A NOVEL MANUFACTURING CELL FOR A NEW GENERATION OF COMPOSITE PROCESSING AND APPLICATIONS

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SUMMARY: A novel manufacturing cell has been developed to open new perspectives in composite and polymer processing by combining intrinsic and geometrical stiffness in an integrated processing operation. Two concepts for combining aligned fibre structures and flow moulding materials have been demonstrated through processing trials. The first technique was demonstrated through a hook comprised of robotically placed UD carbon/PA12 tow overinjected with PA12, combining creep resistance and load introduction with a bulk flow process. Stamp forming of commingled fabrics followed by overinjection moulding formed the second variant, demonstrated with both polyamide and polypropylene based systems. The manufacturing cell, together with subsequent moulding trials and material tests, has scaled the concept and validated the integrated processing philosophy.

KEYWORDS: integrated processing, manufacturing cell, compression moulding, tow placement, injection moulding, new applications.

INTRODUCTION

Successful implementation of composite materials into high volume applications, particularly the automotive industry, requires the consideration of multiple, dynamically interacting, requirements [1]. Fig.1 illustrates the advantages to be gained by reduced vehicle inertia achieved through lean weight materials and construction techniques. However, candidate materials such as thermoplastic and thermoset composites have not made serious inroads into the area of primary vehicle structure. Aligned fibre materials have limited forming complexity and flow moulding materials limited intrinsic

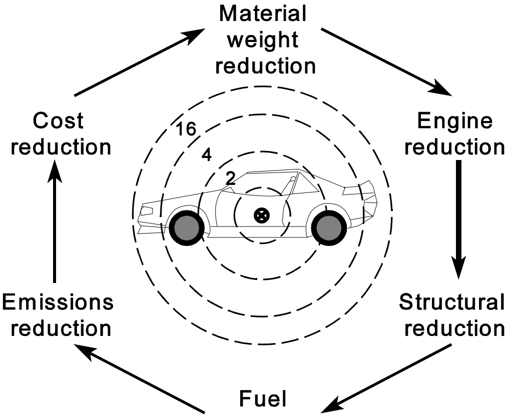

Fig. 1: Driving forces for automotive materials

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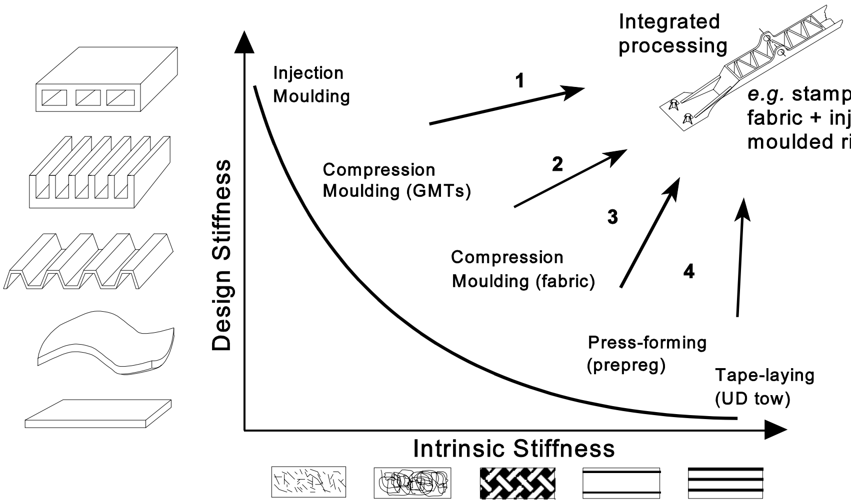

Fig. 2: Integration of design and intrinsic stiffness

stiffness. Recent developments towards meeting this constraint include: overinjection of stamped steel structures [2] and the combination of GMTs (flow moulding) and aligned fibre structures during compression moulding [3,4]. Montell Polyolefins have integrated unreinforced polymer processes through a conceptual manufacturing cell, with the aim of improving the efficiency of processing, increasing design freedom and combining the advantages of different material forms [5]. Ashby [6] has given an extensive discussion comparing the structural efficiencies of different cross-sectional geometries loaded in bending and torsion. Fig. 2 illustrates the advantages of the integrated processing philosophy by combining intrinsic and geometrical stiffness in the same component.

