(PRE)FORMING THE FUTURE OF CARBON FIBRE COMPOSITES

An International Specialised Skills Institute Fellowship.

DR TIM CORBETT

Sponsored by Manufacturing Skills Australia

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1. Acknowledgements

The Fellow would like to thank the following individuals and organisations who generously gave their time and their expertise to assist, advise and guide him throughout his MSA Rilda Mossop Fellowship International Fellowship

Awarding Body – International Specialised Skills Institute (ISS Institute)

The ISS Institute plays a pivotal role in creating value and opportunity, encouraging new thinking and early adoption of ideas and practice by investing in individuals.

The overarching aim of the ISS Institute is to support the development of a "Smarter Australia". The Institute does this via the provision of Fellowships that provide the opportunity for Australians to undertake international skills development and applied research that will have a positive impact on Australian industry and the broader community.

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Since its establishment 28 years ago, ISS Institute has supported over 450 Fellows to undertake research across a wide range of sectors which in turn has led to positive change, the adoption of best practice approaches and new ways of working in Australia.

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Governance and Management

Fellowship Sponsor - Manufacturing Skills Australia (MSA)

The Fellow sincerely thanks Manufacturing Skills Australia for providing funding support in the name of Rilda Mossop to the ISS Institute for this Fellowship. The purpose of the MSA Rilda Mossop Innovation Study Award Fellowship Program is to extend the capability and performance of Australian manufacturing through education and training with resulting workforce development. MSA is the national body responsible for ensuring that manufacturing enterprises have the workforce skills they need to be globally competitive now and into the future. The Fellowship provides an opportunity to gather international intelligence on skills and technologies not available in Australia to benefit the Australian manufacturing industry and support workforce skills development in the following sectors:

• Competitive Systems and Practices • Aerospace • Chemicals, Hydrocarbons Refining • Furnishing • Laboratory Operations • Manufactured Mineral Products • Metal, Engineering and Boating • Plastics, Rubber and Cablemaking • Recreational Vehicles • Textiles, Clothing and Footwear

Personal Acknowledgements

The Fellow gratefully acknowledges his workplace mentor Haydn Law who helped during all aspects of the Fellowship, from the initial Fellowship application, setting a direction, internal workplace dissemination and finally assistance with reviewing the Fellowship report. He would also like to thank Dr Ashley Denmead for his input during final drafts of the report.

The Fellow acknowledges his workplace Carbon Revolution's support in undertaking the Fellowship and releasing the Fellow from his regular duties during the overseas travel component, and subsequent allocation of time in preparation of this report.

The Fellow appreciates and acknowledges the support of ISS and key staff Ken Greenhill, Paul Sumner, Fiona Waugh, Nick Johns, Grace Barrand, Keith Beecher and Wendy Draayers for their assistance throughout the Fellowship, and persistence with helping the Fellow to conclude his report.

The Fellow thanks and acknowledges the universal support received at every organization that he visited.

The Fellow thanks and acknowledges Composites Australia for their assistance with disseminating knowledge from the trip beyond the Fellow's immediate workplace.

Interested parties and potential future Fellow's can find more information about current and upcoming Fellowship opportunities at: www.issinstitute.org.au

Previous Fellowship reports pertinent to the Australian manufacturing industry can be found at: http://www.issinstitute.org.au/fellowships/fellowship-reports/manufacturing/

2. Executive Summary

In 2016 the Fellow travelled to seventeen places throughout Germany and the UK to carry out applied international research as part of an International Specialised Skills (ISS) Institute and Manufacturing Skills Australia (MSA) Rilda-Mossop Fellowship. The Fellow identified a general lack of Australian industry expertise in complex dry fibre preforming, preform assembly and injection of complex parts via the RTM process to produce truly 3-dimensional carbon fibre composite structures that feature excellent surface finish. The skill shortage was identified as part of the Fellow's ongoing position at Carbon Revolution producing parts for the automotive industry, and the Fellow's prior position investigating novel knitting method to preform fibrous material prior to resin injection.

The key findings were:

» Gross level resin richness is typical throughout the industry, even on the back surface of 'A-class' surface finish structures

» Adoption of braiding and over-braiding as a standard automotive serial production process for laminating carbon onto a mandrel

» Most automotive RTM and HP-RTM processes were actually quite simplistic 2D flat panel moldings (not 3D).

Tangible benefits for the industry, occupation and the Fellow's vocational enhancement to emerge from this Fellowship were:

» Immediate adoption of fibre handling expertise in a revolutionary new preforming machine at the Fellow's workplace

» Enhancement of the Fellow's understanding of current state-of-the-art in fibre handling,

Upon return from the travel component of the Fellowship, the main findings of the trip were disseminated through in-depth face to face meeting/s with the current automotive industry leader moulding Carbon Fibre RTM parts in Australia. The Fellow welcomes the opportunity to directly share his experience/s with similar industry leaders and has reached out to Composites Australia, who have featured an article in their Issue 50, July 2019 magazine to assist with dissemination..

In addition to the above, further key recommendations from this Fellowship are:

1. adoption/acquisition of an HP-RTM injection machine at either a University with advanced composites background, but preferably at an industrialisation and technology demonstrator such as CSIRO, Carbon Nexus or a University with composites expertise.

2. creation of a preforming precinct, possibly tied to the above, to demonstrate and improve preforming processes to improve technology uptake in Australian enterprises.

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Previous Fellowship reports pertinent to the Australian manufacturing industry can be found at: http://www.issinstitute.org.au/fellowships/fellowship-reports/manufacturing/

3. Fellowship Background

Fellowship Context

The Fellow identified a general lack of industry expertise in complex dry fibre preforming, preform assembly and injection of complex parts via the RTM process to produce truly three-dimensional carbon fibre composite structures that feature excellent surface finish. The skill shortage was identified as part of the Fellow's ongoing position at Carbon Revolution producing parts for the automotive industry, and the Fellow's prior position investigating novel knitting method to preform fibrous material prior to resin injection.

The reason this Fellowship was important was due to two key facts:

1. Within the industry, fibre handling and fibre delivery to mould tooling accounts for the largest cost component of technical composite components, typically 60% or more of the cost of moulded components. Better fibre handling and preforming technology is required to fill this gap.

2. Resin shrinkage during cure results in significant rework after moulding on aesthetically critical components, which can add significant cost to the process. This is particularly challenging when considering RTM composite parts. Better understanding of the process is needed, and methods to combat this limitation delivered to the Australian manufacturing skills sector.

Fellowship Aims

1. To examine and understand state-of-the-art in resin transfer moulding (RTM) and its various derivatives, the associated handling equipment and machine building capabilities.

   » Resin transfer moulding (RTM)

   » Compression RTM,

   » High pressure RTM

   » Gap moulding

2. To examine direct tow handling and fibre placement technologies:

   » Creel technology

   » Tow delivery, handling and management requirements of different deposition methods, e.g: tow winding vs multiaxial fabric stitching.

   » Approaches to binding and stabilization of dry carbon fibre

   » Deposition approaches and typical deposition rates achievable

   » Automatic placement and end cutting

   » Tailored fibre placement by stitching (TFP)

   » Fibre patch placement (FPP)

3. To examine and understand various fibre conversion processes, converting tow to:
   - Braided fabric
   - Multiaxial non-crimp fabric
   - 2d and 3d woven fabric
   - Hybrid approaches
4. To examine any other novel preforming or fibre handling and management technologies, such technical fibre pick and place robotics, end effectors, and multilayer ultrasonic cutting capability.

Fellowship Methodology

The Fellowship was conducted over a 3-week period from 11th to 29th July 2016. The Fellow targeted leading Industry and Institutional Organisations and was able to visit seventeen organisations spread geographically over Germany and the UK during the 3-week period.

A brief description and summary of each organisation is provided, followed by a thematic summary of:

- braiding,
- tailored fibre placement,
- preforming,
- fibre handling technology,
- RTM processing,
- the broader implication of the level of resin richness noted on all components

Fellowship Biography

Name: Dr Tim Corbett

Employment: Composites Technical Specialist, Carbon Revolution

Qualifications:

- Bachelor of Engineering (Manufacturing) 1st Class Honours 2002
- Doctor of Philosophy, Carbon Fibre Composite Material Science, 2009

Short Biography

Tim Corbett graduated from the School of Engineering and Technology at Deakin University in 2002. During his undergraduate degree, he developed a passion for human powered vehicles (HPV's) and set about developing an innovative monocoque carbon fibre composite vehicle as part of his final year project in a quest to simultaneously improve the aerodynamics and reduce the mass of HPV's. This set about a life-long passion for composites and the broad array of design opportunities offered by their unique structure.

Corbett completed his PhD within the Deakin University Composites group between 2003 and 2008. He examined a new joining technology for carbon fibre materials known as Melding. During this time, he was involved with the Deakin University Formula SAE team, developing the 2003 vehicle bodywork. In 2004 he built carbon fibre wheels for the race car and assisted with their development through 2005 and 2006. These became the forerunner to Carbon Revolution, which further developed and commercialised the wheel technology.

Corbett completed a post doctorate between 2009 and 2012, working on a collaborative project between Futuris Automotive, CSIRO and Deakin University to assess and develop a knitted seat structure. The project won the SAE Automotive Engineering Excellence Silver Award in 2010.

Corbett has since been employed at Carbon Revolution as a technical specialist. He has covered a variety of areas from material characterization, process optimisation, process development, advanced engineering and new process introduction. His desire to improve manufacturing simplicity highlighted a need to understand state-of-the-art industry practice across a range of supporting processes helped form a rationale for the Fellowship.

4. Abbreviations/Acronyms/Definitions

Compression RTM:
A version of resin transfer moulding, where the two sides of the mould tooling can move relative to each other during injection and cure. After the resin is injected, pressure is applied to the two halves of the mould, and they are allowed to move closer to each other during cure. This allows for volumetric shrinkage of resin and purportedly improves surface finish of RTM parts.

Creel:
Carbon fibre tow is wound onto bobbins after it is produced on a carbon fibre line. A creel is a device that allows controlled unwinding of the tow from the bobbin to feed carbon fibre tow to a subsequent process. Many or few creels may be needed depending on the application. Tension feedback can range from simple spring balance through to numeric electric brake control. "Creel" can be used to mean both the singular and plural.

FPP:
Fibre patch placement. Individual patches of dry or prepreg material are deposited on a mould or transfer mandrel to build up a preform

Gap moulding:
A version of resin transfer moulding, where the two sides of the mould tooling are deliberately left partially open in order to create a gap behind the preform that resin can easily flow to. Once the required amount of resin is injected, the tooling is progressively closed, which forces resin through the thickness of the part. Due to the very short through thickness direction, very fast fill times can be achieved with lower injection pressure.

HP-RTM:
High pressure resin transfer moulding. Using pressure between 16 and 50 bar to inject resin into a cavity that has previously been filled with carbon fibre. Due to higher pressure, much higher flow rates and fill times are achieved, but higher mould closure forces are needed to react the increased pressure load.

