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Penetration impact testing of self-reinforced composites

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ABSTRACT

Penetration impact resistance is one of the key advantages of self-reinforced composites. This is typically measured using the same setup as for brittle fibre composites. However, issues with the test configuration for falling weight impact tests are reported. Similar issues have been found in literature for other composites incorporating ductile fibres. If the dimensions of the test samples are too small relative to the clamping device, then the test samples can heavily deform by wrinkling and necking. These unwanted mechanisms should be avoided as they absorb additional energy compared to properly tested samples. Furthermore, these mechanisms are found to occur more easily at lower compaction temperatures due to the lower interlayer bonding. In conclusions, the sample dimensions of ductile fibre composites should be carefully selected for penetration impact testing. If wrinkling or necking is observed, then the sample dimensions need to be increased.

1. Introduction

The number of applications for synthetic polymers continues to grow, because of their low density and generally low cost. They have replaced natural materials and metals in numerous applications. Their use is currently limited to non-structural applications due to their relatively low strength and stiffness. By adding a reinforcing fibre, these disadvantages can be mitigated. Glass, carbon and aramid fibres have been established as polymer reinforcements for several decades. However, these high performance fibres lead to composite failure strains ranging from 1% to 3%.

The mechanical properties of polymers can also be increased by inducing molecular orientation [1]. Polymers can for example be drawn into fibres or tapes [2–4]. These fibres and tapes can then be used to make self-reinforced composites (SRCs), where fibre and matrix are made of the same polymer. This type of composite with only one constituent was first investigated by Capiati and Porter [5]. Different production processes for self-reinforced composites were developed, such as hot compaction [6,7], film stacking [8] and bicomponent tape technology [9,10]. In the hot compaction technology, pressure and heat are applied to stacks of polymeric tapes. By selecting the optimal processing conditions, only the outer skin of the tapes melts, which forms the matrix upon cooling. In the bicomponent tape technology, the polymeric tapes are coated with a copolymer, with a lower melting temperature. Upon compaction, only the copolymer is melted and subsequently forms the matrix cooling. Film stacking consists of adding polymer films in between layers of oriented polymer tapes or fibres. The films have a lower melting temperature than the oriented tape or fibre. The consolidation temperature is chosen between the melting temperature of the film and the oriented tape or fibre.

Extensive reviews of the production and mechanical properties of self-reinforced composites from different polymers can be found in [11,12]. The mechanical properties of self-reinforced polypropylene (SRPP) depend on process parameters such as temperature, pressure and dwell time, and on material specific parameters such as weave architecture and tape draw ratio [13,14]. The process temperature has a strong influence on the tensile properties of hot compacted SRPP: in a 12 °C temperature window, the strength increases from 55 MPa to 140 MPa and then falls back to 27 MPa [13]. Furthermore, higher temperatures increase the interlayer bonding [13,15–17], which is typically quantified by the peel strength.

In addition to low density and recyclability, SRCs are attractive materials because of their excellent impact resistance. For characterization of the impact resistance, instrumented falling weight impact (IFWI) tests are common practice. IFWI tests are commonly used in literature to characterize the impact properties of SRPP [9,18–23], but are actually only standardized for rigid plastics and brittle textile composites in ASTM 5628-96 [24] and ISO 6603-2 [25]. SRPP is more ductile and impact resistant than conventional glass or carbon fibre composites [6], and hence it is ques-

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tionable whether SRPP can be properly tested using these standards.

Many authors published data for the penetration impact energy of SRPP. It is common practice to report values normalized by the thickness of the samples. However, Alcock et al. find a non-linear relation between the penetration impact energy and the thickness [9], so this normalization will induce an error on the following values. For hot compacted SRPP, penetration impact energies of 21 J/mm [20], 52–75 J/mm [19], and 26 J/mm [14] are reported. Bicomponent tape SRPP has an impact resistance of 20–44 J/mm [9], and finally for film stacked SRPP, values of 16–21 J/mm are reported [23].

Swolfs et al. [14] and Aurrekoetxea et al. [21] find that hot compacted SRPP primarily fails due to tape fracture, while delamination also significantly contributes to the energy absorption for the bicomponent tape SRPP [9]. For bicomponent tape SRPP, delaminations are more likely to occur according to Alcock et al. [9]. It is stated in [9,21] that increasing the consolidation temperature improves the interlayer bonding. A high interlayer bonding impedes the development of delaminations and therefore leads to more localized impact damage.

Alcock et al. [9], Crauwels [19] and Tissington et al. [26] show images of samples with severe deformation, such as those in Fig. 1. The former two show images of SRPP samples, while the latter shows that polyethylene fibre/epoxy composites can suffer from the same problem. Under normal circumstances, the main energy absorption mechanisms for SRPP during IFWI tests are tape fracture, delamination and debonding of fibre and matrix [9,21,23]. It is expected that heavily deformed samples will have a higher impact energy absorption, as the energy absorption mechanisms should be limited to inside the clamped region.

