection molded samples were conducted in order to compare presented simulation approach with reality.

61-Effect of Dispersed Phase Particle Dispersion on the Thermal Stability of Recycled Poly(ethylene terephthalate)/Polypropylene Blend

Yew Wei Leong, Hiroyuki Inoya, Supaphorn Thumsorn and Hiroyuki Hamada
Yasuda Sangyo-ko/Tokyo Institute of Technology, Japan

Blending of recycled polyethylene terephthalate (RPET) from waste bottles with polypropylene (PP) was performed in an attempt to enhance the processability of RPET. The idea of blending RPET with PP sprouted from the intention of recycling PET bottles together with their PP-based caps. Therefore, preliminary blending of RPET with PP (RPET/PP) was performed at various PP and compatibilizer contents. The incorporation of compatibilizers reduced the PP particle size and improved the overall homogeneity of the blends. This effectively reduced stress concentration points and enhanced the mechanical performance of the blends. More importantly, the incorporation of PP into RPET significantly increased the degradation temperature of the blends provided the dispersion of PP phase in RPET was excellent.

36-Glass/CBT Laminate Processing and Quality Aspects

Prabhakaran R.T. Durai, Tom Løgstrup Andersen and Aage Lystrup
Risoe, Danemark

Few researchers have reported in the literature the thermoplastic polymers as upcoming resins in developing large sized composite structures using rein infusion techniques. Compared to thermosets, the thermoplastic polymer matrix materials for fibre composites have got promising advantages. One of the principal advantages of true thermoplastic polymers is their ability to consolidate or flow at elevated temperatures; however, this quality also limits their upper-use temperature [1-3].

This article gives brief details on manufacturing of a glass fibre laminate with CBT matrix, which are suitable for resin infusion. At this stage, CBT in powder form was used to manufacture a 5 mm thick laminate by alternating layer of CBT powder and glass fibre No- Crimp-Fabrics (NCF). CBT powder was also used to manufacture a 5 mm thick UD-laminate by filament winding glass fibres onto a frame and cover the fibres with CBT powder before vacuum bagging and consolidation. The present article mainly investigates the process difficulties, control on parameters, and microscopic studies of thermoplastic Glass/CBT 160 laminates.

70-Design methodology of braided fabric as the reinforcement for pultrusion thermoplastic composite and its mechanical properties

Yoshitaka Tanaka, Akio Ohtani and Asami Nakai
Japan Aerospace Exploration Agency/Tokyo Institute of Technology, Japan

Pultrusion process is one of the composite production methods to be suitable for mass production, and continuous productions with uniform cross sections are maintained by using this process. Therefore, the composite structural materials have been produced continuously using this production method. However, there are two problems in pultrusion process, one is the poor mechanical properties in transverse direction because of anisotropic properties, and the other is the difficulty of recycling. In order to overcome these problems, braided fabric with thermo-plastic intermediate material was used as reinforcement for pultrusion in this study. The braided fabric consists of fiber bundles called braiding yarns. The braiding yarns are continuously and diagonally oriented, and the fiber bundle called middle end fiber can be inserted between braiding yarns. The orientation angle of the braiding yarns called braiding angle can be changed freely. By changing the braiding angle, the mechanical properties of the braided composite tubes in longitudinal and circumference direction can be designed freely for satisfying the requirements. Therefore, reinforcing the pultrusion products by braided fabric improves the mechanical properties not only in the longitudinal direction but the circumference direction. However, the dimension (circumference length) of the braided fabric as the reinforcement should be fit the inner circumference length of the pultrusion mold, so it needs designing the circumference direction of the braided fabric before molding. For braided fabric, there are four geometric structural parameters deciding the dimension; cross-sectional area of fiber bundles, cross-sectional shape of the fiber bundle, braiding angle, and the distance between fiber bundles. However, these parameters are not independent value and have the interrelationship with each other. For example, by changing the braiding angle, the distance between braiding yarns, area and aspect ratio of the braiding yarn are automatically changed, and fiber volume fraction and the thickness increase with increase in the braiding angle. Therefore, it is difficult to design the dimension of braided fabric. Moreover, in the case of designing the dimension and the stiffness of the tubular braided composite simultaneously, the design will be more complex The structural parameters and the mechanical properties should be satisfied for achieving the required dimension and mechanical properties. Therefore, the investigation of the structure for the braided fabric as the reinforcement of the pultrusion products will be very important.

In this study, the procedure for designing the circumference length of braided fabric for pultrusion process was proposed considering the structural parameters from the view point of the dimensional design. Additionally, stiffness design of braided composite was also suggested with dimensional design.

	Day 3: Wednesday July 14th, Morning
	Auditorium
8h10-10h30	**Modelling methods I** Chair: Dr. S.Advani, U Delaware, USA
8h10	46-Process development for complex Resin Transfer Molding (RTM) components: optimization of resin injection and laminate porosity Gion Andrea Barandun and Paolo Ermanni, University of Applied Sciences Rapperswil/ETHZ, Switzerland
8h30	9-Proper Generalized Decomposition of LCM models: making possible some simulation dreams Francisco Chinesta and Arnaud Poitou Ecole Centrale de Nantes, France
8h50	44-Numerical simulation of resin flow in fiber reinforcement with stochastic property field Fan Zhang, Philippe Le Grognec, Sébastien Comas-Cardona, Benoit Cosson and Christophe Binetruy Ecole des Mines de Douai, France
9h10	33-Combining a level set method and a stabilized mixed formulation P1/P1 for coupling Stokes-Darcy flows: application to the resin infusion-based processes. Guillaume Pacquaut, Julien Bruchon, Nicolas Moulin and Sylvain Drapier Ecole des Mines de Saint-Etienne, France
9h30	53-Modeling the Resin Flow of Reactive Resins in Liquid Composite Molding Suresh Advani and Pavel Simacek University of Delaware, USA
9h50	66-Development and Verification of a Model of the Resin Infusion Process During Manufacture of Fiber Metal Laminates by VARTM Alfred Loos, Goker Turncol, Kai Long and Roberto Cano Michigan State University/Nasa Langley , USA
10h10	83-A unified continuum mechanics approach to composites manufacturing modeling Maciej Wysocki, Ragnar Larsson and Staffan Toll SICOMP/Chalmers University/KTH, Sweden

46-Process development for complex Resin Transfer Molding (RTM) components: optimization of resin injection and laminate porosity

Gion Andrea Barandun and Paolo Ermanni,
University of Applied Sciences Rapperswil/ETHZ, Switzerland

The development of complex RTM components is still time-consuming and mostly based on trial-and-error procedures. Whereas geometrically simple parts might be produced by well-known injection strategies as radial or peripheral injection, complex 3D components demand more advanced injection patterns. Simulation software may support the development of such strategies, but still depends on user experience and human intuition. Moreover, the inclusion of quality relevant criteria such as laminate porosity is hardly possible.