RTM:
Resin transfer moulding. Using Pressure between 1 and 8 bar to inject resin into a cavity that has previously been filled with carbon fibre.

TFP:
Tailored fibre placement. Typically, a strand or strands of carbon are guided over a carrier material and stitched in place by a following stitch head. The process is repeated and a preform produced with highly customised fibre placement.

Vf
Volume fraction. This refers to the percentage of cross-sectional area of a composite filled with fibre. The higher the number, the higher the loading of fibre in a composite.

5. Fellowship Learnings

The Fellow targeted leading industry and institutional organisations and was able to visit seventeen organisations spread geographically over Germany and the UK during the three week period. A brief description and summary of each organisation is provided, followed by a thematic summary of the key areas of focus: RTM processing, braiding, tailored fibre placement, fibre handling technology and preforming approaches, and the broader implication of the level of resin richness noted on all components witnessed by the Fellow during his travel abroad.

Organisation: Munich Composites GmbH, 11th July 2016, Taufkirchen, Munich, Germany

Contact/s: Felix Frohlich – Managing Director, and Florian Wachter

Munich Composites specialise in the use braiding and over-braiding as a technique for producing composite structures and is a serial producer of a variety of finished composite goods. Munich composites is a young and innovative organisation located within the Airbus innovation facility at Taufkirchen, Munich. Munich has been a successful spinoff of the TUM (Technical University, Munich) innovation program, and started from students who gained experience with braiding machines while studying at TUM. Munich demonstrated a depth and breadth of practical competence in composites and how braiding can be an excellent technological fit in industries outside of aerospace and automotive. They were able to help the Fellow confirm his understanding of braiding basics and both explore and demonstrate a vast range of fibre architectures that can be achieved with braiding.

Organisation: Cevotech, 11th July 2016, Taufkirchen, Munich, Germany

Contact: Felix Michl – Chief Technology Officer

Cevotech is another spinoff from the TUM innovation program. Cevotech specialise in using pick-and-place robots to adhere small patches of dry (bindered) unidirectional roving or patches to create a tailored fibre patch placement (FPP) preform that specifically aligns fibres in the primary directions needed. During the Fellow's visit Cevotech was still in start-up phase and working toward launching a unified CAD-CAM software to interpret preform requirements, predict fibre loading and alignment requirements, and finally integrated robot programming that places material in the required locations. While the technology is impressive and incredibly advanced, compared to other preforming technology the process appeared cost prohibitive to the Fellow from an automotive perspective based on the kg/hour delivery rate claimed to be delivered, versus the capital cost to acquire a production cell.

Organisation: TUM – Technical University Munich - Institute of Carbon Composites LLC – 12th July, Garching Research Campus, north of Munich, Germany

Contact/s: Prof. Klaus Drechsler – Chair of Carbon Composites, TUM department of Mechanical Engineering, Christoph Ebel – Process Technology for Fibres and textiles - Group Leader

The primary objective of the university is training of new engineering students, with ~5300 students at the in the Department of Mechanical Engineering. Coursework is heavily industry oriented featuring applied development projects wherever possible. However, nearly fifty percent of the Institute's funding is derived from industry sponsorship/projects – this was a consistent model across all universities visited by the Fellow. The strong industrial linkages and funding ensured the topics being investigated by the university were/are of relevance to the industry partners. The Chair of Carbon Composites features strong industrial links with the MAI group, the Fraunhofer ICT institute in Augsburg and Inglostadt. The institute has successfully spun-off many of its technologies by fostering close industrial links.

The spinoffs are initially sponsored through the EXIST program, the German Federal Ministry for Economic Affairs and Energy (BMWi). Of great interest to the Fellow were the common research themes shared by many institutes across Germany that implicitly define the challenges faced by the composites industry.

Organisation: IVW - Institut fur Verbundwerkstoffe (Institute for composite materials) – 13th July, Kaiserslaughtern, Germany

Contacts: Jens Schlimmback - Deputy Research Director (Manufacturing Science), David Becker – Research Associate

The Fellow had worked previously with the Deputy Research Director at IVW while completing his PhD on Melding of carbon fibre composites and was able to gain a close and hands on inspection of many elements developed at the IVW facility. The IVW group placed themselves as field leaders in both thermoplastic and thermosetting tape winding and tape laying expertise. The Fellow was able to spend a considerable time with David Becker at their demonstrator office inspecting and discussing many different composites parts, including RTM, back injection, thermoplastic, stitched, continuously compression moulded flat sheet, ultrasonically welded thermoplastic flat sections, and across many different sectors including industrial beams, sports goods, wind energy, automotive and aerospace components. Becker's goal was to standardise measurement methods that establish the permeability of resin through fibrous structure.

Organisation: KSL Composites and PFAFF Industriesysteme und Maschinen GmbH (PFAFF industrial development centre),14th July, Kaiserslaughten and Lorche, Germany

Contact: Johannes Dewald – Global Sales Manager

In the composites industry, KSL is focused on technical embroidery and tailored carbon fibre placement via robotic and interchangeable stitching heads. KSL evolved from the PFAFF sewing machine producers from as far back as the 1970's when they realised they needed to specialise and provide automatable sewing machine units to be competitive with the then growing Chinese labour sector. This led to the automation of many aspects of garment sewing. The Fellow was exceptionally fortunate to tour both the PFAFF industrial sewing centre in Kaiserslautern, and the KSL composites specific department branch office at Lorche. The PFAFF development centre was specifically setup to help customers improve their expertise with their equipment, but also to help guide purchasing decisions. KSL are placed as industry leaders in various stitching technology specifically developed for joining carbon fibre preform material.

Organisation: RWHT Aachen - Institut für Textiltechnik ITA (Textile preforming Institute) and Institut für Kunststoffverarbeitung (IKV) (Institute of Plastics Processing), 18th July 2016, Aachen, Germany

Contacts: Dieter Veit - Academic Director (ITA), Arne Böttcher – Head of department – Composites/PU technology (IKV)

The ITA textile preforming institute at Aachen university was easily the most advanced preforming centre visited by the Fellow during his trip. The institute covered a broad range of technologies with a consistent theme around preforming of composite materials. They had investigated technologies including braiding, tape winding, embroidery and tailored fibre placement, weaving looms and tailored multi-axle (stitched non-crimp) broad good fabric manufacture that also featured tailored fibre reinforcement placement, pultrusion and the use of organo-sheets.

The IKV institute investigate a broad range of plastic injection, compression moulding, spray impregnation and RTM processing of thermoplastic and thermosetting varieties, notably covering both epoxy and urethane formulations, and have a strong understanding of the shrinkage behaviour of resins during their moulding operations.

Organisation: Eurocarbon and Eurobraider, 19th July 2016, Sittard, Netherlands

Contacts: Stephann Voskamp, General Manager

Eurocarbon specialise in serial production of braided tube stock and narrow width woven raw goods used primarily in the composites industry. They produce a large variety of tubestock and can produce custom braided tube. Eurocarbon's sister company Eurobraider specialises in the serial production of over-braided composite preforms and have experience working in the automotive sector and delivering to automotive customers. The Fellow learnt that Eurobraider also offer custom turnkey braiding machines for customers wishing to overbraid components.

Organisation: ZSK Technical Embroidery Systems, 20th July 2016, Kreffeld, Germany

Contacts: Melanie Hoerr, Michael Metzler

ZSK specialise in production of 2D embroidery equipment; they evolved from a garment embroidery background. ZSK Technical Embroidery Systems have found mass adoption in the automotive industry using their technical embroidering equipment to secure strands of wire into seats for in-seat heating. This technology was then adapted to secure carbon fibre rovings/tow to create tailored fibre preforms (TFP) where the carbon can be specifically aligned in the directions needed in the composite structure. The Fellow was impressed with the range of supporting IP that improves machine productivity such as automatic bobbin changeover, and automatic backing material advancement.

Organisation: Van-Wees, 21st July 2016, Tilburg, Netherlands

Contacts: Rein van den Aker

Van Wees specialise in purpose-built machinery for the production of technical textiles in the composites industry, focusing on UD and cross ply/multi-axle technology. They have extensive knowledge of cost-effective creel management, UD thermoplastic and pre-preg impregnation lines, and cross-ply and multi-axle laminating machines. They offer machine building expertise and deliver custom and customised machines.

Organisation: Herzog GmbH, 22th July 2016, Oldenburg, Germany

Contact: Sebastian Stolle

Herzog specialise in the production of a wide variety of braiding machines. They began making machines in 1861 for chords, laces and ropes. Over time they expanded their production to include wire braiding, radial braiding and overbraiding of hoses and wiring looms. In (Herzog's) recent history, they have developed machines specifically for braiding composite material, and have patented the radial braiding method. The Fellow toured their production facility where their focus as premier machine builders (rather than composite specialists) was emphasised.

Organisation: TU Dresden University, 25th July 2016, Dresden

Contact: Andreas Gruhl

While TU Dresden is equipped with a range of high-performance textile equipment such as weaving, knitting, stitch bonding and multiaxle lines, the Fellow was most interested in their braiding capacity: they had a 288-carrier radial braiding machine. The Fellow visited briefly to establish the size and complexity of large-scale braiding machinery designed specifically for braiding carbon fibre.

Organisation: Kraus Maffai, 26th July 2016, Munich

Contact: Erich Fries, Head of Business Unit Composite & Surface

Kraus Maffai are world leader in the area of HP-RTM injection technology. They provide injection moulding, reaction injection moulding and automation packages. Their impingement mixing systems are capable of delivering both epoxy and polyurethane resin systems and offer tooling and injection solutions for both conventional and a range of soft and hard foaming resins.

Organisation: Sigmatex, 27th July 2016, Cheshire, UK

Contact: Claudio Villalobos, Commercial Manager

Sigmatex produce a large range of advanced carbon fabrics ranging from woven spread tow fabrics through to traditional non-crimp dry composite fabric materials. They specialise in woven materials and had a wide range of looms for the production of woven goods including spread tow variants that decrease crimp. They are able to produce tailored weave patterns to produce aesthetic patterns in finished goods of technical composite material, and can tailor weave truly 3D composite structures that can produce net moulded structures. Sigmatex have 2x multiaxle non-crimp lines that are used with both in-line creels and pre-wound + spread tow feedlines.

Organisation: ELG, 28th July 2016 (AM), Coseley, UK

Contact: Frazer Barnes

ELG are a large-scale recycler of carbon fibre composite material. They take a range of input materials ranging from pre-preg offcut waste, dry spool fibre and broadloom fabric, through to finished goods, and convert the waste streams back into a range of usable raw materials depending on the input material. The Fellow was impressed with the level of maturity of many of their processes and quality control and quality assurance systems.

Organisation: Reliant, 28th July 2016 (PM), Luton, UK

Contact: Christian Saville – International Sales Manager

Reliant Machinery build continuous flatbed laminating machines and associated supporting equipment that manufacture laminated automotive fabrics, defence materials such as bullet proof vest interlayers, and a wide range of technical composite precursors from pre-pregs, non-wovens, through to compression moulding of reactive and thermoplastic organosheet. The Fellow was particularly interested in powder binding equipment requirements.

