Tailor-made Thermoplastics with Layer Structures and Continuous Fibre Reinforcement

Hybrid Technology. Novel, complex, multi-layer thermoplastic composite parts for lightweight applications in the transport sector are being manufactured on an application-specific basis by multi-layer/sandwich injection moulding with embedded reinforcements made from continuous fibre preforms. Optimised microstructure and interfacial adhesion are crucial to the outstanding mechanical properties of this new class of materials.

Modern plastics are characterised by two extremes. On the one hand, there are the highly cost-intensive thermoset fibre-composite materials with strengths many times that of steel, and, on the other, there are the thermoplastic commodity products that are unsuitable for industrial applications where safety is crucial. Combining the advantageous properties of these two classes of material may fill the technological gap. Progress in this regard was recently made by the EU project Hyject [1], the background to which is shown in Table 1.

Filling a Technological Gap

The advantages of thermoplastics, namely rapid, cost-effective, energy-saving production, low water uptake and ease of recycling, are serving as the departure point for the development of novel, multi-layer thermoplastic composites for lightweight automotive parts. Multi-layer/sandwich injection moulding involving the use of reinforcing thermoplastic continuous-fibre

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Project partners

Partner	Sector	Project activities and function
StructoForm GmbH, Aachen (D)	Injection-moulding technologies, process development	Concept development, project coordinator, technical management
Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin (D)	Safety and reliability in materials technology and chemistry	Non-destructive and mechanical characterization; scientific management
Promolding BV, Den Hague (NL)	Injection-moulding products	CAD for products, concept development
Savoy Moulage S.A., Cluses (F)	Injection-moulding products	Mould design and construction
Eurocarbon BV, Sittard (NL)	Textile composites	Preform manufacture based on braids
Gurit Suprem, Fluringen (CH)	Thermoplastic composites	Insert manufacture based on UD composites

Table 1. The six members of the consortium and their activities within the project (Source: StructoForm GmbH)

Simultaneous Processing

Horizontal unit (+ optional gas-injection method) ⇨ / Secondary unit ⇩	Injection-moulding (1 cpt) compact	Sandwich (2 cpt) For example, with continuous-fibre core	Sandwich (2 cpt) with foamed core layer
Injection moulding (1 cpt) compact	2 cpt: compact e.g. hard/soft composite	3 cpt: compact e.g. three-layer sandwich with gated soft component	3 cpt: five-layer sandwich with reduced core mass and greater moment of resistance
Sandwich (2 cpt)	3 cpt: compact Five-layer sandwich	4 cpt: compact Seven-layer sandwich	4 cpt: Light weight Seven-layer sandwich with reduced core mass and greater moment of resistance
Sandwich (2 cpt) with foamed core layer	3 cpt: five-layer sandwich with reduced core mass and greater moment of resistance	4 cpt: light weight + sealing e.g. five-layer sandwich with foamed core and gated soft component	–

Table 2. Possible combinations of sub-processes with up to four matrix components

composites inserted as preforms into the mould yields complex composite structures that offer enhanced mechanical properties.

The further development of this injection-moulding technology depends critically on total interfacial adhesion, both within the preforms and at the edges. Selective process optimisation is possible through detailed mechanical testing and novel non-destructive characterization of interfaces using X-ray refraction.

Modular Machine Design Combines Six Sub-Processes

Novel multi-layer composites can be created by sandwich moulding of thermoplastics, with the option of additionally embedding reinforcing or functional elements (Fig. 1). Different thermoplastic matrices may be combined to build up a tailor-made property set in one processing stage. The weight can be substantially reduced if additional use is made of gas injection and foaming methods. The result is complex hybrid materials made from continuous-fibre composite preforms that – in a multi-stage process, if need be – serve as the exoskeletal or endoskeletal (backbone) reinforcements. The injection-moulding process serves to embed the fibre-composite part and to shape its external geometry. The sequence of steps is as follows:.

- Preforming (production of insert parts)
- 1st handling stage (insertion and fixation)
- Sheathing (building up the jacket from one or more layers of thermoplastics, connecting the preform, cooling)
- 2nd handling operation (ejection and stacking)
- Material characterization and testing (mechanical testing, microstructure, interfacial adhesion).

To combine the specific properties of the various component materials in the new material structure, a multi-component injection moulder composed of modular machinery and ancillary units was made. This was progressively expanded to eventually consist of as many as four plasticating and injection units, each of which represents a production sub-process (Fig. 2). The multi-component injection-moulding unit is a 2000-kN machine whose plasticating unit containing a 60-mm screw is complemented by a vertical, modular sandwich plasticator that also serves as an intrusion device. Another secondary module in the L-position allows further multi-functional parts to be attached. Finally, a sandwich-plasticating unit is mounted vertically on the machine nozzle of the secondary module.

This machine configuration can process four thermoplastic matrix components at once and may be augmented with a fluid technique, such as gas-assist and water-assist injection. For this purpose, a modular mono-valve injection unit for introducing inert gas through mould injectors is available. An additional option of sheathing reinforcing preforms made from continuous fibre composites means that up to six different sub-processes can be performed in one operation. Such high functional density enables different material properties to be combined and specific local functional zones to be achieved in one part (Table 2).

Trials on Continuous-fibre Reinforcements

Different high-viscosity and low-viscosity thermoplastics, with or without such fillers as fibres, particles and additives, may be combined to create specific material profiles. In addition, this hybrid sandwich technique uses incorporated continuous-fibre composites (preforms or inserts) for reinforcement. The choice of fibre (glass, carbon, aramid), the number of fibre layers, the fibre angle and the volume-percentage of fibre can all be varied to produce a specific property profile.