Using an optimization software tool based on Evolutionary Algorithms, an injection strategy for a complex wing nose (leading edge) demonstrator component is developed. Both development process and the resulting injection strategy are compared to the commonly used trial and error methods. While a reliable injection strategy cannot be found within a reasonable period by trial and error, the optimization software proposes a more robust, reproducible injection pattern within short time. The optimization includes minimizing of voids as well as complete filling of the cavity. The results show that optimization software contributes to efficient process development and might significantly enhance laminate quality.

9-Proper Generalized Decomposition of LCM models: making possible some simulation dreams

Francisco Chinesta and Arnaud Poitou
Ecole Centrale de Nantes, France

Proper Generalized Decomposition performs a separated representation of the fields involved in a model, i.e. the solution of a partial differential equation. This separated representation allows treating different multidimensional models without a significant impact on the computational efforts. In this work we are considering two issues. The first one concerns parametric models in which parameters (e.g. the permeability …) could be considered as additional coordinates facilitating optimization or inverse identification. The second issue concerns the flow through a preform composed of a number of plies whose anisotropic permeability evolves through the thickness. In this work we propose a 3D solver whose computational cost is the same than the standard 2D solvers allowing richer flow modeling.

44-Numerical simulation of resin flow in fiber reinforcement with stochastic property field

Fan Zhang, Philippe Le Grognec, Sébastien Comas-Cardona, Benoit Cosson and Christophe Binetruy
Ecole des Mines de Douai, France

As an important stage in the Liquid Composite Molding processes, the flow of liquid resin through fiber reinforcement mainly depends on the permeability distribution in the fibrous preform. Therefore, it is important to provide realistic permeability values for the computation codes to precisely predict the flow behavior and filling results. Permeability values of real fabrics usually exhibit high variation due to their intrinsic heterogeneity in architecture and the low reproducibility. However, the randomness of fibrous properties has not been accounted for in available commercial simulation codes for LCM processes.

In this work, an efficient numerical method has been developed to model the flow process through fibrous media with random property field. The implementation is based on the Spectral Stochastic Finite Element Method (SSFEM) proposed by Ghanem et al. (1990). From experimental information of given type of fabric, suitable stochastic process model is constructed for the porosity and/or permeability field. By means of discretization of the stochastic process in both spatial and random dimensions, the SSFEM form of the governing equations for the pressure distribution are derived and solved for the stochastic process response. All kinds of statistics for the resin pressure field can be estimated directly from the SSFEM solution, instead of by performing a large number of deterministic simulations as the statistical method (e.g. Monte Carlo simulation). Numerical examples are given to demonstrate the propagation of uncertainties from the fibrous property to the flow behavior of resin by the developed simulation code.

33-Combining a level set method and a stabilized mixed formulation P1/P1 for coupling Stokes-Darcy flows: application to the resin infusion-based processes.

Guillaume Pacquaut, Julien Bruchon, Nicolas Moulin and Sylvain Drapier
Ecole des Mines de Saint-Etienne, France

Resin infusion-based processes are manufacturing techniques for polymer composites. They have been developed in recent years to solve the filling problems associated with the Resin Transfer Molding processes (RTM). They consist in infusing liquid resin through the thickness of the reinforcement rather than in the plane. They can be modeled as follows: a mold contains initially the resin (a purely fluid domain) and preforms (an orthotropic porous medium). Under the effect of a mechanical pressure applied on the whole stacking, the resin flows into the preforms, which are themselves subject to large deformations. The aim of this work is to focus on the Stokes-Darcy coupled problem with moving interfaces while accounting for the preform deformation, in order to simulate numerically the composite manufacturing processes by resin infusion using the finite element method. In this study, for computation efficiency, a macroscopic description is used.

The fluid flows in a purely fluid domain according to the Stokes' equations, and into the preforms according to the Darcy's equations. The whole domain is discretized in a single unstructured mesh, composed of triangles in 2D and tetrahedrons in 3D. A unified strategy with a mixed formulation in velocity-pressure on the whole domain is used to solve the Stokes-Darcy coupled problem. In the purely fluid domain, a first-order mixed P1+/P1 finite element is used, with a linear continuous interpolation for both pressure and velocity. Velocity is enriched to satisfy the Ladysenskaya-Brezzi-Babuska (LBB) stability condition. On the contrary, for Darcy's equations the LBB condition is not satisfied, and a P1/P1 finite element is preferred. It is stabilized with the Hugues Variational Multiscale formulation (HVM). The second main contribution of this work is to use a level-set method to describe the moving interfaces : interface separating the purely fluid domain and the porous medium, and interface separating the part of the domain which is already filled by the resin from the dry region. In this representation, a signed distance function is defined which passes throughout the mesh elements so that interfaces are independent on the unstructured mesh. Consequently, two level-set functions are involved in our simulation, they can 'naturally' combine and vanish when the infusion is completed. Eventually, the preform deformation is represented with an updated lagrangian scheme, with a special attention paid to the interaction of the preform deformation and the resin infusion. The resin pressure is modified by the permeability change induced by preform compaction, and conversely the mechanical response of the smeared-out saturated porous material is represented via a Terzaghi's model modified according to the current resin pressure.

Finally, a numerical simulation of the manufacturing process by resin infusion is also presented. This simulation shows filling defects and some physical phenomena very useful from an industrial point of view.

53-Modeling the Resin Flow of Reactive Resins in Liquid Composite Molding

Suresh Advani and Pavel Simacek
University of Delaware, USA

In Liquid Composite Molding (LCM), fibrous preforms are placed in a mold and injected with a thermoset liquid resin. Once the preform is fully saturated and the resin cures, the part is demolded. It is necessary to fully saturate the preform without any dry spots or voids for acceptable mechanical properties. To ensure successful filling, numerical analysis of the flow process has been widely applied.

Standard approaches assume that the injected resin does not significantly change its viscosity during the filling process, and as viscosity is a function of temperature and cure, this implies that the process takes place at a constant temperature and that any curing reaction during filling is negligible. For many room temperature resins, this is valid assumption. For some resins in which the curing agent is mixed at the onset of injection, the filling may be isothermal but the resin may initiate cure during the filling thus the viscosity will change during filling but with time only. For such reactive resin systems with isothermal injection, it is possible to transform the flow model of constant viscosity infusion by scaling time or pressure.

The complication arise when the isothermal condition is not valid or for two part systems in which due to in-line mixing as the resin enters the mold, the resin cure and viscosity may depend on location in the mold. For such scenarios, the infusion has to be modeled as non-isothermal, variable cure process, increasing the spatial unknowns from one (usually pressure) to three (pressure, temperature and cure) with coupled flow, energy and cure equations. Moreover, the temperature solution cannot be restricted to the filled part of the mold as the preform temperature may vary with time even in the locations that are not yet saturated, and a dependence of the heat transfer coefficients on resin flow velocity (heat dispersion) must be analyzed. We present an approach in which the resin flow and pressure is evaluated based on the current state of the temperature and cure. Then, the resin flow is advanced and the temperature and cure is re-evaluated and used to simulate the filling at the next time step. The numerical scheme and its virtues along with verification will be discussed. The influence of resin reaction cure kinetics and non-isothermal state on flow modeling results is compared to the results of simplified isothermal modeling. The computational time penalty and the need for parameter determination to characterize cure kinetics and heat dispersion will be discussed.

