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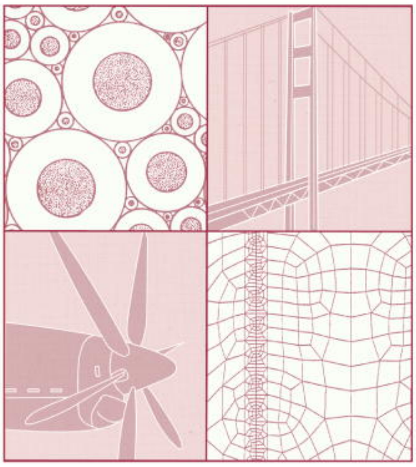

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The effect of temperature and strain rate on the impact performance of recyclable all-polypropylene composites

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Abstract

Highly oriented polypropylene (PP) tapes, with high tensile strength and stiffness achieved by molecular orientation during solid state drawing, are consolidated to create fully recyclable, high performance "all-polypropylene" (all-PP) composites. These composites possess a large processing temperature window (>30 °C) and a high volume fraction of highly oriented PP reinforcement phase (>90%). This large processing window is achieved by using co-extruded, highly drawn PP tapes. This paper investigates the relationship between the impact resistance of all-PP composite laminates based on these highly oriented co-extruded PP tapes, and the temperature and velocity of impact. Unlike isotropic PP, the highly oriented nature of all-PP composites means that a significant influence of glass transition temperature is not observed and so all-PP composites retain high impact energy absorption even at low temperatures. Finally, the ballistic impact resistance of all-PP composites is investigated and compared with current commercial anti-ballistic materials.

Keywords: A. Polymer (textile) fibre; B. Impact behaviour; E. Tape; E. Recycling; Self-reinforced

1. Introduction

A series of recent publications by the same authors describe the creation and mechanical properties of composite materials in which the reinforcement and matrix phase are both polypropylene [1–7]. The creation of these 'all-polypropylene' (all-PP) composites is motivated by the desire to enhance recyclability of composite materials. Conventional composites employ very different materials for the matrix and reinforcement phase and this complicates recycling. At the end of the life of a conventional composite component, recycling essentially requires separation of fibre and matrix, since these typically possess very different recycling requirements. All-PP composites overcome this problem since at the end of the life of an all-PP component, the entirely polypropylene composite can simply be melted down for reuse in a polypropylene (PP) feedstock or even into a subsequent generation of all-PP composite. The development of high modulus, high strength PP tapes allows the creation of high performance all-PP composite laminates which possess a wide range of interesting mechanical properties [3,5], particularly impact resistance [7]. The influence of velocity and temperature on the impact behaviour of all-PP composites is described in this paper, together with a comparison to conventional composite materials commonly used in impact applications.

1.1. Impact response of polymer composites

The response of a material to impact loading will depend on various factors such as the geometry of the structure and striker, the mass and velocity of the striker, and frequency of impacts. Due to their high strength and stiffness, and good energy absorption due to delaminating failure modes, composite materials generally perform well in impact applications. Carbon and glass fibres suffer from a lack of plasticity which means that non-penetrative

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impact loads can lead to (often invisible, subsurface) fibre damage, which can drastically reduce the residual mechanical properties of the composite. Thermoplastic fibre composites typically possess sufficient elastic limits to make them less sensitive to damage from lower energy impacts (see Table 1). Thermoplastic fibres such as UHMW-PE have specific applications as impact defence materials, such as personal protection for military or police personnel from direct projectile impact [8], or as spall liners behind ceramic/metallic armour in armoured vehicles to limit proliferation of shrapnel inside a vehicle following impact [9]. Composite ballistic protection can also provide significant weight savings for automotive defence, compared to steel armour [10,11] and has been assessed as fragment barriers for commercial aircraft [12]. The ballistic impact performance of composites has been modelled with some success to determine the methods of predict deformation [13] and model energy absorption [14].