Organisation: WMG – University of Warwick, 29th July 2016 (AM), Coventry, UK

Contact: Professor Ken Kendall

The Fellow visited the Automotive Composites Research Centre located in Coventry. The centre features a 1700 tonne Engel press, a Hennecke HP-RTM injection machine and variable thickness plaque mould, CNC cutting and pick and place ply assembly cell. The facilities are available to partnered industry groups for industrial development. The research group had a focus on understanding and simulation of injection and permeability of composite materials, and the influence of dry fibre material characteristics such as stitch type or binder type on the formability of dry fibre preforms. The Automotive composites research centre forms part of the UK High Value Manufacturing (HMV) CATAPULT program that aims to drive innovation, reduce lead-time from concept to industrialisation and foster spinoff companies in selected areas.

Organisation: Hexcel Composites, 29th July 2016 (PM), Leicester, UK

Contact: Oliver Wessely

Hexcel Composites Leicester produce a wide variety of broadloom non-crimp and woven carbon fibre fabrics, specialising in the production of non-crimp multi-axle fabrics. They have an inhouse R&D lab to assist customers understanding permeability of their goods, through to strength of finished goods. The visit was able to help the Fellow consolidate his understanding of the common methods and creel technology and dry fibre management technology required to handle dry fibre in the construction/lamination of broadloom non-crimp fabrics.

Thematic Findings:

Braiding:

TUM had a 128 carrier Herzog radial braider and have spent considerable time studying the process. A lot of attention was being given to the characterization of processing defects such as wrinkles and missed tows. In particular, they seemed interested in the mechanical abrasion of fibres that occur during the braiding process and understanding the knock down in material performance that results from the abrasion.

Similarly, it was noted that over tension of spools was common, resulting in pulled tows and gaps in the braided structure. It was noted that utilising a 4-carrier horn gear to achieve 4x4 twill rather than 2x2 twill of a standard carrier results in 15% improvement in stiffness of the braided material. (at the expense of a braiding machine with double the footprint!)

Munich had a braiding machine that could be split in half to make continuously laminated bicycle wheels. The concept had been used elsewhere in the Aerospace industry to form continuous circular ribs. Munich had developed a patent pending method of using inflatable and reusable custom shaped mandrels to overbraid composite material and produce hollow structures. Munich were also producing serial components for the sporting industry using continuously braided material that was subsequently converted into components via more traditional layup processes.

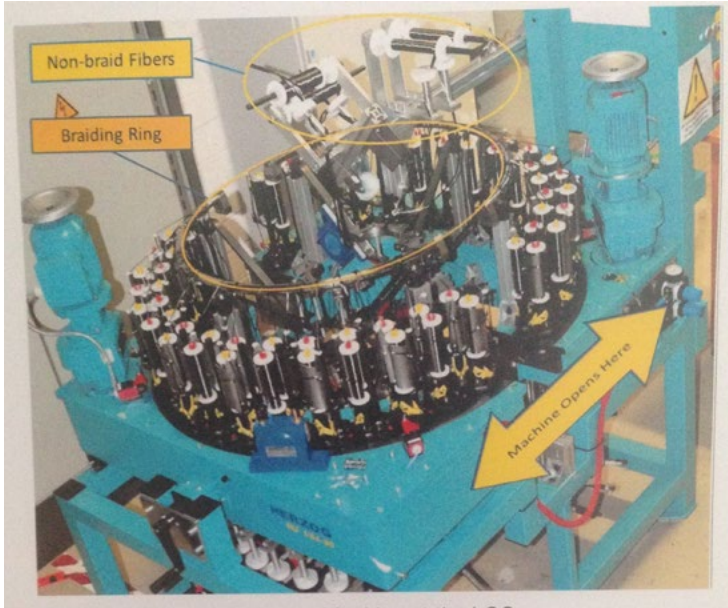


Figure 3. Separable Braiding Machine at the LCC

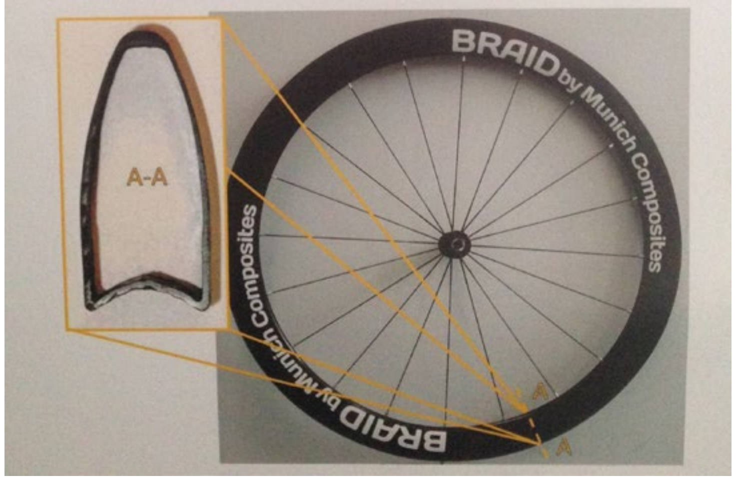


Image 1 – Continuously braided composite bicycle rim

Aachen were interested in similar product and process braid modelling to TUM and had also studied the impact of typical braiding knock down features such as the abrasion of fibres as they move past each other in the braiding process. Aachen had worked with Herzog to produce a fully programmable machine where the trajectory of each carrier is programmable through the machine so that truly unique and 3D braided components could be produced.

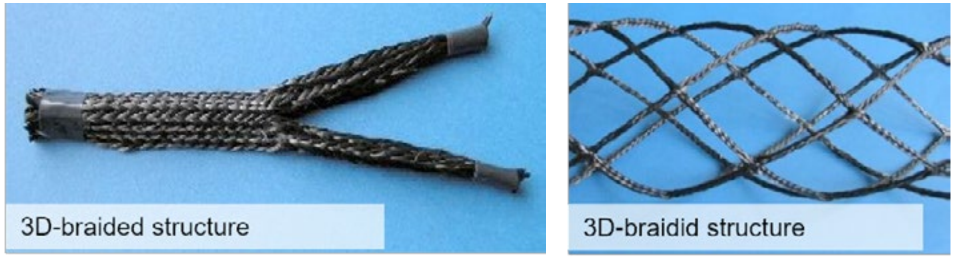


Image 2 and 3 -Truly 3D braided structure from ITA. Images courtesy of Dieter Veit

Eurobraider demonstrated considerable experience with composites and the nuances of braiding composite material. The Fellow was fortunate to witness the serial overbraiding of both simple and very complex mandrels. The Fellow noted that while material laydown on simple structure was rapid, overbraiding of complex structures requires close supervision and frequent manual intervention to ensure quality is ensured.

Eurobraider demonstrated that backup and reversal with traditional braiding machines is possible with overbraiding. This occurs when the mandrel reverses direction through the braiding machine to deposit multiple layers of material onto the mandrel in a single/continuous lamination. This was shown to significantly slow the process and requires either moulded features to facilitate reversal, or complicated robot gripping features to secure material while the machine reverses – thus up to three robots may be required to overbraid mandrels that do not or cannot incorporate features that allow reversal.

The Fellow was impressed by Voskamp's (General Manager) engagement in industry research and commitment to publish journal papers regarding braiding of composite materials. The Fellow was further impressed by Eurobraider's connection with automotive supply chains and in-house serial production of dry fibre preforms for the automotive industry. Voskamp was able to demonstrate various types of bobbin carriers and the importance of carrier design in the performance of quality braiding processes, and further detailed guidance provided as to the specification of equipment appropriate to the needs of a customer wishing to overbraid composite material and enter this market.

Herzog in comparison were very clear that they provided no composites experience with the sale of their equipment, nor guarantee of appropriateness of their machines for the Customers' needs. Having said that, Herzog are a far more experienced machine builder and build all their machines and machine elements in house and have a long history of machine breakdown support. Herzog began building braiding machines in 1861, and have grown and evolved their machines since then, introducing the first radial braiders to the market in 2003. All institutions visited by the Fellow outside of Eurobraider were exclusively supplied by Herzog suggesting there are compelling reasons to work with either supplier. The Fellow suspects the adoption of Herzog radial braiders at various University institutions keen to understand possible improvements in fibre integrity purported to be gained from radial braiding when compared to traditional braiding, has assisted in placing Herzog as the premier supplier despite a lack of published evidence to confirm this.

Dresden also highlighted their investigation into common defects including mechanical abrasion of fibres as they traverse past each other. Dresden carried 288 carrier machine, the largest inspected by the Fellow during his trip. They had spent considerable time shielding the machine to prevent nuisance fibre from entering electrical cabinets of other machines (as had most places visited).

Comparing the many University settings that investigate braiding, and also comparing to composite groups seeking to industrialise the equipment, several common themes were observed. Common among all of the established University investigations, was a universal push to understand process knock down effects on mechanical performance, implicitly suggesting that the process is known to degrade material performance. When focusing on industrial outcomes, it has also been a common outcome that exposing students to braiding machines subsequently resulted in uptake of the technology to produce both continuously and over-braided goods, as has been the case with Munich composites.

Tailored fibre placement

During his trip, the Fellow visited three sites that specialised in fibre placement technology. ZSK and KSL both stitch unidirectional material into a programmed place by following and stitching over the top of a unidirectional tow, whereas Cevotech adhesively bond patches of flat unidirectional material to form a dry fibre preform. ZSK and KSL differ in that ZSK have their roots specifically in customised traditional embroidery (think 2D custom stitched artwork on T-shirts, caps and the like), whereas ZSK originated from PFAFF who were manufacturers of traditional sewing machines, but evolved to incorporate truly 3D integration with, and between, robots and gantries so that placement can traverse all three planes (provided the canvas allows it!).

Perhaps the defining feature of KSL technology for the Fellow in advanced composites is the plug and play nature of the many stitching heads that have been developed by the group. Robots feature plug and play heads that can pick any stitching head type, cutting head or gripper unit to complete a specific task. Devices/heads can then be rapidly changed to complete a multi aspect task e.g. a sample is firstly cut out from a broadloom fabric using an ultrasonic cutting head. The preform is then transferred by a gripper head to a preform draping area. A stitching head is then picked up and used to stitch multiple layers together. And finally, the formed and stitched fibre pack/preform is moved to a moulding station where they are placed in the mould tooling.

The second defining feature of KSL technology for the Fellow was that the stitching thread is carried solely on the stitching head, and that very large bobbin sizes can be carried for extended service between re-loading. It was also noted that the stitching needle and head joggled forward and backward during the stitching stroke, which is contrary to typical sewing machine technology. The significance of this feature means that a continuous stitch path can be programmed on an x-y bed (or X-Y-Z if preferred) without having to instantaneously halt the stitched media while the needle plunges through the composite. Using a traditional stitch head, if a very large bed is used the instantaneous acceleration and deceleration of the entire bed can be considerable. This must be repeated between EVERY stitch stroke. KSL technology successful circumvents this requirement by moving the stitching needle instead.