66-Development and Verification of a Model of the Resin Infusion Process During Manufacture of Fiber Metal Laminates by VARTM

Alfred Loos, Goker Turncol, Kai Long and Roberto Cano
Michigan State University/Nasa Langley , USA

Fiber metal laminates (FMLs) are fabricated by stacking alternate layers of metallic sheets and fiber-reinforced polymeric-matrix prepreg plies. Two common FMLs include ARALL™ and GLARE™ . ARALL™ uses unidirectional aramid fiber while GLARE™ uses either unidirectional or biaxial high strength glass fiber. Both laminates use aluminum alloys for the metallic sheets. FMLs have mechanical and environmental properties that are superior compared with monolithic metal alloys or fiber reinforced polymer matrix composite laminates.

FMLs are currently manufactured by placing the layup of metallic sheets and prepreg plies in a mold and exposing the structure to elevated temperature and pressure in a compression press or an autoclave. These manufacturing methods result in well consolidated structures with good bonding between the metallic sheets and the fiber-reinforced composite. However, these fabrication processes are expensive and the part size is limited by the size of the press or autoclave. In order to overcome these limitations, a program is underway to investigate the manufacture of FMLs by the low-cost VARTM process.

In the VARTM process, resin flow is primarily in the transverse direction which requires that resin pathways be inserted into the metal foils. The size and shape of the pathways must be large enough to permit resin to flow into and wet-out the glass fabrics, but small enough as to not compromise the structural performance of the FML.

A simulation model of the FML, VARTM process was developed using the commercial software package FLUENT. The metal foils, with the flow paths machined into them, were modeled using the “porous jump” boundary condition. The glass fabrics were treated as a three dimensional porous material. The simulation model was used to predict the resin flow into the aluminum/glass fabric preform in order to ensure complete wet-out of the glass fabric layers.

In order to observe the resin infiltration process and verify the model predictions, a flow visualization fixture was constructed. The fixture is identical to the actual VARTM set-up except that the steel tool was replaced with a clear polycarbonate tool and the aluminum foils were replaced with clear acetate sheets. These changes permit the resin flow patterns to be observed during infiltration.

Results of the flow visualization experiments showed that FMLs can be successfully manufactured by the VARTM process when flow pathways are machined into the metal foils. The size of the flow pathways significantly influences the shape of the flow patterns and the total infiltration time. In this paper, the results of the flow visualization experiments and comparisons with model predictions will be reported.

83-A unified continuum mechanics approach to composites manufacturing modeling

Maciej Wysocki, Ragnar Larsson and Staffan Toll
SICOMP/Chalmers University/KTH, Sweden

A current trend in composites manufacturing is to cut down on the number of operations required to produce a component. Thus a series of operations that used to be carried out sequentially are nowadays often combined within a single operation. For example, impregnation of reinforcement preforms, consolidation, forming into shape and, finally, curing or solidification. All these steps may be combined in a single processing operation. This leads to increasingly complex operations, with many sub-processes occurring simultaneously on different spatial and temporal scales. Today, all the individual sub-processes are reasonably well understood. In fact, much research work has been spent over the last 30 years on understanding the various aspects of composites manufacturing[1]. However, the solution of the complex problems that occur in a real operation, involving several coupled processes on different length- and time-scales (cf. papers by Fish and coworkers[2]) received only very limited attention.

In present contribution, an attempt to unify the modelling of the sub-processes is proposed under the umbrella of two-phase porous media theory[3,4]. The idea is to identify a set of relevant phases, i.e. solid and fluid, and assign a separate continuous medium to each phase. The result is a set of overlapping continuous media, each having its own density, velocity and stress field on the macroscopic scale. In addition, we introduce internal variables to describe irreversible micro-processes in the system, such as microscopic infiltration. In our previous work, focus has been on coupling the preform deformation on different scales to the process of micro infiltration. In this work, we extend the previous developments accounting for the micro-compaction as well as the Darcian interaction on the macro scale. As a result a coupled displacement-pressure, fully non-linear total Lagrangian, finite element model is presented. The approach is applied to a representative numerical example, displaying the relevance of the involved sub-processes.

References

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	Auditorium
11h00-12h00	**Modelling methods II** Chair: Dr. Philippe Boisse, INSA Lyon, France
11h00	37-Theoretical Investigations of Flow Phenomena in a Liquid Composite Molding Process using SPH Methodology Prabhakaran R.T. Durai, Tom Løgstrup Andersen and Aage Lystrup Risoe, Danemark
11h20	19-Simulation of LCM Processes with Cellular Automats Markus Henne and Gion Andrea Barandun, University of Applied Sciences Rapperswil, Switzerland
11h40	108-Permeability predictions of dual scale fabrics using level set methods Wook Ryol Hwang and Suresh Advani Gyeongsang National University, Korea/University of Delaware, USA

37-Theoretical Investigations of Flow Phenomena in a Liquid Composite Molding Process using SPH Methodology

Prabhakaran R.T. Durai, Tom Løgstrup Andersen and Aage Lystrup
Risoe, Danemark

The composites industry employs novel fabrication techniques to combine highperformance reinforcements and resins in making composite structures. Resin Transfer molding (RTM) is one of the liquid composite molding (LCM) manufacturing processes in which resin is injected into a mould cavity pre-filled with a fibrous preform. This process involves a viscous thermosetting resin flowing through a bundle of fibers, completed within a limited duration of time, before the resin gels. The flow also should be in such a way that no air is entrapped during the resin fill. Complete saturation of the preform during RTM is necessary for successful manufacturing and performance of the composite product [1]. This process is quite intricate and complicated. Comprehensive studies are necessary and attention should be focused on this problem, involving following areas associated in the resin-flow through the mould.

¬ Resin flow idealized as flow through porous media.
¬ Resin viscosity changes during the flow.
¬ The porosity of the reinforcements as a material property.
¬ Effect of imposed pressure on the porosity and other mould conditions (For example, the nature of venting and their location)

The present paper investigates the flow phenomena (resin) in a resin transfer molding process using Darcy and smoothed particle hydrodynamics technique to study viscosity variations, effect of closed and open vents etc.

19-Simulation of LCM Processes with Cellular Automats

Markus Henne and Gion Andrea Barandun,
University of Applied Sciences Rapperswil, Switzerland

Finite Element Methods (FEM) are at present available for simulating resin injection processes. However, they are extremely time-consuming, and even then they demand excessive computing power if an iterative process is used for optimising the injection parameters; furthermore, the quantitative predictions of the filling time and the evolution of the pressure during the filling of the mould are very inaccurate. For these reasons FEM-based simulation is scarcely ever used in practice.
In the work described here a cellular automat is used to simulate the injection process. The algorithm calculates the pressure in a cell from the pressures in the neighbouring cells and from the properties of the cell. It takes account of all the factors that have an influence, such as permeability, porosity and the geometry of the cavity. It is tuned to give a picture of the mould-filling that is as realistic as possible, using experimental results and values based on experience.