Falling weight impact testing can provide analytical information about the mechanism on impact such as specimen displacement, duration of impact and energy absorption, but are limited to lower velocities, $<10\ \mathrm{m\,s^{-1}}$. The main difference between falling weight impact and ballistic impact is the velocity of testing, and this can result in a different response by the material. In composite systems, ballistic impacts (typically $>250\ \mathrm{m\,s^{-1}}$) involve the propagation of transverse and longitudinal waves through the specimen, which are not seen in lower velocity impacts (typically $<15\ \mathrm{m\,s^{-1}}$). These transverse waves propagate through the thickness of the specimen, while the longitudinal waves propagate along the fibres at the sonic velocity of the reinforcement, V_s

$$V_s = \sqrt{\left(\frac{E}{\rho}\right)} \tag{1}$$

where E is the tensile modulus of the reinforcement and ρ is the density of the reinforcement. A large sonic velocity will allow the dispersion of energy to as large an area as possible, before local strain at impact site leads to failure. The specific energy absorption capability, e_{sp}, has also been proposed as a comparative tool for ballistic fibres [8]:

$$e_{sp} = \frac{\sigma\varepsilon}{2\rho} \tag{2}$$

Where e_{sp} is the specific energy absorption capability, σ is the tensile strength of fibre, and ε is the percentage strain to failure of the fibre.

Fig. 1 compares sonic velocity and specific energy absorption capability for some common reinforcing fibres. Equally performing composites shall be considered to absorb the same energy upon impact. The energy absorption can be described to affect a circular area of composite laminate of radius, r, with an energy absorption described by the specific energy absorption capability, e_{sp}. Since the radius of material absorbing impact is due to the transmission of a longitudinal stress wave in the fibres at V_s, the area, a, of material absorbing impact energy could be described by:

$$a = \pi r^2 \tag{3}$$

or,

$$a \propto \pi V_s^2 \tag{4}$$

Equally performing composites would absorb equal energy, so energy absorbed in this area could be designated, c^2:

$$c^2 = \pi V_s^2 \times e_{sp} \tag{5}$$

Combining constants, gives:

$$c = V_s \times \sqrt{e_{sp}} \tag{6}$$

Since graphically in Fig. 1, axes are V_s and e_{sp}, Eq. (6) represents a curve which describes two materials which have equal performance based solely on these two parameters. However, this curve only accounts for the two criteria of

Table 1
Typical mechanical properties of some common composite reinforcing fibres

Material	Fibre type	Tensile strength (GPa)	Tensile modulus (GPa)	Strain to failure (%)	Density ($\mathrm{g\,cm^{-3}}$)	Reference
PBO	–	5.5	280	2.5	1.56	[8]
Glass	E Glass	3.5	72	4.8	2.58	[56]
	S-2 Glass	4.9	87	5.7	2.46	[56]
Aramid	Twaron HM1055	2.8	125	2.5	1.45	[57]
	Twaron HS2000	3.8	90	3.5	1.44	[57]
	Kevlar 49	2.9	135	2.8	1.45	[57]
	Kevlar 129	3.4	99	3.3	1.45	[57]
UHMW-PE	Dyneema SK60	2.7	89	3.5	0.97	[48]
(gel processed)	Dyneema SK71	4.0	120	4.1	0.97	[48]
	Spectra S900	2.1	79	3.6	0.97	[48]
	Spectra S2000	3.0	116	2.9	0.97	[48]
UHMW-PE (melt processed)	Certran	1.2	67	6.0	0.97	[49–51]
UHMW-PP (gel processed)	–	0.98	36	3.3	0.91	[15]
PP	All-PP tapes	0.45	15	7.5	0.78	[16]