Of the many variations and permutations of stitching machinery developed for industrial, aerospace and automotive customers, the Fellow was particularly impressed by a KSL unit developed to sew a faux stitch line on an injection moulded dash board to create a leather-look automotive dash pad. Due to the flexibility of the dash pad and pre-felting steps, no two dash pads are identical. KSL had developed a vision system to map out the seam line place, and instantly re-program the stitch profile so that stitches are placed precisely along the faux join interface. They had successfully sold units into the automotive supply chain.

In comparison to KSL, ZSK tailored fibre placement is descendant from traditional zig-zig style sewing machine technology, where the stitching head is fixed in space and the sewing bed is moved between stitches – it is critical that the material being stitched is stationary while the needle punctures/plunges through the material, otherwise the stitch needle will break. As a result, the entire bed (a large amount of mass!) must be joggled between each stitch resulting in a large bed having to accelerate and decelerate to a complete stop between every stitch, and this tends to limit the stitch rate achievable with the technology.

One further benefit of KSL style technology was that the carbon fibre material being stitched onto the preform is carried with the stitching head, allowing fully continuous stitching in infinite circles, whereas with ZSK technology the bobbin is removed from the stitching head, meaning that a limited circular range of only slightly better than 360deg is possible before the stitching head must stop, retract from the part and unwind 360deg before continuing the job. Depending on stitch flatness requirement, this also results in stitch twisting and this reduction in material alignment can affect strength and must be accounted for in the design.

From the preceding discussion, the choice between the two suppliers might seem one sided. However, with quality comes price. ZSK is far cheaper than KSL and is great entry level TFP technology. It should be further noted that ZSK have been focused on improving machine utilisation, with automatic feed in of carrier/support material and auto-changeover of (by contrast to KSL) exceptionally small bobbins. As a result, customers can expect very high machine utilisation. The Fellow is happy to freely recommend either supplier, and that choice between them will be determined by the specific requirements of the customer.

Many places visited by the Fellow had utilised programmable stitch heads to secure material around holes or around the edges of preforms, or indeed to secure hardpoint attachments. Furthermore, a common use of the technology at all places that feature the technology, was the use of tailored stitching in the production of heated car seats. It appears to the Fellow that development of tailored fibre placement has evolved from this specific application. For car seats, a heating wire is stitched to a substrate. At some point, the heating wire was exchanged for a strand of carbon, which has given birth to the concept of tailored fibre placement.

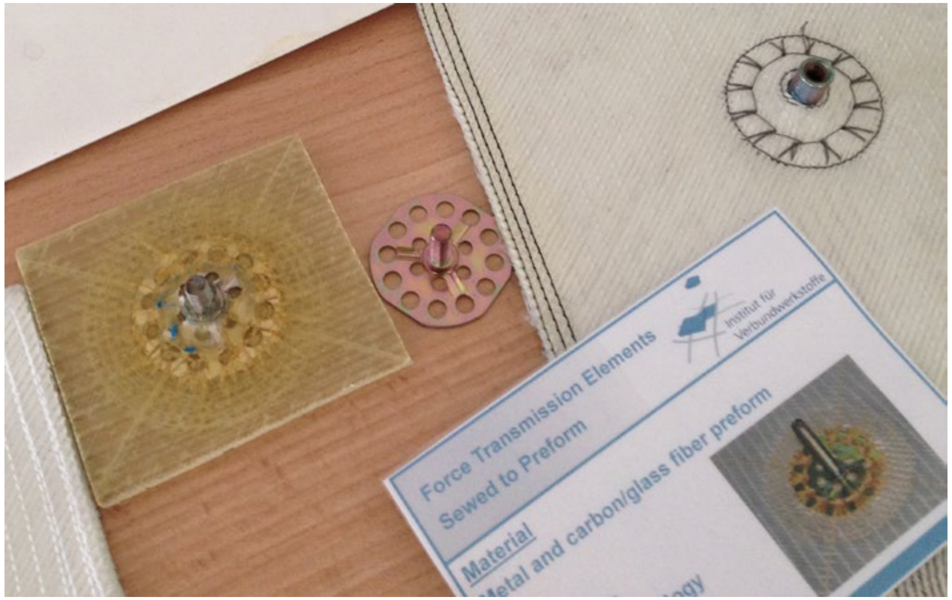


Image 4 – Hard point stitching integration demonstrated at IVW (Kaiserslautern)

In comparison/contrast to KSL and ZSK, Cevotech have approached the tailored fibre placement market with a different technology base, instead using pick and place robots to individually place many(!) small unidirectional patches in a programmed pattern. Cevotech are also unique in that they can place dry fibre patches utilising powder binder to adhere the dry fibre prior to RTM injection. This allows truly 100% customisable fibre pattern, without having to account for fibre termination that results in kinks with stitched technology, or repeatedly having to snip and re-start tow, which is slow in comparison to continuous stitching.

While Cevotech have demonstrated enviable deposition rate of 1 patch per second, when compared to stitching, FPP has a much slower material deposition rate, using more expensive intermediate technology including robot placement and vision systems to confirm all materials are placed as expected. To achieve significant material deposition rates, it requires many robots to operate simultaneously on a single preform, or much larger patches be placed, or both.

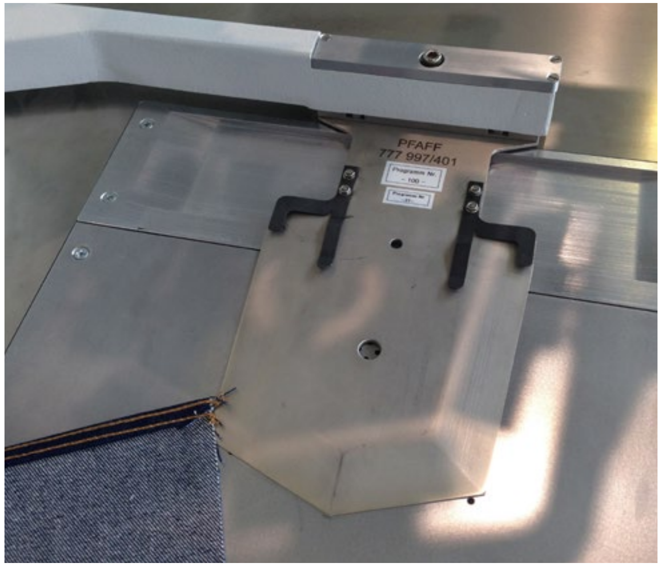
This results in (by comparison to ZSK and KSL) very expensive placement technology. At the time of his trip, the Fellow was not aware if Cevotech had found any adoption of their technology outside of aerospace applications.

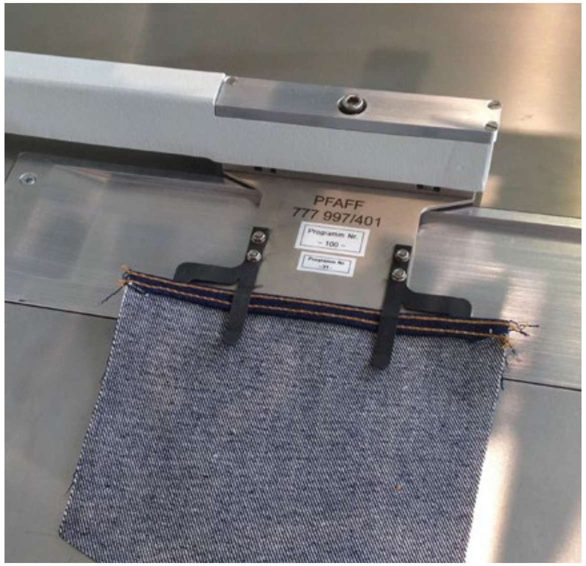
Image 5 and 6 – A dry fibre 3D preform of a bicycle helmet, and its moulded counterpart.

Preforming

Perhaps the more traditionally accepted and employed varieties of preforming are those where broadloom technical goods (such as woven/non-crimp/stitched fabrics) are firstly cut to shape, then formed into 3D shapes, preferably as close as possible to the final moulded shape. The benefit of these approaches compared to tailored fibre placement are that much higher material deposition rates are typically achieved as the fibre has already been converted to broadloom good. Furthermore, this can often be achieved with minimal capital outlay: At the simplest level, a spray tackifier can be used to adhere layers together over a form, and then transferred to the mould tooling when ready. This way, mould layup time is reduced.

At KSL for instance, the Fellow was impressed that many aspects of preforming such as cutting, knitting, folding, stitching and thermoplastic welding were combined into work cells to increase output. Many of the same challenges with garment manufacture and material handling are directly transferable to building RTM composite preforms, and KSL have built on the knowledge base of PFAFF. The Fellow found the aspects of automated jean stitching items demonstrated at PFAFF to be a great demonstration of the likely processes needed to pick, place, fold, secure and stitch items in place, without need for complex robotry to complete these tasks.





Images 7, 8, 9, 10 and 11: Simple material handling system to preform and stitch a fibrous patch at PFAFF

At IVW there was an extensive range of demonstrator parts that had been built up from preformed fibre packs and then injected via RTM. Highlights for the Fellow were a composite impeller and 2 variations of industrial beam moulding. The composite impeller had been constructed from an array of smaller preforms that had firstly been cut, folded and stitched together before being assembled in the injection tooling. The industrial beam was appealing as the main bolt up attachment points were cut from the preform stack before moulding, the edges secured from fraying by CNC stitching, and the openings were moulded in place, which meant that post moulding machining was not required.

Image 12 (left) and 13 (right) – IVW: flat laminates folded and stitched into 3D preforms, which were then assembled into a composite impeller and RTM moulded in a complex multipart tool.

Of particular interest at IVW was a continuous in-line I beam fabrication preforming unit that the Institution had developed. The assembly drew material directly from rolled non-crimp fabric, and progressively folded, flattened, and sewed several source materials to create an I beam preform material. Some of the research outcomes of this specific technology were to establish how well different woven and non-crimp fabrics were able to be pre-consolidated via different preforming process. The group established and measured the compaction reached through each of the processes, before reaching a final Vf up to 55% in the preform. This was the same as the final volume content of the moulded part, which resulted in preforms that could be more easily placed into injection moulding tooling. Various pre-roller and compaction techniques were established to minimise the drawing force of material through the integrated preforming and stitching line.

