Institution: University of Bradford

Unit of Assessment: B12

Title of case study: Expertise in die drawing of polymers leads to new materials, new manufacturing processes, new products and a new company

1. Summary of the impact

Research into die drawing of polymers at Bradford has resulted in a new building material that is stronger and more durable than wood; and new bioresorbable shape-memory polymers for use in medical implants that reduce patient trauma and costs. The wood replacement material is commercialised by the United Forest Products/Dow USA 2010 spin out company Eovations LLC for use in a range of construction applications; the bioresorbable shape-memory polymers have recently been patented (4 patents filed) by Smith & Nephew for use in soft tissue fixations. These impacts form part of a range of exploitations of our oriented polymer technology.

2. Underpinning research

Led by Phil Coates (Professor 1993-present) with Bradford academics John Sweeney (Professor 1995-present) and Dr Phil Caton-Rose (Research Assistant 1998-2000, PDRA 2000-2006, Lecturer 2006-present) as part of the Polymer Interdisciplinary Research Centre, the team (in collaboration with Leeds, IM Ward FRS) has worked on bridging the gap between the science of solid-phase processing of polymers and advanced manufacturing technologies since the early 1990s. Our particular focus is on die drawing of polymer profiles and hot compaction of oriented polymer composite sheets. Our original EPSRC-funded work (1998 onwards) was developed further through partnerships with industry, investment by TSB and further EPSRC support (2011 onwards), and has established the group at Bradford as the leading solid-phase polymer orientation group in the world, evidenced by journal publications, our key, unique, research reference books (1,2), patents, and our industrial research contract portfolio.

The research has developed fundamental understanding of the mechanics of solid-phase deformation behaviour of polymers, with new constitutive relationships and physical modelling used to achieve molecular-related understanding of deformation and feed computer modelling and control of structure. This has underpinned inventive steps in the design and implementation of batch and continuous processes to exploit the significant property enhancements available through solid-phase forming, particularly overcoming hurdles of process rates, and the novel exploitation of filled polymers. Die drawing (1,3,4), invented by Coates, involves pulling solid polymers at temperatures above their glass transition but below their melting point, through converging dies, achieving controlled oriented structures: physical properties increase monotonically with draw ratio (cross sectional area change imparted), and selected oriented polymers exhibit useful shape memory behaviour (3). It is applicable for all length scales (micro to macro products) and a wide range of polymers and cross sections, including biaxially oriented tubes. Initially a batch process, we first demonstrated continuous processing, with industry (5), and have developed fundamental modelling of orientation processing and deformation (6).

Tensile drawing of *filled* polymers normally leads to failure. However, our fundamental understanding of the stress, strain and strain-rate fields incurred in drawing polymers through convergent dies (1), supported by multi length scale finite element analysis, showed that it was possible to control cavitation around fillers to avoid catastrophic failure, by simultaneously strengthening the polymer matrix through molecular orientation and development of crystal continuity (4). By die design, controlled cavitation (in a combined compressive normal stress at the die entry, but increasing tensile axial stress through the die) produces lower density products, and orientation causes higher product strength and stiffness, allowing continuous, high-speed production (~metres per minute) of controlled property products (see Dow exploitation).

We developed a micro-scale version of the die drawing process for bioresorbable materials based on modified filled polylactic acids, exhibiting shape memory (through recovery of the controlled orientation), suitable for cementless in-body fixations (see Smith & Nephew exploitation). Die drawing to a selected draw ratio allows matching of the physical properties such as stiffness and strength of bone for joint or soft tissue repair. The challenging requirement to have shape memory activation at body temperatures has been addressed in our research and patents.

This research has been supported commercially by BP, Solvay, Sabic, Dow, Smith & Nephew, Netlon Tensar, Bridon International, Nylacast, and Arterius in programmes from 1995 to date, totaling ~£1.25m. This work has resulted in 11 jointly owned patents (6 published in the last year).

3. References to the research

1. Ward IM, Coates PD, Dumoulin M. (eds.) (2000) *Solid Phase Processing of Polymers*. PPS Series, Cincinnati, OH: Hanser Gardener Publications.