The present work will investigate whether the standard IFWI test as performed in literature are applicable for ductile fibre composites. A number of assumptions made in literature need to be verified. Firstly, the compaction quality of the SRPP needs to be verified. Secondly, the linear relationship between penetration impact energy and sample thickness will be investigated, as Alcock et al. [9] indicate that this relationship is not linear. Thirdly, the influence of sample geometry and clamp size on the impact resistance is investigated and parameters for the evaluation of configuration-dependent behaviour are proposed. Finally, when an adequate test setup is defined, the authors show the damage mechanisms change with the compaction temperature.

2. Materials and methods

2.1. Materials

Drawn polypropylene tapes are woven in a twill 2/2 pattern by Propex Fabrics GmbH (Germany). The tapes have a linear density of 110 tex, a stiffness of 6.9 ± 1.2 GPa and a strength of 589 ± 24 MPa [20]. Isotropic PP films of the same PP grade and with a thickness of 20 μm were provided by Propex Fabrics GmbH.

2.2. Hot compaction

To produce samples for impact testing, layers of woven PP-tapes with dimensions of 320 × 320 mm^2 were stacked between 1 mm thick aluminium plates. A Fontijne Grotnes LabPro400 hot press was pre-heated for 10 min at the compaction temperature to ensure a homogeneous temperature distribution. The stack was then inserted into the press and kept at the compaction temperature and a pressure of 4 MPa for 5 min. During cooling to 40 °C in 5 min, the pressure was maintained to minimize shrinkage. To aid compaction, the woven PP tapes were interleaved with PP films for some layups. Unless otherwise mentioned, these films were not added.

Unless otherwise stated, the impact tests will be performed on 16 layers of SRPP compacted at 188 °C, without PP films. These samples have a thickness of 2.48 mm.

2.3. Compaction quality

Ultrasonic C-scans were performed to investigate the compaction quality, compacted at different temperatures. An Olympus Panametrics V309SU transducer at 5 MHz and 100 V and 13 mm nominal diameter was used for the scans. The step size was 2 mm and the plates were scanned at 0.2 mm/s. The histograms of the C-scans are processed with the signal processing algorithms by O'Haver [27] to differentiate between areas with a different compaction quality.

2.4. Impact tests

Instrumented falling weight impact (IFWI) tests are performed with different test setups, among which the ASTM D5628 and the ISO 6603-2 standards. A hemispherical striker with diameter 20 mm is used in combination with clamps with inner diameters of 40 and 80 mm and outer diameters of 60 and 100 mm, respectively. The samples are clamped with a force of 2800 N, regardless of the size of the clamp. This corresponds to a clamping pressure of 1780 kPa and 557 kPa for respectively the 60 mm and the 100 mm clamp. A striker with a weight of 26.17 kg is dropped from 1 m height, which is equivalent to an impact energy of 257 J. The penetration impact energy is calculated as the area underneath the force–displacement diagram until the force has dropped below half of its maximum value.

Unless otherwise stated, the square impact samples have a length of 100 mm and the default clamp is the one with an outer diameter of 60 mm.

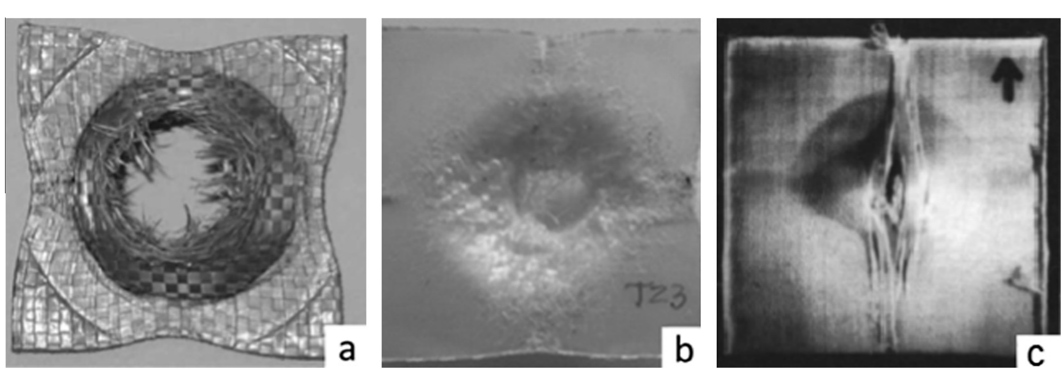

Fig. 1. Heavily deformed impact samples: (a) Alcock et al., bicomponent tape SRPP (reprinted from [9], with permission from Elsevier), (b) Crauwels, hot compacted SRPP [19], and (c) Tissington et al., polyethylene–epoxy composite (reprinted from [26], with permission from Elsevier).