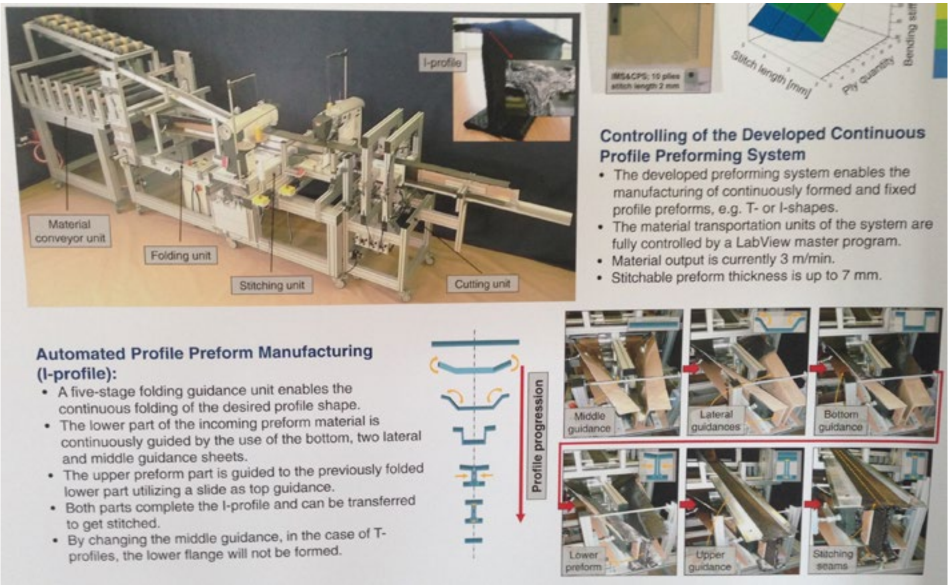


Image 14 – An integrated continuous I beam lamination cell produced by IVW.

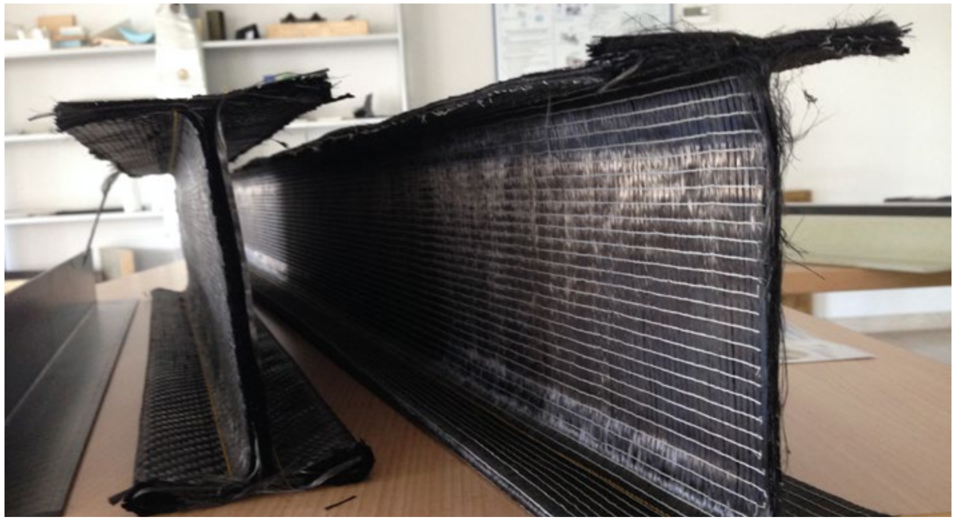


Image 15 – The resulting preforms

Image 16, 17 and 18 – IVW - A complex beam structure from simple flat pack stitched and cut preforms. The fastener holes were moulded, rather than post machined!

One aspect of preforming material not to be underestimated is the cutting of material to size. While off the shelf cutting machines are readily available, and every institute visited had an NC cutting table of some sort, very few were able to engage in fundamental cutting mechanics. Of the many places visited that featured cutting beds with ultrasonic knifes, only KSL were able to provide meaningful design insight. The Fellow was able to discuss briefly how backup material for ultrasonic cutting knifes are handled. In ultrasonic cutting, the knife tip must not contact solid material otherwise the tip shatters. By adding a small 3mm wide bed of rubber material so that the blade does not contact the solid cutting bench this is avoided.

Tow management and delivery systems.

One of the main themes of interest to the Fellow prior to his trip was to better understand the various methods by which tow is directly removed/unwound from the bobbin and handled between the bobbin and its final deposition place, and how this can be achieved at the maximum possible rate. From a high-level perspective, the cheapest way to purchase tow is on a bobbin. By purchasing tow as it directly leaves the carbon fibre line, many intermediate value chains can be avoided, ideally as it is directly pulled from the carbon fibre manufacturing line. Processes such as weaving into a broadloom material, stitching into a non-crimp fabric, and the likes of braiding tube stock, can be seen as waste processes that introduce an array of intermediate handling challenges. Industrial processes that are fed with material from a bobbin and deposited directly onto the final product will eliminate all of these steps and fundamentally reduce waste and cost.

It can be seen that a variety of processes such as tape winding mandrels, robotic tape placement, broadloom weaving and non-crimp stitching all require various types of creel technology and fibre handling equipment to take tow from the bobbin and deliver it to the downstream process or mechanism. Much can be learned from the different approaches taken by various suppliers visited by the Fellow. Quite simply put, “How do you get fibre off a bobbin, and into a useful fabric or onto a mandrel or workpiece, and eliminate unnecessary intermediate steps?”

At TUM, the Fellow discussed and compared broad capability of thermoplastic, pre-pregged and powder-bound (dry) fibre winding and tow placement. Typically, thermoplastic tape placement was the slowest of the three technologies mostly due to the very high temperatures required to locally melt the tape during deposition and consolidation. Most research regarding thermoplastic tape placement focused on the impact of the temperature and pressure settings used in the direct location area of deposition. TUM and other institutions had focused on the typical processing defects such as wrinkles in fibre and missed tow, suggesting these are typical problems perceived by the industry.

Deposition of bindered (dry) unidirectional tape was typically seen as the fastest deposition route. It was understood that programmed control of heating was preferred (ie, not feedback/closed loop in nature) as this resulted in higher deposition rates when compared to feedback controlled tape heating, and that speeds of up to 2m per second were achievable.

A highlight of the visit to IVW was inspecting an in-situ and in-line tape pre-pregging concept that the Institution had developed. The system was free from typical roller bath setups. IVW were able to use the technology to demonstrate the winding of 5million N.m wind turbine shaft via a multistage curing and winding process. A multistage curing process was used to manage and mitigate exothermic behaviour of the resin. The Fellow was able to inspect the creel-based tow delivery systems, pre-pregging system and tow delivery mechanisms used to deposit the pre-pregged tow. Traditional bath style pre-pregging units were also on hand and inspected during the visit for comparison.

Image 19 – simple creel technology was often sufficient for most processing applications.

Most places visited by the Fellow used simple creel systems, leaving the many bobbins far away from the deposition head and simply allowing the bobbin to spin on a spike as means of adding draw-through friction to the tow and prevent overrun. The tow was then passed through simple polished eyelets (which are prone to bunching up the flat tow), and re-spreading the tow close to the delivery head using simple in-line dividers to control the deposition width of the material very close to the deposition point. Of the places visited producing woven materials, this was the only creel method used.

Several of the universities visited had spent time studying the mechanism involved to spread carbon tow into flat ribbons, and the resulting improvement in mechanical performance as a result of improved fibre distribution through the thickness of the composite part. Although this statement is true, larger gains were possible simply by thinning the tape to create very low aerial mass fabrics with negligible crimp – the improvement in fineness of structure then yielded significant material load bearing characteristics. There is a clear trade-off between expense of laminating many very thin layers and excellent mechanical properties, versus a much cheaper structure with several thick layers and reduced mechanical strength.

While not strictly a ‘tow management system’, the Fellow would like to mention the extent of weaving and 3rd axis fibre introduction to woven and non-crimp materials at ITA/Aachen. ITA had, for example, produced 3d carrier scaffolds that carry engineering fibres at significant offsets for simple reinforcing structures, such as those that might be used in prefabricated concrete sections. They had also introduced tailored fibre placement in-line with both traditional weaving and non-crimp stitching lines. Sigmatex had also developed a fully 3D weaving machine capable of producing intricately woven material capable of then being folded out into complex shapes. At the time of the visit, they appeared to be having difficulty finding a customer for the impressive technology.

RTM processing

During his trip, the Fellow was exposed to a variety of resin injection machines and resin transfer moulding strategies. The Fellow was most interested to learn about high pressure injection strategies, as these offer the fastest injection rates, which in turn offer the prospect of utilising more reactive resin systems, which further reduce cure cycle time and improves moulding productivity.

At IVW, David Becker had completed significant work understanding and developing technology to characterize resin flow in HP-RTM, and more particularly in gap moulding. In this technology, the tool cavity is filled with a dry fibre preform but the tooling is only partially closed so that a gap remains between the back surface of the preform and the tooling to inject resin into. Once the correct amount of resin had been injected (and presumably has filled this cavity), the tooling was closed and the “compression” forces resin into the preform through the thickness of the composite rather than along the length. The resulting flow path is several orders of magnitude smaller, so the time to inject and fill the cavity is also an order of magnitude smaller. This in turn allows much more reactive resins to be used, which also further reduce the injection and cure cycle time into the sub-minute cycle time threshold considered the standard required for true high-volume automotive capability.

Becker's work had established the through thickness permeability characteristics, and how the permeability changes as the preform compacts, and how the permeability also changes depending on both whether the fibre is wetted (hydraulic force) and the local pressure difference. An interesting distinction was noted, that if the platens are closed too fast, the hydraulic pressure can compress the un-infused stack and significantly decrease the resin permeability. Instead, initial compaction should be carried out at a lower rate to allow resin penetration prior to increasing hydraulic load to complete the through thickness permeation.

At the time Mr Becker had claimed to be aiming to unify and standardise the permeability measurement standards within this segment of the industry, and papers published since then appear to support this assertion with custom benchtop measurement facility produced with a partner organisation to carry out the task.

Work carried out at IKV (Aachen) paralleled the work at IVW, but also included a much larger emphasis on fundamental cure characteristics and shrinkage behaviour of resins which have a profound influence on the surface quality of moulded parts. IKV had studied gap moulding, HP-RTM moulding and the closely related HP-RTM compression moulding where the front and back tooling surfaces are allowed to compress during cure, thereby taking up volumetric cure shrinkage through the thickness of the component. IKV had also studied the reactivity and impact of both epoxy and urethane resin systems.

Without doubt, the most professionally presented and finished demonstration parts on show during the whole trip were seen at Krauss Maffei. Interestingly, it was noted by Eric Fries that the best surface finish parts were not achieved from the fastest cycle time components. Instead, parts that were left to cure in-mould for a longer period of time (considerably longer than the minimum residency needed to achieve minimum cure to eject parts) so that mould compressive force continued to close the front and back planes of the part closer together and thereby combating cure shrinkage through-the-thickness of the part during post-gelation cure shrinkage. This was seen to improve surface appearance and follow up rework of parts.

Another method to improve the surface finish of parts had been developed by Kraus Maffei, back injection, whereby after cure of the initial composite part, the mould tooling is separated fractionally and fresh resin injected into the A-class surface to fill imperfections that result from cure shrinkage. Furthermore, it was often advantageous to use a different resin system for the back injection/over-moulding process so that a superior aesthetic or working surface finish was produced. For example, the use of a self-healing resin in an over-moulded injection of interior trim parts meant that typical surface wear and scratches were not observed.

Image 20 and 21 – the Fellow was struck by level of cleanliness and professional finish of demonstrator parts presented at Krauss Maffei.