2. Ward IM, Sweeney J. (2012) *The Mechanical Properties of Solid Polymers*. (3rd Edn), Chichester: Wiley.

3. Coates PD, Caton-Rose P, Ward IM, Thompson G. (2013) Process structuring of polymers by solid phase orientation processing. *Science China: Chemistry* 56(8): 1017-1028.

4. Coates PD, Davies GR, Duckett RA, Johnson AF, Ward IM. (1995) Some routes for tailoring of polymer properties through processing. *IChemE Transactions*, ChERD 73(A): 753-770.

5. Taraiya AK, Nugent M, Sweeney J, Coates PD, Ward IM. (2000) Development of continuous die drawing production process for engineered polymer cores for wire ropes. *Plastics, Rubber and Composites* 29(1): 46-50.

6. Sweeney J, Caton-Rose P, Coates PD. (2002) The modelling of large deformations of pre-oriented polyethylene. *Polymer* 43: 899-907.

(1), (3), and (6) are the three references best indicating the quality of the work.

Evidence for the quality of the research is also evidenced by the award of the following peer-reviewed and competitive grants:

EPSRC GR/M37417 *Solid phase processing of polymers: stress-strain laws for process and product property prediction*, £134k, 1999-2000, PI Sweeney.

TSB CRD/134, TPAB019K *The design & manufacture of smart materials for orthopaedic applications*, £245k, PI Coates, 2008-2010.

Innovation and Knowledge Centre RTD Proof of Concept: *Smart Fixation Devices for Soft Tissue Repair*, Ref RG.MECH.476547, PI Coates 1.6.11-31.12.11, part of EPSRC/GP032483/1 Regenerative Therapies and Devices, PI Fisher, Leeds (2009-2014).

EP/K004204/1 *Science Bridges: Bradford-China Programme for Pharmaceutical Sciences and Medical Technology*, £1.25m, 2009-2012, PI Coates.

EP/G042365/1 GLOBAL *Promoting research partnerships in Advanced Materials for Healthcare*, £499k, 1.4.12-31.3.13, PI Coates.

KTP Nylacast *KTP008611* £180k, 2012-2014, PI Caton-Rose.

4. Details of the impact

Novel Polymer composite building materials – spin out company in the USA
Dow Building Products Inc. (a,b) had a goal of inventing the leading deck board material, and approached us in 2004, because of our previous and ongoing research and facilities in solid phase orientation processing of polymers as well as our group's IP portfolio and track record with industry in this area (including Tensar geogrids, Bridon International Trulift elevator rope cores (b), and hot compaction technology resulting in CURV^{TM} material currently exploited by Samsonite). Dow realized *"that the development of thermoplastic composite solid state die drawing technology in the world was now centred in the University of Bradford"* (a). In 2005 we started a Dow-funded project to produce a light weight, high-stiffness material to act as a wood replacement in civil engineering applications. 2005-2010 funding was £305k cash and >£350k in-kind support (materials, technical input). This support demonstrates the commercial value to the company of this product of our research, underlined by their further US investments of $2m and then $16m indicated below, and the significant patent portfolio now in place (a,c).

Our research and development work took polypropylene plus 46 wt% talc, initial density of 1.34 g/cm^3 and flexural modulus 1 GPa, to a similar-to-wood product target density of 800kg/m^3 and 4 GPa modulus. Dow Building Products invested in the manufacturing technique and product we developed, our knowledge allowing Dow *"to significantly accelerate its research efforts"* (a). Our collaboration in setting up a $2m pilot line in Michigan (2008-2009) to demonstrate continuous processing, first demonstrated with Bridon International (b) in 2000, *"contributed to successful scale-up"* and *"provided valuable trouble shooting capabilities"* (a). The products replicate the structure of wood (exhibiting a fibrous nature due to oriented polypropylene) with key performance enhancements in weatherability, toughness, and reliability, and include decking, cladding, fencing, and trim.