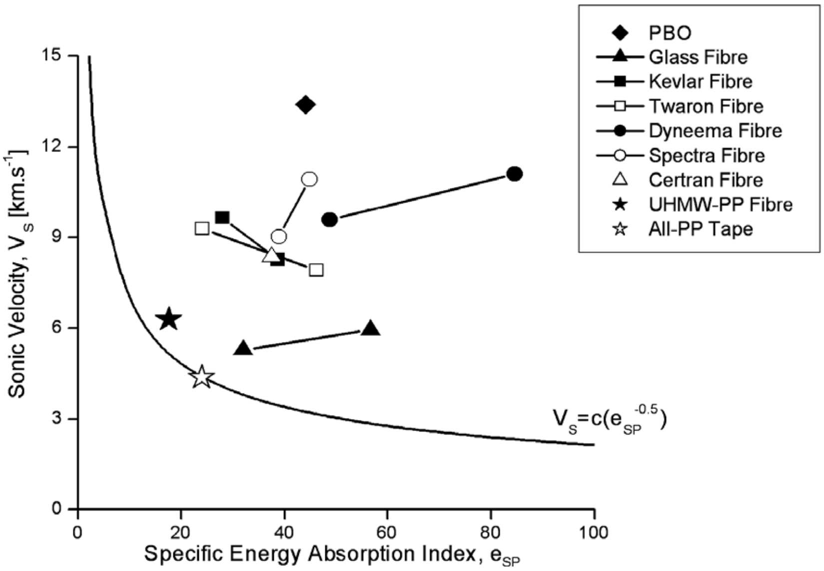

Fig. 1. Specific energy absorption capability index vs. sonic velocity for various fibres showing the curve predicting equal ballistic energy absorption performance based on Eq. (6). Data taken from Table 1.

sonic velocity and specific energy absorption capability of the fibres as described in Fig. 1. It can be seen that neither the highest draw ratio PP tapes used in this study [16], nor a highly oriented UHMW-PP fibre [15] feature highly in either axis and so would be unlikely candidates for ballistic applications. In fact, both the PP tape and the UHMW-PP fibre show similar performance on this graph, since UHMW-PP falls near the curve of equivalent performance for PP tapes. Using the design criteria described above, it can be seen that the PP tape used in this research would have a performance just below that of glass fibres. Thus high modulus, high strength, low density and large strain to failure are required to provide good ballistic impact resistance, but this method does not exhaustively determine the suitability of a reinforcing fibre for a ballistic application, due to the range in possible (non-fibre-related) energy absorption methods during ballistic impact, and also the fibre architecture within the composite. This calculation also assumes that the reinforcing elements (fibres or tapes) exhibit constant mechanical performance (i.e. tensile strength, strain to failure and modulus) regardless of the applied strain rate. Previous research has indicated that the mechanical properties of all-PP composites are largely unaffected by strain rate [4], when comparing mechanical properties at strain rates $>1\ s^{-1}$.

One of the main performance indicators for ballistic performance is the V50 number. This merely gives the velocity at which a particular panel will stop 50% of a certain type of projectile fired at it [17]. Thus a material can have a range of V50 values, each referring to a specific projectile or specimen thickness. Another value which is perhaps more useful to compare different materials is the energy per areal density absorbed by a material, which considers specimen dimensions, density and energy of the projectile. This research considers impact from a falling weighted striker and also ballistic impact by 9 mm full metal jacket (FMJ) parabellum projectiles and 1.1 g (17 grain) fragment simulating projectiles (FSPs). FSPs are machined steel cylinders which simulate projectiles from fragmentation grenades or shrapnel from explosions [18]. Fig. 2 shows a 1.1 g FSP, on the left-hand side, and a plastic firing sabot on the right-hand side. Nine-millimeter bullets are considered here because they are typical projectiles from common handguns. There is a range of different international ballistic standards which specify the energy per areal density of a material that is required to stop a given type of projectile.