The Fellow noted the considerable size of moulding presses present at all institutions visited that had developed HP-RTM moulding. This is certainly a pronounced, but possibly unfounded, barrier to entry to HP-RTM processing. WMG in particular, were quick to point out that forces involved in HP-RTM are actually still quite low when compared to compression moulding, and that only a small percentage of the capacity of their 1700 tonne Engel v-Duo press was needed to react the forces of HP-RTM injection.

Resin Richness

During his visit to all organisations, the Fellow was most intrigued to examine the resin richness of demonstration parts, and paid acute attention to this detail. Resin richness can be described as pockets of the laminate not properly filled with fibre, or pockets of the laminate where fibre is not adequately pressed against the mould surface, and thus appear resin rich.

At IVW for instance, moulding of I and T beams showed obvious surface shrink back resulting from non-uniform Vf, and surface artefacts consistent with porosity in the part (below, right). In fairness, the I and T beams were industrial components where these artefacts were not considered critical to performance.

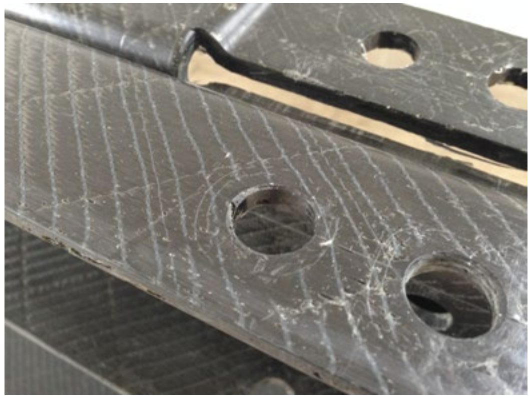


Image 22 (left) and 23 (right) – Complex I-beam structures fabricated by IVW with fixing points moulded into the structure (different aspects of the same component featured earlier in images 16/17/18)

In particular, a full demonstrator RTM car chassis floorpan part was on show in the main foyer of IVW, and this part demonstrated extensive resin runner/race tracks throughout the part to improve mould filling. The absence of fibre in the resin race tracks allow resin (and thus also pressure) to bypass fabric and maximise resin flow to extremities of the mould. When resin enters fibre filled sections, the flow is restricted and slows down remarkably. The part featured lots of resin rich areas showing room for improvement and certainly not to the standard the Fellow was expecting for automotive parts.

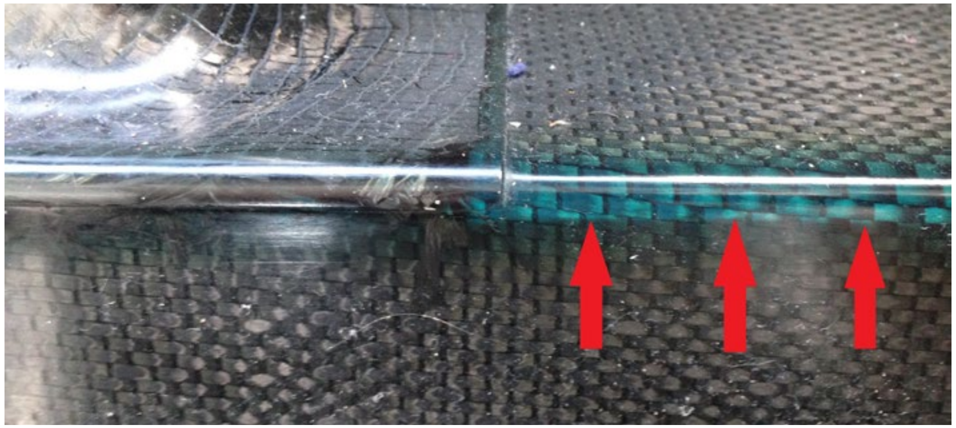


Image 24 and 25 – Demonstrator automotive floor panel on show at IVW. An extremely advanced moulding that still showed obvious signs of resin richness at corners and print through from rear-side resin racetracks.

At IKV, a bonnet demonstrator panel was on demonstration showing a class A surface finish. The front surface was certainly impressive. However, the Fellow noted that the backup structure on the reverse side of the structure had extensive resin richness shown by the regions of white.

Image 26 – Resin richness on the B-surface of a HP-RTM part. (white regions)

Image 27 – Resin richness on the B-surface of a HP-RTM part. (white regions)

In tubular braided components, resin richness was noted in almost all of the corners of rectangular cross section components in both industrial beams and automotive chassis structures.

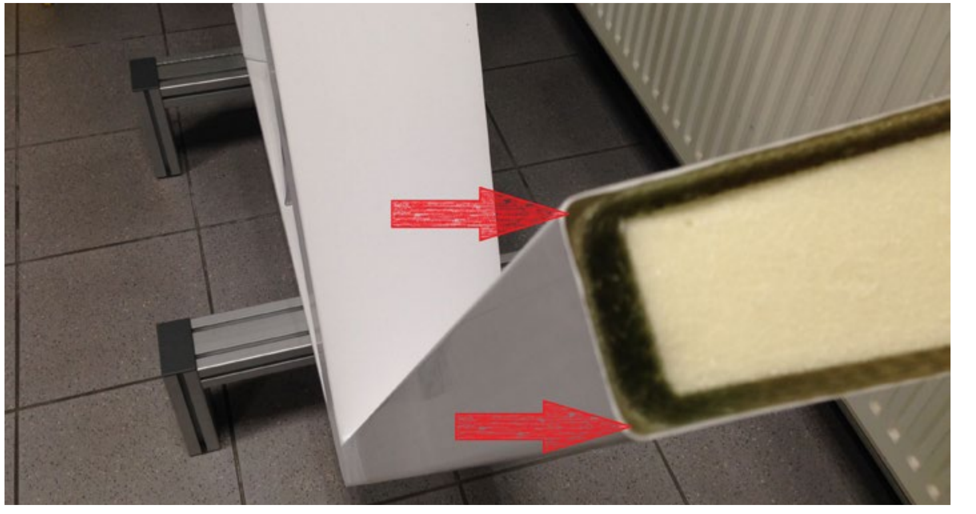


Image 28 (top) – Industrial beam demonstration at Eurobraider – resin rich corners in a braided tube (red arrows). The artefact was not apparent from the external finish, presumably due to a pre-cured gelcoat.

Image 29 (right) - Automotive chassis beams at Eurobraider featuring resin rich corner radii. (red arrows)

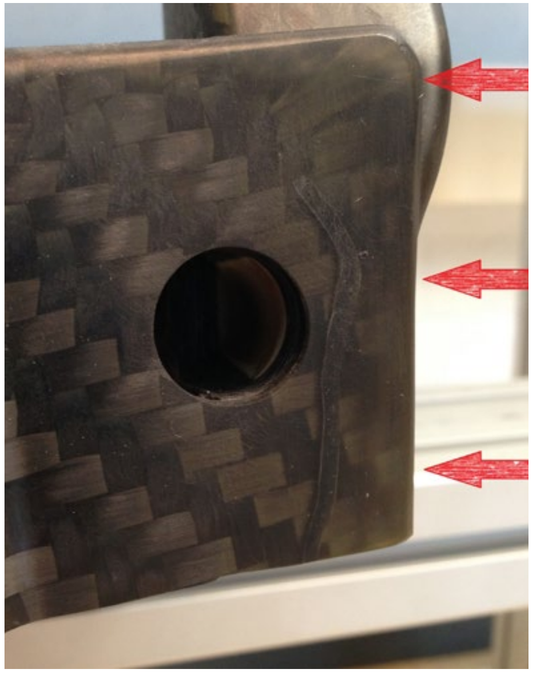


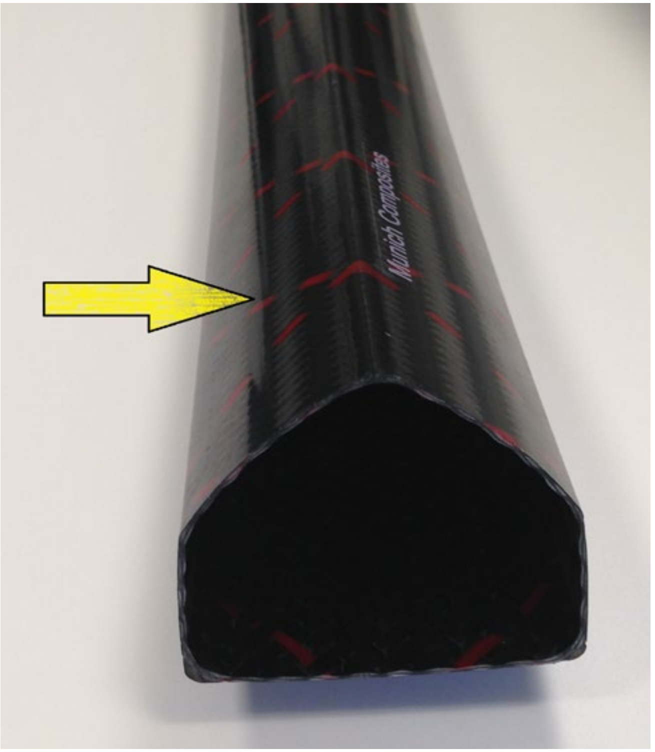
Image 30 - Automotive chassis beams at Eurobraider featuring resin rich corner radii. (red arrows)

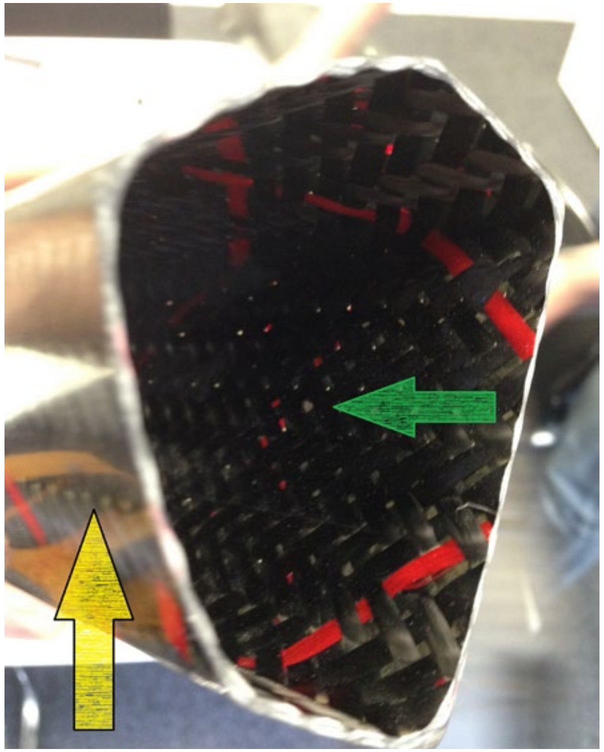
Demonstrator parts at Herzog included an automotive cross member/bumper and a demonstrator panel produced by Munich composites. Similar to the box section components from Eurobraider, the Herzog bumper featured heavy resin richness at the corners that had cracked extensively.