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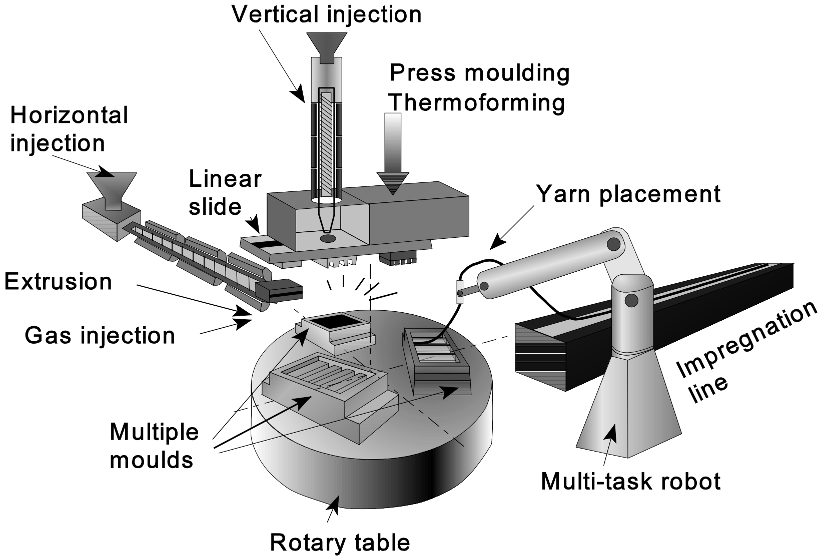

Fig. 3: Integrated processing cell

A novel manufacturing cell has been developed [7], integrating different polymers and composites together with multiple processing operations to open new perspectives in the conversion of polymer composites (Fig. 3), subject to an international patent [8]. This has achieved a synergy of the load bearing ability of aligned fibre structures and the geometrical complexity obtainable from flow moulding materials. Robotic tow placement (Fig. 4), injection units, an extrusion head and compression moulding have been combined under integrated control, extending current and developing new application areas for polymer composites. The control unit permits the selection of different sequences of processing steps required for the manufacture of a given part. Three upper tools locate on a linear slide and three lower tools mount on a rotary carousel (Fig. 3), combining several processing techniques in an integrated sequence.

