Institution: BRUNEL UNIVERSITY (H0113)

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Reduction of non-degradable waste from used plastic food packaging materials

1. Summary of the impact (indicative maximum 100 words)

The production of plastic (polymer) waste and the difficulties associated with its disposal is a major environmental challenge. Many polymer food packaging structures are made using thermoforming processes in which hot thin oil-based polymer sheets are forced under pressure into moulds and then cooled to become thin-walled packaging structures. These structures are not eco-friendly and do not degrade after use. Thus unless they are recycled, which is a complicated process and mostly does not happen, these structures cause major environmental problems worldwide.

Researchers in Brunel Institute of Computational Mathematics (BICOM) have undertaken extensive computational modelling of the thermoforming of packaging structures made from bio-materials (thermoplastics). This computational work, together with the necessary laboratory experiments which were executed by Brunel engineers, has contributed to a far better understanding of the behaviour of starch-based biodegradable food packaging. In turn, the availability of such knowledge has contributed to the steady move by food packagers and food retailers towards the adoption of such packaging which is helping to reduce the amount of long term non-biodegradable waste produced.

2. Underpinning research (indicative maximum 500 words)

Since 1993 Professor J R Whiteman, Drs S Shaw and M K Warby, and research students in BICOM have undertaken research into the computational modelling of thermoforming processes for thin polymeric sheets. Initially for oil-based materials, the research covered the large deformation of hot polymeric sheets into moulds in order to form thin-walled packaging structures. New applications were treated and numerical techniques based on the theoretical work [1] were proposed. These computational models required knowledge both of the viscoelastic/elasto-plastic behaviour and of the material properties of the oil-based polymeric materials. Design tools, based on finite element models of forming processes, were delivered to the British companies: CMB Technology (CarnaudMetalBox plc); Autotype International Ltd; John McGavigan Ltd [2]-[4]; and to the US Army Research Laboratory, Langley. The state was reached whereby, for many relevant packaging shapes, the wall thicknesses of the structures could be predicted for a range of polymeric materials such as Bayfol® and Polypropolene.

Over the past two decades it has become increasingly clear that oil-based polymer packaging is creating much non-biodegradable waste, which typically ends up at landfill sites. With this in mind, Whiteman and Warby collaborated with Professor J Song (Department of Mechanical Engineering, Brunel) on a project applying computational modelling and experimental analysis to thermoforming processes for bio-degradable thermoplastic starch sheets. This work, funded by the Department for Environment, Food and Rural Affairs from 2004 to 2008, brought together the industrial partners: Dassett Process Engineering Ltd; Marks and Spencer Plc; Heygates Ltd; Leistritz Extruders; Institute of Food Research; Pactiv Ltd and Northern Foods Plc.

At the time thermoplastic bio-materials were relatively new and, unlike oil-based materials, their material properties were not well understood. In particular, the behaviour of starch-based bio-materials during thermoforming is affected by their moisture content. The researchers at BICOM developed new computational models for the deformation of a bio-plastic membrane during thermoforming, under temperature and moisture content variation. The parameters required for these models were determined experimentally by Song and co-workers using a thermoplastic material sourced by Plantic plc. This research [5]-[8] provides an insight into how different parameters (including temperature and moisture content) affect the wall thickness and other properties (such as strength and stiffness) of a structure during thermoforming. Such information is essential for the design of moulds and processing of raw material while manufacturing starch-based bio-degradable food packaging.

3. References to the research (indicative maximum of six references)

Papers in International Journals:

1. I. Babuska, J.R. Whiteman, T.Strouboulis. Finite Elements; An Introduction to the Method and Error Estimation. Oxford University Press, (2011).
2. M.K. Warby, J.R. Whiteman, W-G Jiang, P. Warwick, T. Wright. Finite element simulation of thermoforming process for polymer sheets. Maths and Computers in Simulation, **61**, 209-218, (2003).
3. W-G Jiang, M.K. Warby, J.R. Whiteman, S. Abbott, W. Shorter, P. Warwick ,T. Wright, A. Munro, B. Munro. Finite element modelling of high air pressure forming processes for polymer sheets. Computational Mechanics **31**, 163-172, (2003).
4. M. Karamanou, M.K. Warby, J.R. Whiteman. Computational modelling of thermoforming processes in the case of finite viscoelastic materials. Computer Methods in Applied Mechanics and Engineering **195**, 5220-5238, (2006).
5. D. Szegda, J. Song, M.K. Warby, J.R. Whiteman. Computational Modelling of a Thermoforming Process for Thermoplastic Starch. American Institute of Physics, Proceedings **908**, 35 – 47, (2007).
6. D Szegda, Experimental Investigation and Computational modelling of the Thermoforming Process of Thermoplastic Starch. PhD Thesis, School of Engineering, Brunel University, (2009). http://bura.brunel.ac.uk/handle/2438/3445
7. S. Shaw, M.K. Warby, J.R. Whiteman. Discretization and modelling error in the context of the rapid inflation of hyperelastic membranes. IMA Journal of Numerical Analysis, **30** 302-333, (2010).
8. S. Shaw, M.K. Warby, J.R. Whiteman. Computational Modelling of Some Problems of Elasticity and Viscoelasticity with Applications to thermoforming Projects. IJNAM **3**, 320-329, (2012). http://bura.brunel.ac.uk/handle/2438/6699

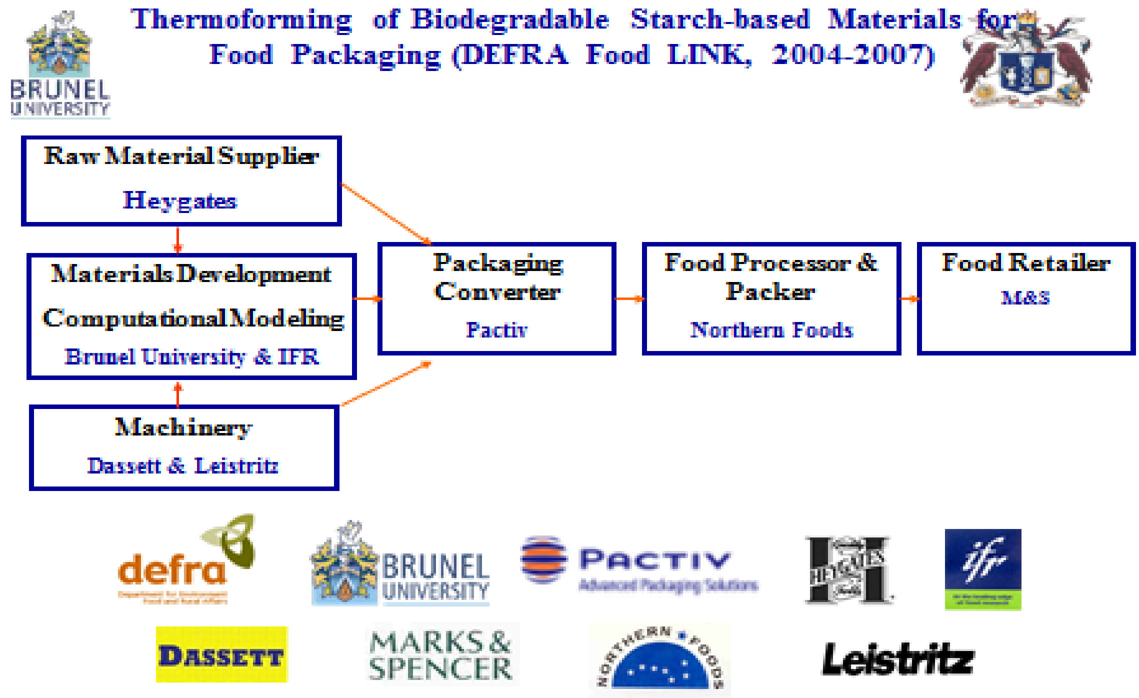
Background Research Grants and Contracts, with Outcomes