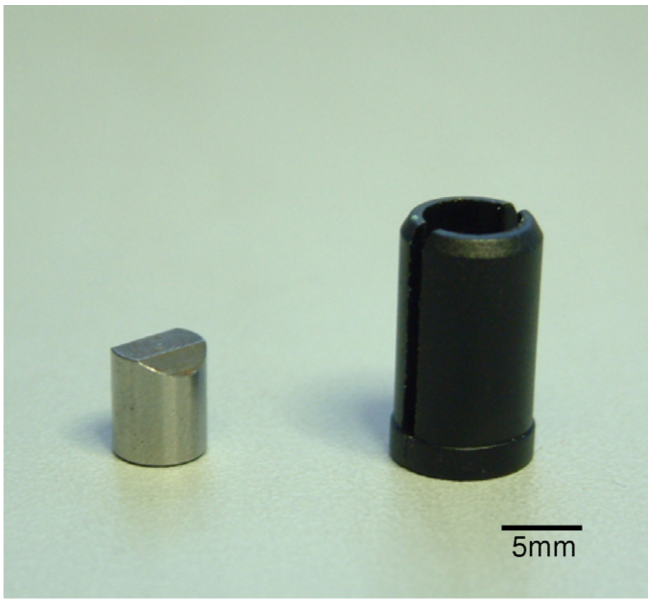

Fig. 2. Fragment simulating projectile (FSP) (left) with plastic sabot (right) for ballistic testing designed to simulate impact by explosion fragments. The FSP has a diameter of 5.39 mm and length of 6.35 mm.

One of the most popular of these is the American National Institute of Justice (NIJ) range of standards, which specify that a minimum number of ballistic projectiles must by stopped by a defined area of specimen.

Despite Fig. 1 indicating that PP is unlikely to be an ideal candidate for highly impact resistant applications, the very high volume fraction of reinforcing phase present in all-PP composites compared to traditional composites, combined with their low density may enhance their competitiveness.

The effect of composite processing conditions on the response of all-PP composites to falling weight impact with a constant velocity has been investigated [16] and is published elsewhere [7]. However, since all-PP composites are wholly thermoplastic, it may be expected that there is a strong relationship between mechanical properties and temperature, which may influence impact resistance. To determine the energy absorbed during impact at different temperatures, falling weight impact tests at temperatures between −50 °C and 120 °C are investigated. In addition, these impact tests were performed at a range of velocities to determine the effect of impact velocity on energy absorption. Finally, some initial ballistic impact tests were performed on all-PP plates to investigate the response of all-PP composites to very high velocity impacts. This ballistic testing also allows a comparison to be made between all-PP and some current ballistic commercial materials.

2. Experimental method

2.1. All-PP laminate production

It has previously been shown possible to create highly oriented PP tapes, with high tensile strength and stiffness, by molecular orientation achieved during solid state drawing [19–29], and thus it is conceivable to use these tapes as a reinforcement for a composite material. However, the risk of molecular orientation loss during thermal processing complicates composite production, since conventional thermoplastic matrix composites often employ high temperature, low viscosity melts to achieve good wetting of the reinforcement phase. Much has been published on alternative processing routes to achieve single polymer composites [30–39], however, existing technologies have some inherent limitation which reduce their viability, such as small temperature processing windows or low volume fractions of reinforcement limiting the ultimate mechanical properties of the composites. Highly oriented, high modulus fibres or tapes can be effectively welded together by melting the surface of the tapes and applying pressure to achieve a good bonding and fill any voids between the tapes [40]. In these mono-extruded tape or fibre systems, this process becomes highly sensitive to compaction temperature, since there is a risk of molecular relaxation during consolidation of tapes or fibre bundles into composites.

The research reported in this paper focuses on the use of co-extruded tape technology to create all-PP composites with a large temperature processing window and high volume fraction of reinforcement. In previous publications [1–3,5,7,41] and a series of theses [16,42,43], these composites have been described, as has a novel processing route which shall be summarised here. A tape with a skin:core:skin structure is produced by co-extrusion of a ethylene-propylene copolymer skin with a polypropylene homopolymer core. The relative proportions of this tape are 1:20:1 (skin:core:skin) and the tape is co-extruded at a rate of 6 m min^{-1}. This tape is subsequently drawn in a continuous two-stage drawing process through hot air ovens [28] and leaves the final oven at 102 m min^{-1}. Thus when drawn, the tape has a draw ratio of 17 and has approximate dimensions of 2.15 mm wide and 0.65 μm thick. This drawing process results in a high degree of molecular orientation and the drawn tapes possess a high tensile strength (∼450 MPa) and stiffness (∼15 GPa). While the mechanical properties of the PP tapes is clearly less than conventional composite reinforcements such as glass fibres (see Table 1), the high volume fraction of reinforcement present in all-PP composites ($V_f > 90\%$) allows all-PP composites to have competitive mechanical properties with conventional PP matrix composites [5].