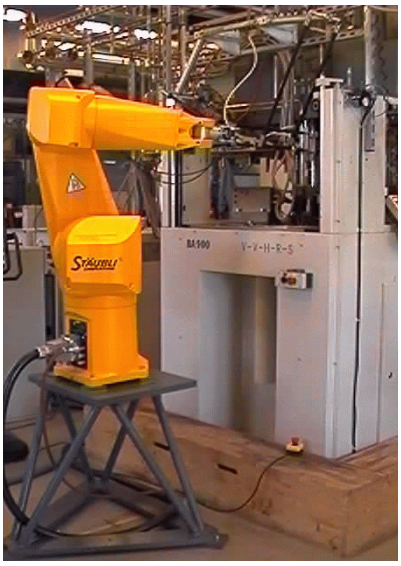

Fig. 4: Robotic tow placement

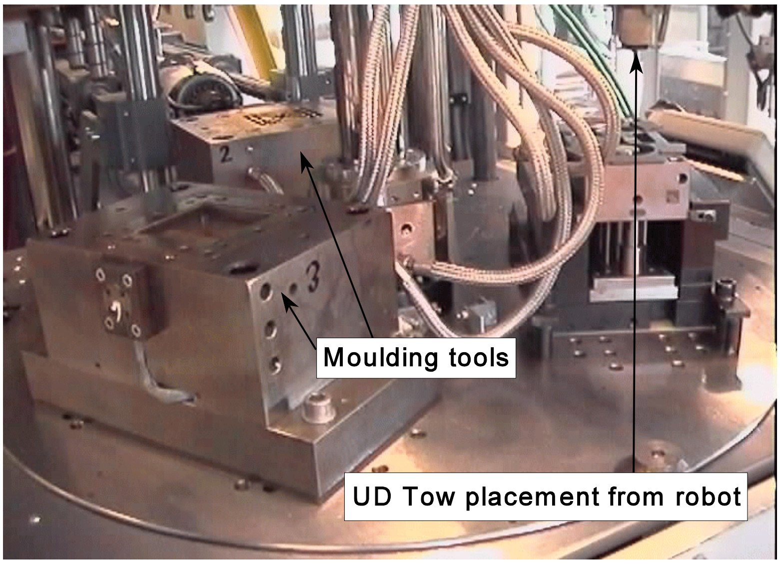

Fig. 5: Rotary tool carousel

To process a component combining intrinsic and design stiffness would require traditionally the use of separate processing equipment. Before the second operation, the partially finished component must be heated, involving an additional energy cycle, to recreate the interfacial thermal conditions. Fig. 6 illustrates the energy and time saved by performing the bonding as an integrated operation. To combine two components produced via the separate processes of injection moulding and fabric stamping would require the use of welding techniques. The three operations and hence additional costs (extra thermal cycle, storage and transportation) associated with conventional welding are reduced to one integrated cycle using the manufacturing cell.

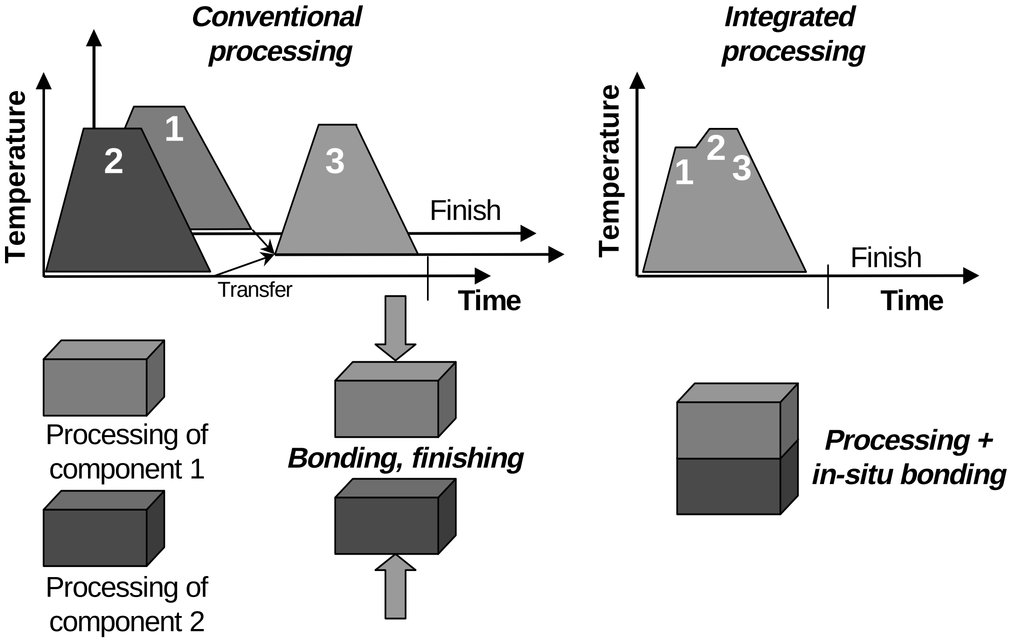

Fig. 6: Integrated processing with in-situ bonding

This is achieved by optimising the temperature of the overinjected or compressed composite with that of the initially processed sub-component [7]. Semi-crystalline thermoplastic resins can be bonded by bringing the adherents into contact at a temperature above the crystalline melting temperature. Following local surface rearrangement and intimate contact, fusion bonding occurs as a result of inter-diffusion across the interface, with crystallisation completing bond formation during the cooling phase [9]. The required thermal conditions are an average interfacial temperature above the melting point of the polymer. Non-isothermal conditions between the two sub-components results in heat transfer from the molten polymer to the solid substrate where local melting of a thin layer occurs. During the cooling phase, crystallisation occurs from the remaining crystals around the new solid and liquid interface and propagates through the original interface. Non-isothermal processing of polypropylene based systems has been shown to reduce the time to reach the maximum fracture energy from 300s (for isothermal processing) to 40s [9]. Work in progress aims to understand the interrelation between processing parameters, heat transfer and the resulting interfacial conditions.

These ideas are now being demonstrated via two concepts to produce components of varying size and added value.