Essentially the algorithm correctly represents the filling process. In particular the effects of the local permeability and porosity of the material are realistically portrayed.
It is also possible to simulate correctly the effect of several independently switched injection points. On the other hand there is room for improvement in considering different cell densities and in taking account of the cavity dimensions.

108-Permeability predictions of dual scale fabrics using level set methods

Wook Ryol Hwang and Suresh Advani
Gyeongsang National University, Korea/University of Delaware, USA

A new finite-element scheme which recasts the Stokes-Brinkman equation for flow analyses in dual-scale porous media as a single equivalent momentum equation over the entire domain has been developed and applied to predict the effective permeability of dual scale fabrics. The proposed scheme uses a structured regular rectangular mesh to discretize the domain and employs the level-set method to describe the porous media allowing for inclusion of complex geometrical features easily. Bi-periodic boundary conditions are applied for flow analysis in a representative volume of meso-scale porous structures. The scheme is applied to flow past two regular periodic geometries of elliptic fiber tows in 2D, representing uni-directional fiber tow in a textile fabric to predict the bulk or effective permeability and its dependence on the fiber volume fraction, the aspect ratio of the ellipse, the fiber tow permeability and the degree of compaction of the fiber tows. Only results of how the fiber tow permeability influences the effective permeability are presented due to space limitations.

	Sala Balint
1h00-12h00	**Laminates** Chair: Dr. A.Loos, Michigan State Universtiy, USA
11h00	8-Experimental observation and analytical modelling of the resin flow inside an out of autoclave prepreg Timotei Centea and Pascal Hubert Mc Gill University, Canada
11h20	41-Simulation of nonisothermal prepreg-press-processes for high volume automotive applications Florian Klunker, Matthias Voigt, Wangqing Wu, Widyanto Surjoseputro, Santiago Aranda and Gerhard Ziegmann TU Clausthal, Germany
11h40	43-Constitutive modelling of UD reinforced thermoplastic laminates for stamp forming predictions Sebastiaan Haanappel and Remko Akkerman University of Twente, Netherlands

8-Experimental observation and analytical modelling of the resin flow inside an out of autoclave prepreg

Timotei Centea and Pascal Hubert
Mc Gill University, Canada

Out of autoclave prepregs are vacuum bag processed in conventional ovens. Because the maximum pressure available to suppress voids is therefore one atmosphere, gas evacuation is critical to obtaining low porosity parts. Such prepregs initially allow the removal of air and other volatiles through non-impregnated “evacuation channels” and through interply gaps. Then, during elevated temperature processing, the resin matrix infiltrates these regions to ensure a uniformly impregnated and void-free composite. The nature and behavior of the microstructure thus relates to a number of processing parameters and quality factors, and is of great interest.

The microstructural behavior of such an out of autoclave prepreg was investigated for a simple processing cycle using a novel method. First, flat laminates were partially processed to different stages of debulking and elevated temperature cure. Then, samples from each laminate were scanned using x-ray microtomography (micro-ct) to obtain high-resolution, three-dimensional microstructural information at each processing state. From this data, the progressive impregnation of the initially dry areas and the evolution of void areas within the laminate were quantified.

The observed behavior was then modelled analytically. The complex nature of the prepreg microstructure was reduced to a base geometry, and equations of flow within a porous media were combined with known resin property models to simulate the infiltration of dry areas. The model was then used to predict the behavior for different cure cycles.

The above work achieved three distinct results. The first is a methodology for obtaining high resolution three dimensional information about a prepreg’s microstructure. The second is an understanding of the microstructural evolution of an out of autoclave prepreg. The third is a model for predicting the above evolution for any processing cycle.

41-Simulation of nonisothermal prepreg-press-processes for high volume automotive applications

Florian Klunker, Matthias Voigt, Wangqing Wu, Widyanto Surjoseputro, Santiago Aranda and Gerhard Ziegmann
TU Clausthal, Germany

For the application of composite parts in the automotive industry a high volume production is necessary. The IFC Composite GmbH has developed a highly automated procedure to produce 250.000 leaf springs a year with a nonisothermal prepreg-pressing process.
With the use of flow and curing simulation the process design of leaf springs with a thickness up to 100 mm will be investigated. This paper show models and methods for material characterisation, mainly focussed on the thermodynamic balance of the resin.
For the numerical simulation ALE-methods were coupled with conduction-convection equations to track the flow of mass and energy. The results are used to find the optimal process parameters for the control of the prepreg-press-processes.

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43-Constitutive modelling of UD reinforced thermoplastic laminates for stamp forming predictions

Sebastiaan Haanappel and Remko Akkerman
University of Twente, Netherlands

Stamp forming of thermoplastic composites at high temperatures is frequently used to obtain non-critical secondary parts for the aerospace industry. Typically, pre-consolidated laminates with a woven reinforcement, a uniform thickness and lay-up orientation are used. Extending the application of thermoplastic composites to structurally loaded primary parts, can be achieved by using a unidirectional (UD) reinforcement with an inherently higher specific stiffness. Additionally, novel automated placement processes of UD reinforced thermoplastic tapes, support the development of tailored blank designs in terms of thickness and lay-up orientation variations. A primary part will subsequently be produced by stamp forming a tailored blank.

To support the development of guidelines for tailored blank designs and stamp forming processes, predictive tools need to be further developed. An in-house developed finite element code that accounts for large deformations in anisotropic materials [1] with a woven reinforcement will be extended with constitutive relations, to be developed for UD reinforced thermoplastics.

During stamp forming UD reinforced plies with a molten thermoplastic, both intra- and inter-ply mechanisms are driven by viscous actions between the individual fibres. Unlike trellis type deformation mechanisms in woven fabrics [2], intra-ply mechanisms as strain transverse to the fibre directions and shear are expected to dominate. Inter-ply and tool-ply friction is also strongly related to the thermoplastic's viscosity, as an interacting thin film at the interfaces can be imagined. Initially, forming trials on a doubly curved geometry will identify the dominating deformation mechanisms, based on which tailored characterisation experiments will be chosen or designed. Finally, performing these experiments will supplement the material data for stamp forming simulations.

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	Day 4: Thursday July 15, Morning
8h00-8h10	***Announcements of Day 4***
8h10-8h55	**Keynote lecture 3 : Dr. Laurent Bizet, Université du Havre** “Processing plant fiber composites with LCM techniques: from comparisons to opportunities” Chair: Dr F. Trochu, Polytechnique de Montreal, Canada
	Auditorium
9h00-10h30	**Natural Fiber Composites I** Chair: Dr F. Trochu, Polytechnique de Montreal, Canada
9h00	77- Capillary effects in vacuum assisted resin transfer molding with natural fibers Gastón Francucci, Analía Vázquez, Edu Ruiz, François Trochu and Exequiel Rodríguez University of Mar del Plata, Argentina/Poly Montreal, Canada
9h20	60-An Approach to Model Resin Flow in LCM Preforms made of Swelling, Liquid-Absorbing Natural Fibers Reza Masoodi, Hua Tan, Krishna Pillai and Ronald Sabo Forest Products Laboratory/University of Wisconsin, USA
9h40	49-Processing and mechanical properties of unidirectional hemp/paper/epoxy composites Mathieu Robillard, Gilbert Lebrun and Lotfi Toubal Université du Québec à Trois Rivières, Canada
10h	56-Comparison of in-plane permeability between flax and glass stitched fabrics Christopher Re, Laurent Bizet and Joël Breard Université du Havre, France