In 2010 Eovations LLC was formed in the USA by United Forest Products/Dow to further develop and commercialize 'Eotek' products (a,d). This $16m investment created 64 jobs (13 in the research area). Our fundamental contribution is explicitly credited on the Eovations web site (c,e) and in the USA technical press (f), while the Eotek website (g) shows the hurricane resistance of our materials. Dow filed 3 patents with us as co-inventors, prior to the launch of Eovations, with 10 auxiliary patents filed to date (a,h). We transferred ownership of specific polymer orientation technology to Eovations, LLC in early 2010 (h), retaining the rights to develop IP for our other potential routes to exploitation, e.g. shape memory products for use in health care (see below) and new research areas in health including oriented stents and anisotropic drug elution products. The company has three lines in Michigan, and a new production plant opening in Alabama. Because of commercial confidentiality in this early phase of the company, they have not disclosed market share, but have indicated it is millions of dollars (a). Follow-on products will include marine, transportation, and recreation applications.

Shape memory – tissue repairs for all ages
Die drawn shape memory polymers products based on Bradford research and aimed at the rapidly growing world market for both younger (sports injuries) and older (arthritic/ osteoporotic/ trauma-involved) patients, are being commercialised by Smith & Nephew (S&N), a global leader in medical devices (i). Estimated 2013 markets (USA and Europe) for shoulder fixations are 1,109,000 procedures, of value ~$856m and knee ligament reconstructions at 982,000 procedures, of value ~$309m. Our programme with S&N, building on our polymer orientation research, focussed on high performance bioresorbables (2006-2008), bone and ligament fixation (smart materials) (2008-2010) and design /manufacturing feasibility for shape memory fixations (2013). Collaboration with S&N continues, for example two joint EPSRC research proposals in 2012 each included support (~£200k contribution from the company) on manufacturing and biomedical materials development have been submitted.

Shape memory polymer implants match conventional tissue fixation devices, with significant additional benefits as they reduce trauma to patients and total costs. Being smaller devices they need smaller incisions with faster patient recovery times, improve placement accuracy of fixations and reduce product inventory, as an expanding device will be able to cover a range of hole sizes. Our modified poly-L-lactic acids shape memory implants provide sufficient locking stresses, with the required profile of decay of stress for potential in-vivo applications, and have excellent biocompatibility. Smith & Nephew filed four patents with us in October 2012. The programmes with Smith & Nephew have been supported with £567k cash and >£200k in kind. This support demonstrates the commercial value to the company of this product of our research, underlined by their significant patent portfolio now in place (i).

5. Sources to corroborate the impact

Contacts for indication of impact (of the specified products and our world-leading capabilities in solid phase orientation processing) include:

a. Research Director of Eovations LLC, and the key contact for the full research cooperation with Dow; he can comment on the unique position Bradford holds worldwide for solid phase orientation processing of polymers and polymer composites.

b. Technical Manager, Bridon International – interests in exploitation of oriented polymers in cable applications (e.g. engineered elevator cores, marine cables) and continuous die drawing – the first successful demonstration of this was with Bridon.

c. http://www.eovationsllc.com/about/index.htm – the page on the web site for the Dow/ Universal Forest Products spin out, Eovations LLC commercialising our solid phase orientation technology, which explicitly credits us.

d. General Operations Manager, Universal Forest Product Incorporated (UFPI, who own the majority of Eovations) liaison with Eovations; he can comment on UFPI's vision for the technology.

e. www.eovationsllc.com

f. http://www.plasticstoday.com/articles/real-wood-feel-function-wood-polymer-composite-041520132 Article in US trade magazine, Plastics Today, published April 25th 2013 (available as pdf if required) – extolling the virtues of Eotek products, and clearly crediting the Polymer IRC at the University of Bradford.

g. http://www.eotek.com/resources/default.aspx - a striking example of hurricane impact resistance in the oriented polymer composite building products, achieved by our technology.

h. Recently retired IP Manager from Dow Building Products, worked on the IP for the Bradford/Dow/Universal Forest Products (UFPI) large scale thermoplastic composite solid state die drawing technology.

i. Head of Biomaterials, Smith & Nephew: - able to reflect the value of Bradford's collaborative research on shape memory materials, with input from S&N colleagues in Boston and St Louis.