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Material properties

Compression and tensile properties of self-reinforced poly(ethylene terephthalate)-composites

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ABSTRACT

Tensile and compression properties of self-reinforced poly(ethylene terephthalate) (SrPET) composites has been investigated. SrPET composites or all-polymer composites have improved mechanical properties compared to the bulk polymer but with maintained recyclability. In contrast to traditional carbon/glass fibre reinforced composites, SrPET composites are very ductile, resulting in high failure strains without softening or catastrophic failure. In tension, the SrPET composites behave linear elastically until the fibre-matrix interface fails, at which point the stiffness starts decreasing. As the material is further strained, strain hardening occurs and the specimen finally fails at a global strain above 10%. In compression, the composite initially fails through fibre yielding, and at higher strains through fibre bending. The stress-strain response is reminiscent of an elastic-perfectly plastic material with a high strain to failure (typically over 10%). This indicates that SrPET composites are not only candidates as semi-structural composites but also as highly efficient energy absorbing materials.

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1. Introduction

Improved energy efficiency and reduced fuel consumption have become increasingly important in order to stay competitive in the transport industry. As examples, the commercial truck industry is subject to stringent emission legislations, and the aerospace industry sees constant pressure to reduce fuel consumption of aircraft. Weight reduction has proven to be an efficient way of reducing the fuel consumption of both road and airborne vehicles. To achieve improved weight efficiency of vehicles, the use of lightweight alloys and composite materials has increased significantly during the last decade. A major challenge is, however, to reduce the weight of structures while reducing costs and improving the recyclability of the structural materials. Traditional composite materials are commonly based on thermoset matrix materials reinforced with

carbon or glass fibres. This class of composite material is generally manufactured using a matrix infusion process followed by a time consuming curing (and cooling) process, which results in an overall long manufacturing lead time and, consequently, high costs. Further, thermoset based composites are generally brittle, have low fracture toughness, low inter-laminar toughness and poor recyclability. In particular, recycling of thermoset matrix based composites has proven to be very costly since no efficient process to separate fibres from the matrix exists [1]. Using thermoplastic matrix materials, new opportunities for cost-efficient manufacturing and improved recyclability are enabled. As an example, thermoplastics can be reheated and rapidly formed using a variety of techniques such as folding, blowing, stretching and stamping. They can also be remelted and recycled into new structures. In order to improve the mechanical performance of thermoplastics it is, however, intuitive to reinforce them with carbon or glass fibres. Doing this will, however, inflict on their recyclability.

This has paved way for a new generation of composite materials where the fibres and the matrix are made from the

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same base material. This class of composites are termed all-polymer composites or self-reinforced polymer (SrP) composites. Some examples of commercially available SrPs include poly (ethylene terephthalate) (PET) [2] and polypropylene (PP) [3] SrPs. SrP are thus an emerging class of composites attributable to the possibility to rapidly manufacture lightweight and recyclable parts with a density well below traditional filled polymers [4,5]. The fibres used in SrP's have higher molecular orientation which results in improved stiffness and strength compared to the unreinforced matrix materials. The matrix material is commonly amorphous and/or out of a polymer with lower melting temperature. The fibres are much more ductile than the matrix, which is unusual for composite materials, but results in the ability to absorb a high level of energy when (plastically) deformed [6]. SrPs can also be made from commingled fabrics which will eliminate the resin injection process; something that will be described in more detail later in this paper. The material processing is then reduced to heating the commingled material to its melting temperature followed by a cooling process. To date, only a limited number of studies have investigated the mechanical properties of SrP materials. Hine and Ward [7] investigated the mechanical properties of woven PET that was manufactured using a hot compaction process. They found that the SrPET had approximately 2.5 times higher tensile strength and stiffness compared to the isotropic basic material. Yao et al. [2] investigated the mechanical properties of PET fabrics and films manufactured using a film stacking technique. They showed that tensile strength increases about 2.5 times when the PET matrix is reinforced with PET fibres. Alcock et al. [3] investigated the compression properties of self-reinforced PP made out of co-extruded all-PP tapes. They used an experimental setup where test specimens were end loaded to failure. It was found that the co-extruded all-PP tapes fail by tape buckling and delamination. The authors further concluded that the drawing mechanism of PP tapes enhances the tensile properties of the polymer structure but does not affect the compression properties. Therefore, no enhancement of the compression properties was found using drawn all-PP tapes as compared to bulk PP material. This study provides a detailed investigation of the mechanical properties of SrPET composites manufactured from commingled fabrics. The focus is on understanding the compressive response of the material but the material tensile properties are also presented in order to give a complete picture of the material behaviour. In order to build a clear understanding of the overall stress-strain response of the material coupled to the dominating failure mechanisms, traditional carbon and glass fibre reinforced thermoset and LPET matrix materials have been used for comparisons. The main objective has been to investigate if SrPETs have improved mechanical performance compared to the PET bulk material and if the potential increase of ductility results in improved energy absorption capability.