Keynote lecture 3

Processing plant fiber composites with LCM techniques: from comparisons to opportunities

Laurent BIZET, Laboratoire Ondes et Milieux Complexes, FRE 3102 CNRS, University of Le Havre
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Interest and doubt are usually both in mind when talking about plant fiber or natural fiber composites. Do these composites for example have less environmental impacts than glass fiber composites? This uncertainty and others imply an increase of scientific knowledge in the domain. During the last twenty years, a few specific studies have been carried out on LCM processing techniques applied to plant fiber composites. This presentation aims to review the potential and questions about LCM compared to other processing techniques in the field of plant fiber composites. Relevant properties of plant fibers for processing composites will also be presented. Examples of impregnation of plant fiber fabrics will be shown throughout measurements of permeability, which is one of the most important characteristics of LCM techniques. Finally, mechanical properties of plant fiber composites will be described as a function of processing techniques and other important parameters.

77- Capillary effects in vacuum assisted resin transfer molding with natural fibers

Gastón Francucci, Analía Vázquez, Edu Ruiz, François Trochu and Exequiel Rodríguez
University of Mar del Plata, Argentina/Poly Montreal, Canada

Automotive industry has shown in the last years a growing interest in the use of green composites. Fibrous reinforcements made from natural resources have the advantage of being renewable, abundant, and cheaper than synthetic fibers and pose comparable mechanical properties. Liquid Composite Molding (LCM) techniques have proved to be suitable for processing natural fibers. Nevertheless, few issues still to be resolved, such as fiber impregnation and bonding to the polymeric matrix. Capillary effects have shown to be key in the impregnation of the fibers, mainly when the resin is infused or injected at low pressure. In the case of natural fibers, important capillary effects take place during impregnation due to the hollow structure of the fibers, small diameter and molecular polarity. In this work, the capillary pressure of a woven jute fabric was measured for different fiber volume fractions and its effect on permeability was studied. Permeability tests were conducted with different fluids in order to evaluate the impact of the chemical nature of the fluids in the infiltration process. This research gives an insight on capillary effects occurred during LCM with natural fibers.

60-An Approach to Model Resin Flow in LCM Preforms made of Swelling, Liquid-Absorbing Natural Fibers

Reza Masoodi, Hua Tan, Krishna Pillai and Ronald Sabo
Forest Products Laboratory/University of Wisconsin, USA

Environmental concerns make it attractive to replace artificial fibers (such as glass and carbon fibers) with natural fibers (such as jute and wood fibers) in polymer composites. However, the flow of resins through a preform made from natural fibers during a composites manufacturing process such as liquid composites molding (LCM) is not completely understood because of the swelling of natural fibers that happens due to the absorption of liquids by the fibers. Unlike the artificial fibers, the natural fibers undergo swelling on coming in contact with certain liquids and cause changes in the porosity, and hence permeability, of the fiber-mats within an LCM mold.

In this paper, we are going to present a theoretical model for the macroscopic flow of resin during mold-filling inside a hard-mold LCM process where the liquid absorption and swelling of fibers is accounted for through a modified continuity equation employing additional sink and source terms. The governing equations, which include the Darcy's law, are obtained from application of the volume averaging method. The flow equations are implemented in a numerical simulation using our in-house porous-media flow simulation PORE-FLOW©, which employs the well-known finite element/control volume algorithm to simulate isothermal flows in an LCM mold during mold-filling. Under certain simplifying assumptions, analytical solutions of the given governing equations are shown to exist for simple flows. An experimental study of the flow of resin-like test liquids through a compressed bed of natural fibers is conducted under the 1-D and radial flow configurations. These experimental results are used in the validation of our numerical and analytical results.

49-Processing and mechanical properties of unidirectional hemp/paper/epoxy composites

Mathieu Robillard, Gilbert Lebrun and Lotfi Toubal
Université du Québec à Trois Rivières, Canada

Natural continuous bast fibers (hemp, flax…) are gaining popularity in composite materials because they can advantageously replace glass fibers. In unidirectional (UD) composites, it is found that their intrinsic properties are equivalent to those of unidirectional glass fibre composites but it is difficult to get repeatable results because of the variability in the properties of bast fibers compared to glass. Their quality is largely affected by the weather conditions, the extraction location along the plant and the techniques used to extract them (retting, bleaching…). In this work, unidirectional hemp/paper/epoxy composites are manufactured by adding sheets of paper at the surface of a unidirectional layer of hemp fibers before molding. The composites are tested under tensile and shear loads and the results compared with those obtained for UD hemp composites made without paper. The results show a significant increase of the reproducibility in strength and modulus of the composites when the paper is present. A significant increase in strength and modulus was also obtained compared to the base epoxy properties. Difficulties were encountered in the shear tests using the Arcan test setup. These are finally presented to open the discussion about the possible causes of such difficulties.

56-Comparison of in-plane permeability between flax and glass stitched fabrics

Christopher Re, Laurent Bizet and Joël Breard
Université du Havre, France

Plant fibers associated with an organic matrix are interesting and promising composite materials. Flax and hemp fibers are good examples because their specific mechanical characteristics are comparable to glass fiber ones [1]. Nevertheless knowledge on plant fiber composites has to be increased. Different types of investigations must be carried out to optimise these composites: mechanical characteristics of plant fiber composites, optimisation of interface between fiber and matrix, good choice and development of appropriated matrix, environmental impacts and choice of appropriated manufacturing processes.

This study deals with processing plant fiber composites by the way of Resin Transfer Molding which is a suitable technique to obtain resistant unidirectional flax composites according to Oskman [2]. In the present work, measurements of in-plane permeability of flax preforms are obtained and discussed. Two types of flax preforms are prepared with stacks of a stitched unidirectional fabric on one side and a stitched biaxial +45/-45 fabric on the other side. The originality and interest of both fabrics consist in their composition drawn on untwisted flax fibers. Permeability values have been measured under unsaturated and saturated conditions in the two principal directions for the biaxial +45/-45 fabric and in the longitudinal direction for the unidirectional fabric. To avoid critics on absolute in-plane permeability values [3], a stitched biaxial +45/-45 glass fabric with the same stitching and same areal weight than the flax biaxial +45/-45 fabric has been manufactured and its permeability has been measured in the same way than flax fabric. Unidirectional flax fabric is compared with an industrial unidirectional glass fabric. The comparison between the four types of preforms (biaxial flax vs biaxial glass and UD flax vs UD glass) has been achieved on the different volume fractions of fibers accessible with our permeability measurement device.

Results show that in-plane saturated permeability values for biaxial +45/-45 flax fabric are five or six times lower than for biaxial +45/-45 glass fabric at the same volume fraction of fibers. In-plane saturated permeability for unidirectional flax fabric is at least five times lower than glass one. The higher the fiber volume fraction is, the lower the difference between both unidirectional fabrics is. An attempt of explanation of difference in permeability between the flax fabrics and the glass fabrics is given based on microstructure and on wetting behaviour of both flax and glass fabrics. This analysis is helpful to understand restrictions in the use of plant fiber composites and to optimise flax fabrics.