Image 31 (top) and 32 (left) – Vehicle bumper, showing heavy resin richness and cracking at corner of the beam

While the sample produced by Munich was an order of magnitude better, we can still see evidence of fibre bridging and resin richness at the corners of the section. It is worth noting that by using an inflation bladder during cure, an excellent exterior surface finished was achieved but with increasing surface undulation on the interior surface as a result.

At WMG, the Fellow was able to observe HP–RTM injected flat panels of triaxle braided material that were noted to be of good quality. The Fellow noted that, as with other automotive composite components, the panel utilised integrated resin runner channels on the backside of the panel to assist infusion rate and quality. The Fellow also noted regions on the surface of the panel that are characteristic





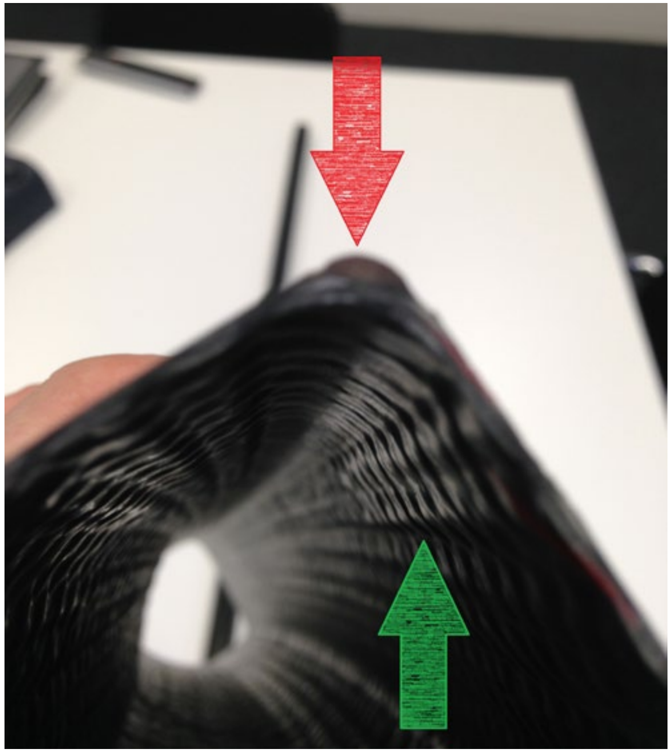
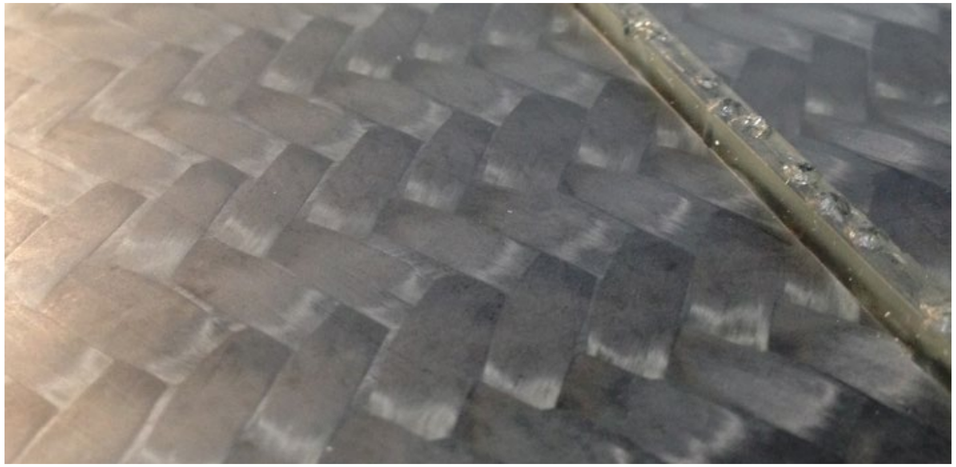


Image 33, 34 and 35 – Compound beam produced by Munich Composites, showing areas with excellent external surface finish (yellow arrows), undulating internal surface (green arrows), and resin rich corner (red arrow).

of surface porosity despite the sample meeting aerospace porosity requirement of less than 1%. It was also clear to the Fellow that there were minor areas that were un-infused at the surface of the part where the higher Vf regions of the triaxle component of the fabric were present close to the surface of the mould. The Fellow also noted that all 'high-quality' test panels observed featured integrated resin runner channels to improve impregnation time of parts.



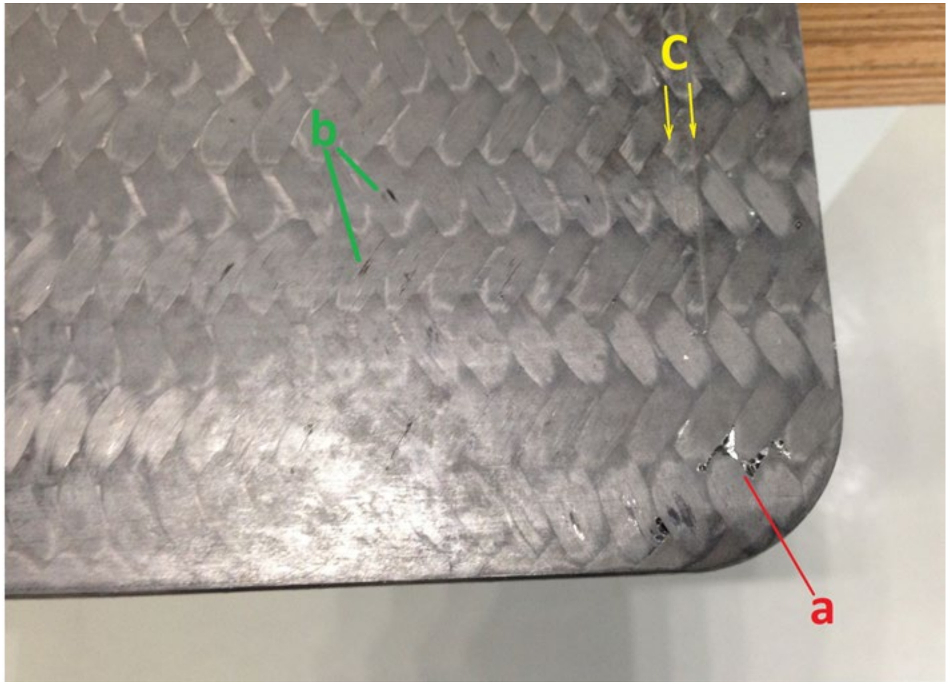


Image 36 (top) and 37 (right) – Good quality HP-RTM infused triaxle braided composite panels made at WMG, showing a small resin racetrack on the backside surface of a panel. (a) surface porosity in a low Vf region, (b) unwetted surface fibres in a high Vf region/s, and (c), print-through on the front of the panel from the backside resin racetrack.

Across all host industry and institutions visited, the Fellow was truly inspired by the magnitude and complexity of components and demonstrator work that had been carried out. But yet on all instances, it was clear that all places visited found it impossible to mould components with excellent surface finish on all surfaces, and that this became more apparent as part complexity increased. Resin rich corners and edges in particular were common. While many parts were subjected to considerable injection and tool compaction pressure, which one would presume to fix some of these defects, they still exhibited surface porosity. On a few occasions, the Fellow was surprised that this trade-off seemed normal and to be accepted practice.

6. Personal, Professional and Sectoral Impact

The international experience helped the Fellow to gain a deep understanding of the advantages, but just as importantly, the limitations and disadvantages of each of the preforming methods that were investigated. The age-old adage that carbon fibre “is not black aluminium” continues to hold true, and fibre architecture is paramount. It follows that any preforming techniques employed must deliver fibre in the required direction and rate. There are only a limited number of cost-effective preforming techniques, each of which carry a limited range of application. Therefore, design that neglects the limitations of the available preforming techniques will severely impact the cost effectiveness of mass manufacture of complex parts.

There are no magic bullets, one stop shops or single standout technologies set to overturn the advanced composite RTM industry, but that each of the technologies visited will continue to find new applications.

More specifically, the Fellow notes the following aspects that will be beneficial in his personal life and professional career:

» Made great connections with many of the businesses visited, and has no hesitation recommending any of the places visited for Australian industry to engage with

» Developed hands on and tactile understanding of a broad variety of the fibre handling and processing methods employed in the composite industry. This included being able to compare and contrast:

    » Non-crimp multi-axle broad loom fabric manufacture, vs woven jacquard loom style manufacture (not discussed in significant detail in this report), through to truly 3D woven structures

    » braiding, including various braiding applications and suppliers

    » various levels of creel technology and control systems

    » tape laying and mandrel winding of various forms of carbon tow

    » tailored fibre placement and tailored stitching of multilayer preforms

    » various broadloom cutting and knitting technologies

» Compare and contrast various types of RTM injection and limitation of HP-RTM injection equipment when comparing epoxy and polyurethane formulations

    » Traditional RTM (bucket pumps)

    » High Pressure RTM (impingement mixing)

    » Gap HP-RTM

    » Compression HP-RTM

    » Back injection/surface re-injection

» Helped the Fellow understand that although automotive RTM processes appear well refined from a distance, they are often quite rudimentary in nature and the quality of parts were less than expected by the Fellow, particularly if parts were more complex than simple 2D panels.

» Where complex RTM and preform processes are used, quite often very significant resin richness is present, particularly at corners where “black aluminium” design approaches have been employed

» Helped validate the Fellow’s pre-existing fundamental knowledge of various preforming and injection processes, and that every pre-forming technique has both advantages AND disadvantages and clear limitation of scope of use, and that often these limitations ARE obvious by simple inspection

» And again, that design HAS to be made to account for the manufacturing process route being utilised, further accounting for the cost vs mass premium that the final customer finds appealing.

Sectoral Impact

At the Fellow's place of employment, learnings from the overseas investigation were reviewed immediately via group meeting and follow up one-on-one dissemination with key internal stakeholders and technology experts. The knowledge from the trip helped our technical experts confirm and update their areas of expertise where appropriate.

The Fellow can report that at least three new relationships have been forged with groups that the Fellow visited, so that Carbon Revolution could:

» improve existing processes,

» understand and solve technical challenges via the specific know-how and expertise of particular University groups that were visited,

» unlock linkages to international groups to create new subcategories of material supply, unique to Carbon revolution

Specifically, and prior to the trip, the Fellow had been working on a revolutionary new concept for preforming dry carbon fibre material and key decisions regarding fundamental principles remained open during the trip. Many of the learnings from the trip drove fundamental machine design decisions of this particular machine design, which now forms a key link and backbone of the manufacture of carbon fibre wheels:

» The technology will be employed on all new wheels manufactured at Carbon Revolution.

» Already, over half of the wheels manufactured at Carbon Revolution are produced on this machine

» To date, some ~2million dollars has been invested directly in capital acquisition of this equipment, expended via projects with bespoke and specialist local machine building vendors

» Has allowed significant automation of a major aspect of wheel manufacture.

» The technology has resulted in a ~1kg reduction in wheel mass over their pre-existing design, the Fellow is not aware that this can be achieved via traditional preforming methods observed while overseas.