INTEGRATION OF TOW PLACEMENT AND POLYMER OVERINJECTION

Integrated processing of tow placement with polymer overinjection has achieved the synergy of a very high specific strength UD carbon tow placed and consolidated by robot onto a mould with overinjection of polymer. Utilisation of a commingled uni-directional 69% (wt.) carbon fibre and PA12 tow, with a tensile modulus of 110GPa, offers a local 18 times stiffness increase over 40% (wt.) short glass fibre reinforced polypropylene injection moulding compounds. The fibre tow would be placed (minimising waste) in regions of high operating load and at areas of load introduction (giving creep resistance) with the overinjected polymer forming an external complex shape, additional attachment points, specific surface properties, or a semi-structural feature. Tow placement is optimised to control void content evolution during processing. The placement process provides sufficient in-situ consolidation to hold the tow in position for subsequent overinjection, but with final void content reduction induced by the high overinjection pressure.

The prototype line has shown successful integration of tow lay down and overinjection with optimisation of interlayer healing and solidification. Tow was placed into a common lower mould on the lower carousel before rotation under the vertical injection unit where the upper tool locates before overinjection. An example is shown in Fig. 7 and 8 (commingled carbon 69%.wt /PA12 and powder impregnated carbon 49%.wt/PA12 respectively) where UD tow has been placed into a generic hook mould before overinjection of PA12. Tow was placed for the hook shown in Fig. 7 directly onto a warm (80°C) injected preform to maintain placement accuracy and reduce fibre architecture disruption during overinjection. Tow for the hook shown in Fig. 8 was again placed onto a preform, but with the preform removed (preform at 20°C during placement) before overinjection, thereby increasing flexural properties and total carbon content.

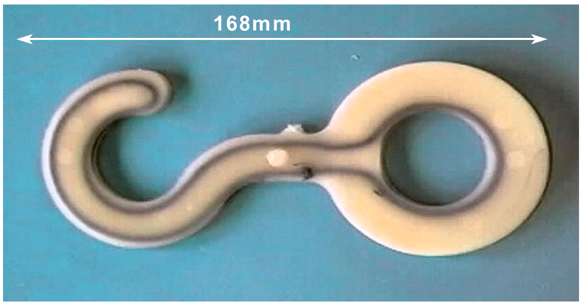

Fig. 7: Commingled carbon/PA12 tow overinjected with PA12

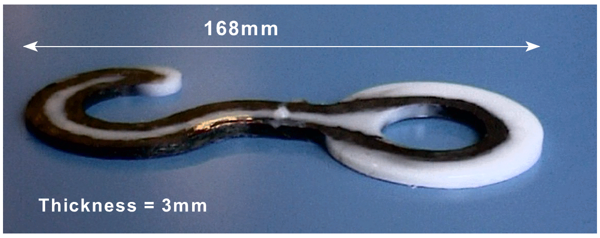

Fig. 8: Powder impregnated carbon/PA12 overinjected with PA12

Table 1 summaries the cycle times and processing parameters used to manufacture the hook shown in Fig. 8. Injection of the tow placement preform is assumed to take place of line with direct recycling. Tow placement times are currently the limiting factor in cycle time reduction, with a current maximum placement rate of 150 mms^{-1} (reduced rates for curvature). Using one robotic placement unit, shorter lay down times and hence smaller components would be better suited to volume production, with optimisation of cell design using 2 or more robots for larger components with increased tow placement cycle times. Current work aims to achieve cycle times of 120 seconds (geometry dependant) through optimisation of each processing stage [10].

Fig. 9 illustrates the possibilities of this technique where the overinjection of integral mounting brackets and cosmetic items occurs with the structural, creep resistant, member.