- From European Community, 750,000 EU, Jan 1994 - Dec 1996, Numerical and Physical Study of Material Forming Processes (Collaboration with Univs of Paris, Stuttgart, Aachen, Twente, Eindhoven, Palermo, Swansea) & companies from the European polymer industry, particularly Elf-Atochem AG and Centre de Mise en Forme des Matériaux, Sophia Anlipolis, France. Outcome: Reports on thermo- forming processes produced for the network and associated companies.
- From EPSRC, £176,000, Sept 1999-Aug 2003, Computational Modelling of Thermoforming and In-Mould-Decoration Processes. Collaboration with Autotype International Ltd and John McGavigan plc, who contributed an additional £90,000. Grant under the EPSRC Material Processing for Eng Applics programme. Outcome: Design tools produced based on finite element models of forming process for transforming thin polymer sheets (primarily BAYFOL®) into thin-walled structures. Results and software for associated In-Mould-Decoration processes delivered to companies. PI Whiteman.
- From United States Army Research Office, Durham, NC, $223,433, Aug 2000-Nov 2003, Adaptive Space-Time Finite Element Methods for Dynamic Viscoelastic Problems. Outcome: Numerical schemes produced and tested in collaboration with US Army Research Laboratory, Langley, Virginia. PI Whiteman.
- From EPSRC, £39,341, Jan 2001-July 2004, Nonlinear Modelling and Computational Simulation in Applied Polymer Viscoelasticity. Grant under the Engineering International Collaboration Programme. Outcome: Numerical schemes produced in collaboration with colleagues from the US Army and ICES, University of Texas at Austin. PI Whiteman.
- From United States Army Research Office, Durham, North Carolina, $249,287, Aug 2004 – July 2007, Development of Multi-adaptive Simulation Technologies for Nonlinear Solid Polymer Viscoelasticity. Outcome: Numerical schemes produced in collaboration with US

Army Research Laboratory, NASA Langley, Virginia, and reports and code delivered. PI Whiteman.

- From DEFRA Food LINK Programme, 2004 – 2008, Thermoforming of Biodegradable Starch-Based Materials for Food Packaging. Biodegradable Starch Mano-Composites for Thermoformable Film Packaging for Food Products (AFM 200) – FT1505. PI Song.

4. Details of the impact (indicative maximum 750 words)



Packaging structures based on thermoplastic bio-materials are being increasingly used by food retailers with the result that, as they are bio-degradable and/or compostable, the amount of waste which is being produced is being significantly reduced. This research has contributed to the steady increase worldwide in the use of biodegradable plant based materials in food packaging structures. This uptake is, in turn, generating a demand for further knowledge of the material properties and behaviour of thermoplastic bio-materials.

The thesis [6] and all the computational results on the forming processes for thermoplastic food packaging containers were delivered to the company **Plantic** plc, (http://www.plantic.com.au), the world's largest manufacturer of starch based materials for packaging, who sourced the materials. In response, Plantic stated that 'the company is pleased to receive the outcomes of the project which will be included on our website and which will provide technical information for our clients, many of which are multinational firms.' Furthermore, **Pactiv** plc (http://www.pactiv.com), one of the largest suppliers in the world of food containers for packaging (e.g. to Marks & Spencer plc), similarly confirmed that 'the outcomes from the project will help us to modify our designs and processing facilities for packages produced from new eco-materials.'

There is strong motivation from governments worldwide for the adoption of biodegradable materials in food packaging, both to reduce the amount of non-degradable waste that litters the world and also to avoid the use of oil-based products in the packaging arena.

The research described above has been disseminated through presentations made at a number of major international conferences including:

i) NUMIFORM 2007, 5-day international conference on Materials Processing and Design: Modeling, Simulation and Applications, University of Porto, Portugal (see [5]).
ii) CMMSE 2010, 4-day international conference on Computational and Mathematical Methods in

Science and Engineering with approximately 130 presentations, Almeria, Spain. (Proceedings, Volume 3, p 849-852, ISBN13: 978-84-613-5510-5). http://gsii.usal.es/~CMMSE/images/stories/congreso/volumen1_10.pdf

In addition, the work is cited by engineers/mathematicians world-wide, for example:

i) Thongwichean, T., Pahlakormkule, C., Chaikittiratana, A. Finite element analysis for thermoforming process of starch/biodegradable polyester blend. AIJSTPME 5(2), 33-37, (2012).
ii) Saedpanah, F. A posteriori error analysis for a continuous space-time finite element method for a hyperbolic integro-differential equation. BIT Numer Math (2013) 53:689–716 (2013).

5. Sources to corroborate the impact (indicative maximum of 10 references)

Pactiv plc was closely involved in the DEFRA funded project. Since the end of the funding period Pactiv plc has been taken over by the Pregis Corporation. The contact is now with Pregis.

Contactable:

D and D Manager, Pregis (formerly Pactiv).

General Manager – Technology, Plantic Technologies Ltd.