» The machine delivers carbon fibre material (kg's per hour) at a capital efficiency far better than competing technologies.

Due to IP restriction with his place of employment, the Fellow is not able to divulge further information regarding the venture.

More generally, the Fellow was impressed with both the breadth and depth of combined industry and government funding emerging from the BMWi series automobile, where intensive use of composite materials was fostered. Likewise, the heavy use of composite materials in aerostructure at Airbus that in turn drove technical solutions to practical problems encountered. The writing was, quite literally, on the walls of almost every technology outfit visited by the Fellow. The Fellow notes that the imperative to drive to high composite structure loading then resulted in industry adoption of many new technologies. That is, they had a problem in search of solutions, and this then generated innovation.

The Fellow was further impressed by the level of industry involvement in University level training and research, with most institutions reporting approximately half of their revenue being generated from industry involvement, which in turn fosters competitive university engagement with industry.

7. Recommendations and Considerations

Specific outcomes already enacted:

In 2015, through workplace experience and prior engagements, the Fellow identified a lack of specific understanding of practical limits of many preforming techniques and fibre handling expertise needed to develop a next generation preforming machine at his workplace. Upon immediate return from the Fellowship, many aspects covered on the trip were incorporated into a successful new machine design at the Fellow's workplace.

Recommendations and considerations for future work:

RTM processing

More generally, the Fellow had identified a series of limitations with RTM processing and resin shrinkage via experience at his workplace and prior engagements. This led to the Fellow approaching many University organisations and an HP-RTM supplier. Many of these technologies considered show great promise in unlocking very rapid tooling throughput, injection and cure cycle times, and that these should be adopted by new comers to RTM processing. However, it was noted that this increase in rate comes with unavoidable loss of surface quality, at very least on the B tooling surface, but typically on all moulded surfaces to varying degrees. Although some promising work-arounds were identified, the Fellow found no compelling evidence of breakthrough technology in this arena.

Nothing was found that addresses resin shrinkage through very thick section composites, particularly where those sections lie perpendicular to the mould closing axis. This is a fundamental question that appears to be technically impossible to resolve in epoxy/thermosetting plastics. New/other routes around this problem must be found, and the Fellow can see that this is an area of obvious international appeal from both a research and industrialisation perspective.

The Fellow therefore recommends Government incentive, perhaps via industry leverage and the various CRC/ARC/linkage grants, for the acquisition of demonstrator HP-RTM equipment and associated press, through any of the industrial engineering Universities in Australia but preferably a campus with expertise in advanced composites, or technology demonstrators such as CSIRO and Carbon Nexus. This would be particularly beneficial, as it is practically impossible to move mould tooling internationally on an ad-hoc basis for either assessment or development of the manufacturing process – this is currently a major limitation to Australian enterprise. The equipment would ideally be accessible to both industry and research groups while also fostering student engagement to foster innovation and spinoff companies such as those observed through TUM: Cevo-Tech, Munich Composites and Blackwave Composites.

Preforming and fibre handling

Similar to RTM processing, but to a lesser extent due to the portability of lightweight preforms, the Fellow can see that access to a variety of demonstrator technologies will assist with uptake of these technologies in Australia and help ensure these new technologies are appropriate to the needs of the organisation. Australian industry would benefit from the following many technology demonstrators:

» Braiding machine/s made available for industry engagement – the Fellow is encouraged to learn that a 48 carrier Herzog machine has been installed at RMIT. The Fellow would like to see such an instrument made available as a testbed for industry engagement.

» Stitched TFP R&D style machine for SME's to access and learn from to assess appropriateness for their ventures, or even for small batch processing.

» Robotic pick-and-place cell to demonstrate effective end effectors

» Investment into research focused on high volume fraction preforming of dry fibre material

  » Adoption and research of emulsion-based powder binders and their impact on processability, preforming, and characterization of properties of finished good using this avenue.

  » Research, characterisation and industrialisation of thermosetting powder binders (compared to more traditional thermoplastic powder binders)

» CNC tape winding and robotic tape placement technology demonstrators, as have recently been acquired and implemented at UNSW.

During the Fellows overseas trip, nothing was found that addresses compacting dry fibre to its final RTM moulded thickness of typical Vf of ~60%. Many instances of 50-55% were noted, however this can still present a significant challenge to mould tool closure in complex parts where material lies parallel to the tooling closure direction. This shortfall needs to be addressed and represents an excellent Institutional investigation topic.

Government and industry should continue to support organisations such as FSAE, ECO marathon, solar car design and streamline HPV that foster competition and innovation among the next generation of composites and automotive engineers. The Fellow noted involvement in such activities at all University institutions visited, and indeed many of the specific technical vendors. The setting can in many cases spark mutually beneficial collaboration between industry, university and student outcomes.

In summary:

Specifically, the Fellow has developed an innovative new preforming machine at his workplace as a direct outcome of the Fellowship.

After contacting Composites Australia, the Fellow and this Fellowship have recently been featured in their July 2019 magazine. There is also the possibility of attending and presenting at a future Composites Australia seminar pending broader industry appetite for the insights gained during the Fellowship.

Broadly, the Fellow sees that lack of access to a variety of technology enablers as a significant hurdle to overcome for Australian industry and enterprises to enter the RTM composites sector. This could possibly be overcome by the agglomeration of multiple preforming and injection technologies being acquired and made available through University and Industrialisation groups (such as Airbus), as was broadly observed throughout his overseas experience.

8. Appendices

Appendix 1: Article: Composites Australia

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Connection

The official magazine of Composites Australia

Inside

FELLOWSHIP LEADS TO STEP-CHANGE PREFORMING TECH

COMPOSITES – A SOLUTION FOR MELBOURNE'S PUBLIC HEALTH

STARTING UP AND COMMERCIALISING BALLISTIC HELMETS

Fellowship leads to step-change preforming technology

Unveiled at the Geneva Motor Show on 6 March 2018, Ferrari's remarkable 488 Pista featured a set of optional 20-inch carbon fibre wheels made by Carbon Revolution in Geelong. The beautiful aerodynamically efficient supercar was already 91kg lighter than its predecessors, and by using Carbon Revolution wheels, Ferrari was able to save an additional 40% in weight on its wheels alone.

So what is the secret of a company that ascended from a start-up in a Geelong garage a mere 12 years ago, to supplying "the most technically advanced wheel on the planet" to global car makers like Ford and Ferrari – all of it achieved against the backdrop of a cost sensitive and conservative supply chain?

In the case of Ferrari, the marketplace requirements for an optional wheel on a road-going supercar are Herculean. The 488 Pista is said to have a top-speed of 340 km/h; accelerating from 0–100 km/h in 2.85 seconds 0–200 km/h in 7.6 seconds. The wheel is attached to a vehicle that weighs just over 1.5 tonnes. The wheel takes all the forces from the road through the tyre and into the car structure. It must handle hundreds of horsepower from the drivetrain and sustain extreme forces from hitting potholes and curbs. Inside the wheel sits a brake disc and calipers, which can reach temperatures of up to 1,000 degrees Celsius, just a few centimetres from the wheel.

To deal with this level of extreme fatigue over a lifespan of more than 300,000 kilometres, the wheel needs a lightweight, fibre and polymer-based carbon fibre composite component that is precision engineered and of aerospace quality.

Kerryn Caulfield and ISS Institute Fellow Dr Tim Corbett

Dr Tim Corbett, an Engineering and Doctoral (PhD) graduate of Deakin University and a foundation employee of Carbon Revolution, believes that the company's secrets to success are its investment in continuous research and development in step change efficiency technologies, global partnerships, an active patent strategy …and testing, testing and more testing…

Technical Specialist with Carbon Revolution, Tim was awarded an International Specialised Skills Institute (ISS Institute) Fellowship in 2016 to examine and understand state-of-the-art RTM systems for 3D parts, direct tow handling and fibre placement, novel preforming technologies, as well as carbon fibre conversion processes used in the advanced manufacturing R&D institutions in Europe.

Carbon Revolution's "most technically advanced wheel on the planet"

Carbon Revolution's 3000m² Waurn Ponds manufacturing facility is being expanded by 7,000m² to allow the company to lift its output from 10,000 wheels a year to half a million wheels per year in the long term

Prior to his Fellowship, Tim had been working on a revolutionary new concept for preforming dry carbon fibre material. His quest was to unlock very rapid tooling throughput, injection and cure cycle times, without losing surface quality on all moulded surfaces, as well as to address resin shrinkage through thick section composites, particularly where those sections lie perpendicular to the mould closing axis. Another area of investigation was to understand and benchmark resin richness in complex 3D structures that can result from various different preforming technologies. Resin richness, he notes, are pockets of a laminate in concave areas that are not properly filled with fibre. He found that many preforming processes were surprisingly susceptible to resin richness, particularly in challenging parts. Tim's findings drove fundamental design decisions about this bespoke invention, which is now a principle process in manufacturing the company's carbon fibre wheels. The innovative new preforming machine is in the genre of additive manufacturing and delivers carbon fibre material (kgs per hour) at a capital efficiency far better than competing preform technologies. Importantly, the technology has resulted in a ~1kg reduction in wheel mass over the company's pre-existing design.

"One of my conclusions after examining all that was on offer in Europe, was that to produce consistent, repeatable, dimensionally accurate, high-quality carbon fibre automotive components with precisely finished surface aesthetics we had to develop our own technology and build our own machines", explained Tim. "While this wasn't the cheapest or fastest route to market, it was the surest for tooling optimisation and for reducing material usage and cycle times."

During its 12 year journey, Carbon Revolution was able to attract funding to industrialise and automate its unique processes as well as fuel its expansion. Local private investors, Acorn Capital, global wheelmaker Ronal AG of Switzerland, Deakin University and the federal Clean Energy Finance Corporation have supported the company thus far. An ASX listing has been mooted "inside a year" that will propel Carbon Revolution to the next level of development

The company has announced a $100 million expansion of its Waurn Ponds manufacturing facility, which will eventually add 500 workers to the payroll. The expansion adds 7000 square metres to Carbon Revolution's 3000m² footprint and will allow the company to lift its output from 10,000 wheels a year to half a million wheels per year in the long term.

One consequence of the company's success is competition from rival carbon fibre wheel technologies. Tim believes the company is fortified by developing its own manufacturing processes and equipment and owning its own IP. Indeed, Carbon Revolution currently has 41 patents covering its manufacturing processes and designs, with another 14 pending.

It is safe to speculate that there will always be markets for automotive components that make a car go faster. Reducing unsprung mass helps a car's suspension work more effectively. Reducing rotating mass will make the car accelerate and stop faster and conversely reduce fuel consumption. All this makes the future promising for lightweight carbon fibre automotive components with beautiful finished surface aesthetics.

Like the legendary style of the Ferrari brand, Australia's own Carbon Revolution's is on the rise and capturing attention all over the world.

Written by Kerryn Caulfield, Executive Manager of Composites Australia Inc.

Further information on the International Specialised Skills Institute and its Fellowships can be found at http://www.issinstitute.org.au.

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