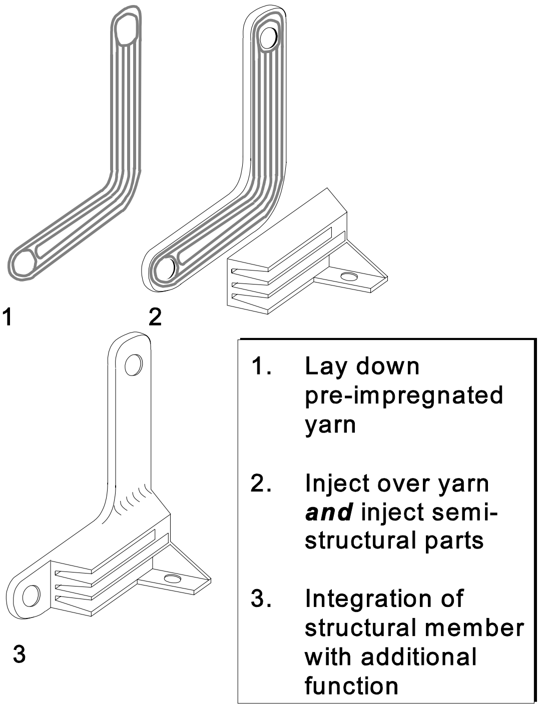

Fig. 9: Integration of tow lay down and overinjection

Table 1 Process step break down and parameters for Fig. 8

Process step break down		***Processing parameters***	
Tow placement time: 3 turns of 470mm using 48k powder impregnated tow, (s)	70	Placement velocity (mms^{-1})	20
		Placement nozzle temperature, (^{o}C)	260
Overinjection: Tool closure, injection, hold, cooling, ejection, opening time, (s)	100	Placement pressure, (bar)	15
		Nominal injection pressure, (bar)	~500
Lower table rotation, (s)	2	Injection temperature, (^{o}C)	260
Cycle time/hook (sequential), (s)	***172***	Tool temperature, (^{o}C)	80

INTEGRATION OF FABRIC STAMPING AND POLYMER OVERINJECTION

The second concept extends injection moulding technology and the stamping of fabrics through identifying the inherent limitations of the two techniques and combining the advantages of both. The shaping freedom of neat polymers or short fibre reinforced systems will always be superior to that of continuous fibre materials, but they do not offer the required stiffness or creep resistance obtained by continuously reinforced polymers. The stamping of aligned fibres followed by overinjection increases mechanical properties beyond injection moulding compounds and offers geometries unattainable with fabrics, in one component. The conventional range of fabrics would be formed at high speed off line. This variant would be suited to components where the tailored fibre architecture offered by tow placement is not required.

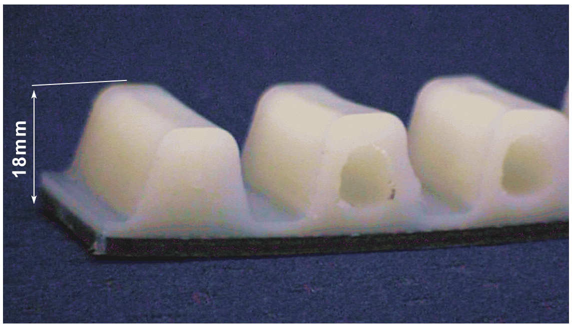

Fig. 10: Stamped commingled carbon/ PA12 fabric overinjection moulded (gas assisted)

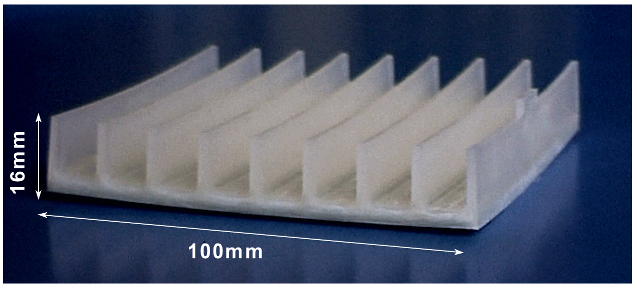

Fig. 11: Stamped commingled glass/ PP fabric overinjection moulded

The integrated processing cell has been used to combine compression and injection moulding, shown for two components in Fig. 10 & 11. An example of PA12 overinjection (EMS Chemie L20G) onto compression moulded commingled carbon/PA12 (Schappe Technique balanced weave 69% .wt carbon) in shown in Fig. 10, with gas assist used to reduce component mass near to the neutral axis and aid the release of internal stress. Fig. 11 shows PP (Montell VM6100H) overinjected onto a compression moulded commingled glass and PP stamped plate (Vetrotex: 'Twintex', balanced weave 60% .wt glass). Only one processing sequence and heating cycle was needed, reducing the time to manufacture the final part, energy consumption and handling logistics. Table 2 summaries the cycle times and processing parameters used to manufacture the ribbed plate shown in Fig. 11.