All attempts to use braids directly for reinforcement have met with failure. The higher melt viscosity that is typical of thermoplastics prevents adequate impregnation of the fibre bundle during injection moulding, with the result that a solid composite is not formed.

Thermal pre-consolidation of braids with a mixture of carbon and thermoplastic fibres, however, yields mechanically stable composite preforms that are rigid enough to withstand injection moulding (Eurocarbon BV, Sittard/Netherlands). Good results have also been obtained with composite inserts made from carbon fibre-UD profiles containing thermoplastic matrix (Gurit Suprem, Fluringen/Switzerland). Special holders help to fix these kinds of reinforcing elements in the mould.

The intended applications of the parts made in this novel hybrid process determine the shape of the reinforcing elements. Pipe-like preforms made from consolidated braids are eminently suitable for rod-shaped components, such as levers, stabilizers, switch rods and push rods, pedals, stands, and handlebars, as well as stretched, hollow, parts. To be able to quantitatively characterize the material

The Hyject consortium

The Hyject consortium sponsored by the EU Commission was founded in 1999. In the course of an EU project six participants developed complex multi-layered thermoplastic composite parts for lightweight transport applications. Future activities include the development of applications for the new hybrid technology with industrial partners; these applications are either being planned or already in the initial phases. StructoForm is performing the process-engineering feasibility studies on the pilot equipment.

properties and the microstructure of the braid-reinforced hybrids, Promolding BV, The Hague/Netherlands, developed hollow, cylindrical test specimens that it dubbed "dog bones" (Fig. 3).

Flat composite inserts may be used for applications that require a rigid core, e. g. compact gear levers with moulded-on functional zones. Furthermore, preform combinations, such as wound cages and local radial reinforcements, can be made from UD profiles.

Moulds for the Hybrid Technology

The mould technology for the new hybrid process is dictated on the one hand by the requirements of the insertion process and, on the other, by the downstream stage of sheathing with monolayer or multi-layer thermoplastics. Series production of components can be built up using the proven concepts of multi-component processing. The core-back, rotary plate or indexing plate techniques are used for multi-stage sheathing or gating of thermoplastic zones. Moulds with slides and cores that move in synchronization with the process were specially developed for producing the precise internal contour of the dog bones (Savoy Moulage SA, Cluses/ France; Fig. 4).

A wound hollow structure for special applications was generated by the gas-injection technique. This was used to produce a car brake pedal with braid reinforcement (Fig. 5). The transfer and stack mould techniques are used for sheathing the preform in two consecutive mould stations. Optimum mould temperature control, specifically for the high performance thermoplastics PPS, LCP, PEI, has been realised by means of dynamic oil temperature control using an online process monitor.

Non-destructive Characterization of the Microstructure

Given the complex internal structure of multi-layer and hybrid thermoplastics, targeted material development requires a thorough understanding of the microstructure, especially of interfacial and fibre adhesion. Modern X-ray diffraction topography was used for this [2].

The position of the carbon fibre braid and its fibre adhesion within the PA matrix of a hollow cylinder is visualised with the aid of X-ray refraction computer topography (XR-CT) [3] (title picture). Comparison with conventional CT reveals the inadequate absorption contrast of the carbon in PA. Refraction topography permits quantitative determination of the specific surface, caused by inadequate impregnation of fibres within the preforms. Figure 6 shows the correlation between the mechanical properties and the specific surface in the carbon fibre preforms of different test specimen grades.

With just 3 vol.% carbon fibres in 0° and ±45° orientation in the dog bones, it was possible to double the rigidity and treble the strength relative to pure PA 12. Increasing the content of carbon fibre can substantially increase these characteristic values; 50 vol.%, can yield the very high characteristic values of thermoset composites (according to model calculation).

Summary and Outlook

Injection-moulded thermoplastic multilayer composites and complex composite-reinforced hybrid structures may be produced by selective use of the multi-component, sandwich and multi-layer techniques as well as of embedded, high-strength continuous fibre preforms. A new class of thermoplastic materials offering favourable cost-benefit ratio has thus been created that constitutes an alternative to elaborate thermoset, die-cast and lightweight metal components. The multi-component injection-moulding machine developed here will be used on further industrial development projects. ■

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Title picture. X-ray computer tomographs (CT) of a dog-bone cylinder with carbon fibre braid in PA 12 matrix; left: conventional CT with cross-section of density information; right: the X-ray refraction CT with interfacial contrast of the fabric shows its position and the non-adhering fibres

Fig. 1. Sandwich composites: Multi-layer and hybrid techniques with continuous fibre preforms for injection moulding of sandwich composites from four components A to D

Fig. 2. Multicomponent injection moulder with modular machine and aggregate parts

Fig. 3. Carbon-fibre braid with PA 12 fibres, thermally consolidated preform and hollow-cylindrical PA 12 dog-bone test specimens with integrated preform

Fig. 4. Injection mould with hydraulically powered cylinder core (top) and sleeve (bottom) for dog-bone hollow cylinder with preforms

Fig. 5. Process stages for a hybrid car brake pedal featuring carbon fibre braid reinforcement, PA 12 matrix and cavity made by gas injection

Fig. 6. Carbon fibre preforms in test specimens: Correlation of the mechanical properties and the specific surface of the carbon fibre preforms in cylindrical test specimens of varying degrees of quality
Festigkeit = Strength; Qualität = Quality
Steifigkeit = Stiffness; Rel. Einheit = Rel. unit,
Spez. Oberfläche = Specific surface