10h50- 12h20	**Natural Fiber Composites 2** Chair: Dr Nakai, Tokyo Institute of Technology, Japan
10h50	17-Impregnation state in short fiber thermoplastic pellet and mechanical properties of composites Yuqiu Yang and Hiroyuki Hamada Kyoto Institute of Technology, Japan
11h10	75-Compression moulding of flax-fibre reinforced composite materials Pierre Dumont, Laurent Orgéas, Maxime Hubert, Bernard Vermeulen, Philippe Vroman, Sabine Rolland du Roscoat and Jean-Francis Bloch Université de Grenoble/ENSAIT, France
11h20	14-Study of the Compaction Behavior of Jute Fabrics in Liquid Composite Molding Processes Gaston Francucci, Exequiel Rodriguez and Analía Vazquez University of Mar del Plata, Argentina
11h40	74-Effect of processing on the durability of fiber reinforced plastics Takeshi Okayama, Yasunari Kuratani, Yuki Kadoma, Masanori Okano, Asami Nakai and Hiroyuki Hamada Kado Corporation/Kyoto Institute of Technology, Japan

17-Impregnation state in short fiber thermoplastic pellet and mechanical properties of composites

Yuqiu Yang and Hiroyuki Hamada
Kyoto Institute of Technology, Japan

In order to satisfy both requirements for environment protection and high mechanical property of composites, hybrid of nature fiber and glass fiber in polypropylene is proposed and carried out in the current study. In particularly, hybrid pellet was adopted to mold hybrid composites by injection process. Firstly, the impregnation station of two fibers in both pellet and dumbbell shape composite were investigated before and after molding process by microscope upon the polished surface. Then the mechanical properties were discussed based on tensile tests. Finally, this study discussed the measurement methods of fiber content in the natural fiber hybrid composites. It is found that the traditional burn-out and density method are not suitable for those composites. Therefore, image analysis method was proposed.

75-Compression moulding of flax-fibre reinforced composite materials

Pierre Dumont, Laurent Orgéas, Maxime Hubert, Bernard Vermeulen, Philippe Vroman, Sabine Rolland du Roscoat and Jean-Francis Bloch
Université de Grenoble/ENSAIT, France

Flax-fibre mats can be used to reinforce polymer matrices to obtain compounds moulded by compression. Due the interesting physical properties of flax fibres, these materials offer a suitable alternative to classical glass-fibre compounds such as Sheet Moulding Compounds (SMC), Bulk Moulding Compounds (BMC) or Glass Mat Thermoplastics (GMT) for producing semi-structural parts. But it is well known that these latter classical materials exhibit rather complex flow phenomena such as fibre orientation, fibre-matrix separation and smooth polymeric skin-layer development. These phenomena depend on materials parameters such as the microstructure of the fibrous reinforcement, the matrix rheology and the content of mineral fillers, as well as on the process conditions such as the strain rates, the temperature of the mould and of the compoundsand the quality of the contact between the mould surfaces and the compound.
There are structural analogies between flax-fibre mats and glass-fibre mats, e.g. consolidation of the fibrous mat by needle-punching. Thus, this study aims at determining the rheological phenomena occurring during the compression moulding of flax-fibre reinforced compounds. It will allow a better understanding of the analogies between compounds with plant-fibres and glass-fibre compounds, as well as to reveal specific phenomena.

Tested flax fibre mats were produced by carding. A cross-lapper was used to form webs of required basis weight. Then they were consolidated: i.e. they were needle-punched once or twice. These mats were impregnated with a mineral oil matrix Versagel®. It is a transparent material, which can be easily handled at room temperature. Its viscosity is close to viscosities of opaque industrial suspending polymers when heated at moderate temperatures (≈ 103−104 Pa s at 1 s−1 and 50°C).

Lubricated simple compression tests were performed at various constant axial strain rates. At the macroscopic scale, the density of the obtained part was analysed by a simple weighting technique. At the microscopic scale, the microstructures of the initial and deformed suspension were analysed using 3D images obtained by performing X-ray microtomography experiments (European Synchrotron Radiation Facility, Grenoble, France). Results show the influence of the strain rate velocity, of the initial geometry of the tested samples on the flow pattern, as well as of the microstructure of flax-fibre mats.

14-Study of the Compaction Behavior of Jute Fabrics in Liquid Composite Molding Processes

Gaston Francucci, Exequiel Rodriguez and Analía Vazquez
University of Mar del Plata, Argentina

The growing interest in reducing the environmental impact of materials is leading to the development of new materials or composites, based on natural resources. Natural fibers are biodegradable and consume the same amount of CO2 during the plant growing than the produced during fibers degradation. Other advantages of natural fibers are: low cost, low densities, less abrasiveness (less wear on tooling, ease of handling), good specific properties, easily recyclable, lower health risk for the producer workers than glass fibers and good thermal and sound insulation properties. Also, there are a wide variety of fibers available throughout the world. On the other hand, natural fibers have some limitations, such as moisture and water absorption and lower thermal stability (they suffer lignocellulosic degradation at low temperatures, about 200°C) which limits their use in some applications, and also the processing temperatures. Liquid composite molding (LCM) techniques, such as resin transfer molding (RTM) or vacuum infusion (VI) seems to be a good choice for processing these materials. In addition to the LCM low processing temperatures, fibers do not suffer thermo-mechanical degradation as in the extrusion process. The study of the compaction response of the reinforcements used in LCM processes is of major importance, because it affects the processing variables such as clamping forces and fabric permeability, the part quality and thickness, fiber volume content, and composite final mechanical properties. In this work, the compaction behavior of natural fiber reinforcements is analyzed. It was found that natural fibers structure affected the compaction response of the preform by increasing the permanent deformation. The effect of fluid absorption on the compaction behavior of jute woven fabrics and sisal fiber mats was analyzed by changing the immersion time of the fabrics in the test fluid. It was found that fluid absorption reduced the compaction pressure in natural fiber performs due to fiber softening. This phenomenon was not observed in glass fiber mats.