While previously consolidated commingled fabrics have been used here for overinjection, an optimised system would use a carousel with a fabric preform heating station before rotation of the hot fabric to the upper and lower warm stamping tools. In practice, the heating and stamping stages could be performed concurrently, so the preheat time is not considered here. Results presented previously by Breuer and Neitzel [11] have been used to define the time for the stamping phase (performed isothermally here). After consolidation and forming of the fabric, the stamped part would remain in the lower tool while the upper injection tool is moved into place via the upper linear slide, thereby reducing tooling requirements to 3 half moulds. The overinjected polymer then melts locally the surface of the fabric, forming the required interfacial properties. An injection temperature of 240°C with a tool (and hence sub-component) temperature of 80°C gave the required interfacial conditions. To reduce tool wear, a net shaped preform or

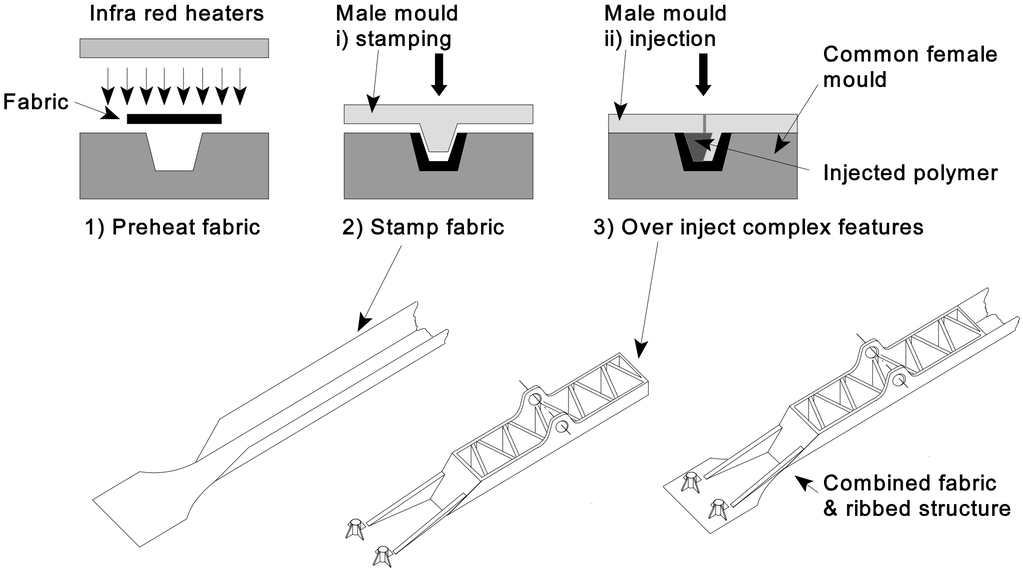

Fig. 12 Stamping of fabrics with overinjection

trimming of the stamped part would be needed before overinjection. This is shown schematically for a component of increased complexity in Fig. 12.

Applications under consideration include structural components in the automotive & machine tool industries where injection moulding does not offer the required performance and fabrics cannot be formed to the required geometry. If commodity materials (such as glass/PP) were used in an automotive application, increased surface properties could be obtained by combining a PP or PP/PA blend core with a PA layer (via compatibiliser additives such as maleic anhydride or hyper branched polymer [12,13]) overextruded or injected as the surface material.

Table 2 Process step break down and parameters for Fig. 8

Process step break down		***Processing parameters***	
Heating of fabric [11]	35	Stamping rate, (mms^{-1})	10-100
Stamping of fabric (transfer, deep drawing, cooling), (s) [11]	15	Material preheat temperature, (^{o}C)	220
Overinjection: Tool closure, injection, hold, cooling, ejection, opening time, (s)	100	Nominal injection pressure, (bar)	~500
		Injection temperature, (^{o}C)	260
Lower table rotation x 2, (s)	4	Injection tool temperature, (^{o}C)	80
Cycle time/ribbed plate (seq.), (s)	***118***		

SUMMARY

Two concepts have been presented for combining advanced composites (for high performance) and engineering plastics (for geometry, surface performance and appearance) in the same component by integrating processing techniques. The integrated processing concept introduces new perspectives in part design, offering design freedom, multi-functionality and fine local tailoring of performance in an optimised and rapid sequence of integrated operations. Two materials and processing operations were considered, namely: combining UD tow placement with overinjection moulding and commingled fabric stamping with overinjection. These concepts have been taken to an advanced level by investigations using industrial scale laboratory equipment and are now ready for industrial development, demonstration and exploitation.

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