2. Description of materials and method

2.1. Constituent materials and manufacturing methods

SrPET plates were manufactured from fabrics with commingled yarns. In a commingled yarn, matrix fibres and

reinforcing fibres are blended. These yarns are woven jointly to form a dry fabric including both the fibres and the matrix. Two types of commingled fabrics were used: The first was a weave with 80% of the fibres in one direction and 20% in the perpendicular direction; this fabric will be denoted UD hereon. The other commingled fabric type was a balanced twill 2/2 weave (denoted Twill). The base matrix material (LPET) has a melting point of around 160–180 °C. The fibre material is a high tenacity PET (HPET) with a melting point of around 260 °C, which is significantly higher than for the LPET. The SrPET plates were manufactured using a vacuum consolidation process with a pressure of 0.95 bar under atmospheric pressure. The temperature was increased incrementally up to 220 °C for 12 min ensuring that the matrix material melts and fully impregnates the HPET fibres, leaving a minimum amount of voids. The consolidation time of the material is governed by the consolidation pressure and temperature and can be as short as 5 minutes when a pressure of 0.95 bar is applied at 230 °C. All Sr-PET plates were manufactured by Comfil® ApS [8]. For reference purpose, two additional types of different materials reinforced with glass or carbon fibres were manufactured. The first reference material was based on the same LPET matrix material as used in the SrPET plates. These plates were reinforced with T300-3K carbon (denoted C) fibres or E-glass (denoted E) fibres. The plates were manufactured from a balanced, commingled twill 2/2 fabric using the same vacuum consolidation process as for the SrPET plates. These plates were also manufactured by Comfil® ApS [8]. The second reference material was based on Vinyl-Ester Dion® 9102 matrix material from Reichhold (denoted VE) [9]. The VE plates were reinforced with T300-3K carbon (denoted C) or E-glass (denoted G) fibres which are the same as in the reference plates with LPET matrix. The plates were manufactured from a balanced twill 2/2 weave with the same areal weight of fibres as the reference plates based on LPET, and approximately the same fibre architecture. These plates were manufactured in-house using a traditional vacuum infusion process with a curing pressure of approximately 1 bar under atmosphere pressure, followed by a post curing cycle at 71 °C for 4 hours and 82 °C for 2 hours. One final reference plate was manufactured out of bulk LPET without any reinforcement. The manufacturing process was the same as for the SrPET plates and the plates were manufactured by Comfil® ApS [8]. Table 1 presents a summary of the physical and geometrical properties of all used materials. The fibre volume fraction of C/LPET and G/LPET is lower than the fibre volume fraction of the C/VE and G/VE composites. This is partly due to the commingled fabrics that were used in the LPET composites and partly due to the difference in the manufacturing process.

In order to evaluate the quality of the laminates, small pieces of the material were embedded in epoxy and mechanically polished using abrasive paper. Optical micrographs were then used to check the quality of the plates (see Fig. 1). The micrographs show no dry fibre bundles or other defects of significant size. The SrPET-UD plate shows the lowest amount of fibre crimp while the SrPET-Twill plate has a high amount of fibre crimp. The reference plates with carbon or glass fibres had

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