74-Effect of processing on the durability of fiber reinforced plastics

Takeshi Okayama, Yasunari Kuratani, Yuki Kadoma, Masanori Okano, Asami Nakai and Hiroyuki Hamada
Kado Corporation/Kyoto Institute of Technology, Japan

Composite materials have been in use for a few decades now. Their advantages over other materials for high-performance, lightweight applications have attracted many industries such as aerospace, automobile, infrastructure, sports and marine to explore and increase their usage. However, composite materials, to be applied to structure with long service life, need to be guaranteed for the corresponding period of time from failure, which is usually a result of an evolutionary process of material degradation in the service environment. To provide proper durability of the material, it needs to study its long-term behaviour under load and its endurance limit. The most widely used durability criteria establishing the dependence of material strength on the time of loading are based on the concept of the accumulation of material damage induced by acting stresses and intensified by the degradation influence of service conditions such as temperature and moisture. Therefore, cycle fatigue test, creep test and stress-relaxation test is used in the durability of the material.
The path to the design and manufacturing of composite structures was pursued in evolutionary as well as revolutionary ways to give composite material with more high quality and high performance. They ranged from using hand-lay-up and cost intensive autoclave processing to the use of automated processes such as resin transfer molding. However, as consideration of the durability of the material, long-term behaviour of each composite materials made by hand-lay-up processing, autoclave processing and resin transfer molding might be different because the interfacial properties between fiber bundle and matrix is different due to different flow process of matrix. In other words, the impregnation condition to fiber might affect the mechanical properties in long-term.
In this study, fatigue properties and stress-relaxation behaviour in three kinds of composite materials were performed to investigate the effect of the processing for the durability. The composite material was made by hand-lay-up processing, autoclave processing and resin transfer molding. In only autoclave processing, the prepreg sheet was used in the manufacturing of composite. Moreover, crack propagation behaviour was investigated in detail by the observation of fatigue fractured area. In the stress relaxation test, the test was performed under the water. And the prediction for long-life master curve given by the test was discussed.

	Sala Balint
10h50-12h20	**Nanocomposites I** Chair: Dr. C. Dransfeld, FHNW, CH
10h50	4-Permeability and compressibility of CNT-CNF grafted Textile Reinforcement Stepan V. Lomov, Lesley Beyers, Larissa Gorbatikh, Ignaas Verpoest, Vitaly Koissin, Zelijko Kotanjac, Mehmet Karahan KU Leuven, Belgium/Uni-Twente, Netherlands/Uludag University, Turkey
11h10	7-Flow and Filtration Modelling of Carbon Nanoparticle Loaded Thermosets in Liquid Moulding Elisabete Reia da Costa, Alex Skordos and Ivana Partridge Cranfield University, UK
11h20	35-Dispersion of Carbon Nanotubes in Resin Systems using Chaotic Mixing Jie Chen and Ranga Pitchumani Virginia Tech, USA
11h40	91-Nadir Kchit, Farida Bensadoun, Catherine Billotte, Edouardo Ruiz and Francois Trochu. A Study of Nano-Clay Composites made by Liquid Composite Molding Polytechnique de Montreal, Canada

4-Permeability and compressibility of CNT-CNF grafted Textile Reinforcement

Stepan V. Lomov, Lesley Beyers, Larissa Gorbatikh, Ignaas Verpoest, Vitaly Koissin, Zelijko Kotanjac, Mehmet Karahan
KU Leuven, Belgium/Uni-Twente, Netherlands/Uludag University, Turkey

The paper studies compressibility and permeability of a CNT/CNF-grafted woven carbon reinforcement. It is shown that the pressure needed to achieve the target fibre volume fraction of the perform increases drastically when CNT/CNF are present in the preform. This can lower the achievable fibre volume fraction for economical vacuum assisted light-RTM manufacturing and increase the pressure requirements in autoclave processing. The permeability of the preform is found to be non-affected by the presence of CNT/CNF.

7-Flow and Filtration Modelling of Carbon Nanoparticle Loaded Thermosets in Liquid Moulding

Elisabete Reia da Costa, Alex Skordos and Ivana Partridge
Cranfield University, UK

The incorporation of carbon nanoparticles into polymer matrices, such as epoxy resins, leads to an improvement in electrical, mechanical and thermal properties of the final fibrous composite. A homogenous and stable dispersion of carbon nanoparticles is a prerequisite for the effective transfer of their unique properties to the composite. A stable and homogeneous dispersion is also very attractive for the manufacture of advanced composites for the aerospace industry via liquid moulding technologies. The infusion of fibre reinforcements with nano-filled resins brings along some processing issues that need to be addressed in order to optimise the quality of produced components. The first issue has to do with the high viscosity attained when a high carbon nanoparticle content is used in combination with a good state of dispersion. Injecting resins with high viscosity requires higher pressures and an increasing number of gates in order to accelerate the filling and avoid resin gelation and formation of dry areas in the final part. Another issue concerns the filtration of particles by the reinforcement during the infusion, which if not controlled can lead to structures with graded concentrations. In addition, the clogging of the pores due to accumulation of nanoparticles results in deceleration of the resin flow due to a drop on the reinforcement permeability, which can affect the flow profiles obtained. In this work different carbon nanoparticles (0.25 wt.%) were used to modify an epoxy matrix for liquid moulding. Carbon and glass fabrics were infused in a mould which allows visual inspection of the flow front position. Filtering of carbon nanoparticles was characterised by means of Scanning Electron Microscopy (SEM) imaging and electrical conductivity measurements.

A filling modelling methodology that incorporates filtration effects was developed. The proposed method combines the conventional Darcy's solution with a set of equation representing the flow of suspended carbon nanoparticles. In addition to pressure, two field variables are introduced in the problem: (i) a retention concentration which expresses the amount of nanoparticles retained by the reinforcement and; (ii) a liquid suspension concentration which expresses the amount of CNT in the resin. These two fields are connected via a mass balance which also incorporates a convection term to allow for the transfer of nanoparticles by the flowing resin. The kinetics of retention and possible resuspension are expressed by a constitutive law that assumes linear dependence of suspension rate on the flux of nanoparticles and of resuspension rate on fluid speed and local retention. Analytical solutions for the simple cases of linear and radial flow are derived, whilst a finite element implementation which allows solution in the case of non-linear material behaviour and complex geometries is developed.

35-Dispersion of Carbon Nanotubes in Resin Systems using Chaotic Mixing

Jie Chen and Ranga Pitchumani
Virginia Tech, USA

Carbon nanotubes and polymer nanocomposites have shown great promise in a wide range of applications, and are the subject of much investigation in recent literature. Uniform distribution and dispersion of carbon nanotubes in polymer matrices is critical in realizing the full potential of composites incorporating the nanotubes. However, dispersion of carbon nanotubes remains a challenging problem. This paper explores the use of chaotic fluid mixing phenomenon for dispersing carbon nanotubes in resin systems. Chaotic advection exponentially stretches and folds fluid in situ and the trajectories of the periodic points in the flow form a braid that leads to so-called topological chaos. It is expected that topological chaos could significantly enhance the chaotic mixing of carbon nanotubes. Computational simulations are used to analyze dispersion effectiveness and the flow features as a function of resin properties, mixing configuration, and carbon nanotube morphology and loading.

91-Nadir Kchit, Farida Bensadoun, Catherine Billotte, Edouardo Ruiz and Francois Trochu.

A Study of Nano-Clay Composites made by Liquid Composite Molding

Polytechnique de Montreal, Canada

This study seeks to improve the mechanical and flammability properties of glass fiber reinforced unsaturated polyester composites by introducing nanoclay particles in the resin. The dispersion of nanoparticles is the most important parameter in nanocomposite fabrication. Several mixing techniques were tested and evaluated, and the resulting mixture was analyzed by rheology, mechanical tests and microscopy. The best approach was found to be the sonication of the nanoparticles dissolved in the styrene, followed by the addition of the unsaturated polyester (UP) resin while stirring mechanically the mixture and finally, letting the added styrene evaporate. Fiber glass/UP/Cloisite30B nanocomposites were manufactured by resin infusion (SCRIMP for "Seemann Composites Resin Infusion Molding Process"). Mechanical properties such as interlaminar shear strength, flexural properties and fracture toughness were determined and compared to conventional fiber glass/UP composites. The flammability properties were also measured in the 60 s vertical burn test and compared to both conventional fiber glass/UP composites and fiber glass/UP composites with addition of flame retardant APP. The addition of 3wt.% of nanoclay improved on one hand the impact resistance by 10% compared to the conventional composite. On the other hand, the flammability improved by 30% when compared to conventional composites and by 5% when compared to conventional composites with 30wt.% APP. Hence using nanoclays brings a definite improvement as long as it remains as viscosity of the mixture remains reasonable for processing by resin infusion.

Day 4: Thursday July 15, afternoon	
	Auditorium
13h45-14h45	**Nanocomposites 2** Chair: Dr Pascal Hubert, Mc Gill University, Canada
13h45	42-Development of manufacturing process for polymer/carbon nanotubes network composites Pavel Riha, Petr Slobodian, Robert Olejnik and Petr Sáha T Bata University/Academy of Sciences, Czech Republic
14h05	82-Study of the Processing Conditions of PCL/clay nanocomposites: morphology, molecular weight degradation, thermal and mechanical properties Leandro Ludueña, Vera Alejandra Alvarez and Analia Vazquez INTEMA/Uni Buenos Aires, Argentina
14h25	93-Quantification of nanoparticle dispersion techniques using the Poisson distribution Benjamin Boesl and Gerald Bourne US Army Research Lab/Uni Florida, USA
15h00	***End of conference***

42-Development of manufacturing process for polymer/carbon nanotubes network composites

Pavel Riha, Petr Slobodian, Robert Olejnik and Petr Sáha
T Bata University/Academy of Sciences, Czech Republic

The progress in fabrication and application of polymer/carbon nanotubes (CNT) composites depends on how effectively CNT properties are integrated for the benefit of composite system. Currently, the CNT are used mostly as particulate reinforcement, what accounts for a ten to thirty percent increase in the materials' performance. The technical problems, such as CNT aggregation and dispersion do not allow achieving efficient and effective load transfer to dispersed CNT what results only a modest material reinforcement. For reaching the theoretical values of CNT properties the composite should be loaded evenly with very high volume filler fraction and the CNT should provide good interfacial bonding between the CNT and the polymer chains.

The promising method to fabricate dense polymer/CNT composites is to link the polymer with the preformed entangled carbon nanotubes network structures of buckypaper (BP). The network can transfer maximally unique CNT properties into the composite and bring substantial improvements in structural strength, weight savings and energy consumption. The first polymer with CNT network was fabricated in 2001 when it was managed to disperse nanotubes into a liquid suspension and then to filter it through a fine mesh. Consequently, the nanotubes sticked to one another and formed a thin film of pure nanotubes which was fixed by polymer solution to form a polymer composite. This, rather laborious procedure, may be circumvent by interlocking porous polymer filtrating membrane with entangled CNT. The membrane on which CNT collect and form a network during CNT suspension filtration is infiltrated partly by CNT and that way linked with the CNT network.
To increase the polymer/CNT network interconnection, a hot press molding process was used to make composite sheets. Finally, the solid bulk composite was manufactured by hot pressing from the stacked multiple-layers of sheets. Both the composite sheets and bulk polymer/CNT network composites were subjected to tensile tests and the electric resistance tests.
The theoretical model was developed to predict the influence of compressive deformation on resistance of the polymer/CNT network composite that is dominated by the intercontact resistance between nanotubes. The local force between nanotubes increases during the compression allowing a better contact between them what in turn lead to the decrease of intercontact resistance. The total resistance of the composite is considered to be governed by the distribution of individual intercontact resistances that can be described by the cumulative distribution function for the two-parameter Weibull distribution. The measured inverse dependence of the macroscopic composite resistance on compressive strain is in accordance with the model prediction.
The project was financially supported by the Czech Ministry of Education and Sport (MSM 7088352101), the Czech Ministry of Industry and Trade (project 2A-1TP1/068), the Grant Agency of the Academy of Sciences (GAAV IAA200600803) and by the Institute of Hydrodynamics Fund AV0Z20600510.

82-Study of the Processing Conditions of PCL/clay nanocomposites: morphology, molecular weight degradation, thermal and mechanical properties

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Packaging is the biggest industry of polymer processing. Food industry is its principal customer. Despite environmental problems, polymer packaging European market is increasing in about millions of tons per year. Foreseeing future laws about reducing the weight and volume of these products, cheap and biodegradable polymeric products are receiving growing attention. Polycaprolactone (PCL) belongs to this class of synthetic biodegradable polymers. PCL is linear, hydrophobic and partially crystalline polyester that can be slowly consumed by micro-organisms. The performance of PCL can be greatly enhanced by the dispersion of nanometer-size particles. From previous works it was found that 5 wt. % of montmorillonite modified with dimethyl, dehydrogenated tallow, quaternary ammonium (Cloisite 20A supplied by Southern Clay Products) leads to the best dispersion degree of the reinforcement inside the PCL matrix. In this work the effect of processing conditions on the morphology, molecular weight and mechanical and thermal properties of the pure matrix and PCL/C20A nanocomposites was studied. For this porpoise the resident time (2, 3 and 4 minutes), the temperature profile along the compounder barrel ([60,80,100]°C; [60,90,120]°C; [70,100,130]°C) and the screw rotation speed (50, 100 and 150 rpm) were changed from the reference processing condition (2 min;[60,90,120]°C;100rpm). The as extruded materials were characterized by transmission electron microscopy in order to analyze the clay morphology, gas permeation chromatography to study the possibility of polymer molecular weight degradation by severe processing conditions and differential scanning calorimetry to find differences in the crystallinity of the matrix. Then, films 0.5mm thick were prepared by compression molded to be mechanically characterized by static tensile tests.

93-Quantification of nanoparticle dispersion techniques using the Poisson distribution

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This article presents a technique to quantify the particle dispersion state of a nanocomposite through comparison to the statistically random Poisson distribution. Two dispersion techniques (ultrasonic and orbital shear mixing) were used to create nanocomposites consisting of a small volume percent of ZnO nanoparticles dispersed in an epoxy matrix. The particle fields were imaged in three dimensions using a tomographic process within a focused ion beam. The three dimensional particle fields were obtained from multiple random locations across multiple samples. The particle fields were then digitized using data analysis software where the particles were treated as discrete points in the field. The dispersion state of the field was then quantified by comparing the number of discrete points (particles) within a defined interrogation area to the expected value determined from the Poisson distribution. Using this analysis tool, the fabrication techniques were compared for their relative effectiveness in creating a random distribution of nanoparticles. Results showed that the dispersion of nanoparticles in composites fabricated through the use of an orbital shear mixing device compared favorably to those fabricated using ultrasonic mixing techniques while dramatically reducing the sample preparation time and complexity, as well as allowing for increased industrial scalability.

Notes