This tape is then woven into a plain weave fabric with an areal density of ∼100 g m^{-2}, at a rate of approximately 600 m^2 h^{-1} using commercial polyolefin tape geotextile weaving apparatus. The all-PP fabric is shown in Fig. 3 and is used for subsequent composite laminate production. Plies of the fabric are cut and stacked in a close fitting mould, which is then subjected to heat and pressure in a hot press [5]. The application of pressure forces the fabric plies into close proximity and also causes a physical constraining effect which has been shown to artificially raise the melting temperature of highly oriented polymers [41,44]. This effect further protects the high degree of molecular orientation in the tapes by preventing relaxation during consolidation. The application of heat causes the skin layer of the tapes in the fabric to soften and molecular interdiffusion occurs between the skin layers of adjacent

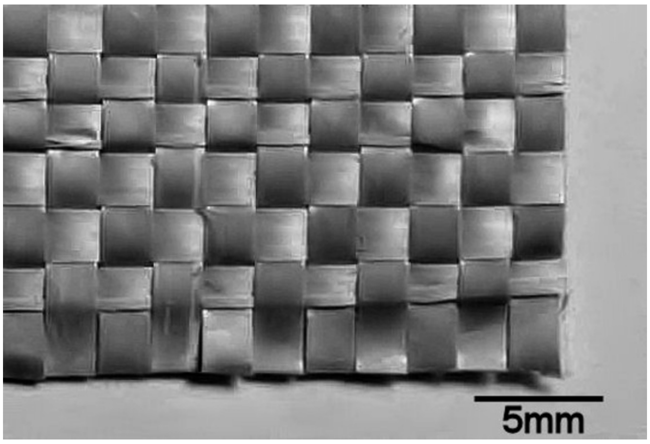

Fig. 3. Photograph of the woven all-PP tape fabric, prior to consolidation into composite laminates.

fabric plies. The copolymer used as the skin layer possesses a lower melting temperature than the homopolymer core and hence allows tapes to be effectively welded together at temperatures far below the melting temperature of the homopolymer core. Upon cooling, the all-PP composite laminate is now formed, comprising of the highly oriented propylene homopolymer reinforcement phase bonded together by the isotropic ethylene-propylene copolymer matrix phase. Fig. 4 shows a photograph of a consolidated laminate, in which the woven tape structure of the fabric is clearly visible on the surface of the composite laminate. These laminates can then easily be cut into specific geometries for testing.

The proportional thickness of the skin to the core layers can be altered during co-extrusion, but since the skin layer is present only to facilitate intertape bonding and is unoriented so the skin layer does not significantly contribute stiffness to the composite. In addition to the tensile mechanical properties of reinforcements in a composite system, the interfacial properties are responsible for many of the failure modes. In order to consolidate PP tapes into a coherent all-PP composite, the effect of the tape manufacture and consolidation parameters on the interfacial properties of these tapes must also be considered. The interfacial properties of all-PP composites were the focus of a recent research study [6] and are presented elsewhere.

Throughout the research on all-PP composites, one recurring phenomenon is the strong relationship between processing parameters and the mechanical properties of an all-PP composite laminate [5]. The effect of processing conditions is also apparent in the response of all-PP laminates to low velocity impact, and this is the subject of a separate publication [7]. The low velocity impact resistance was seen to be strongly related to the interfacial strength between constituent fabric plies in consolidated all-PP laminates. A higher interfacial strength between neighbouring all-PP fabric plies is achieved by consolidating the laminates at higher temperature or pressure, and this was seen to lead to more localised damage absorption and hence lower falling weight penetrative energy absorption. Conversely, the relatively weak interface in poorly consolidated laminates allowed the spread of damage to a much larger area, which resulted in greater overall energy absorption and hence a greater resistance to falling weight penetrative impact.

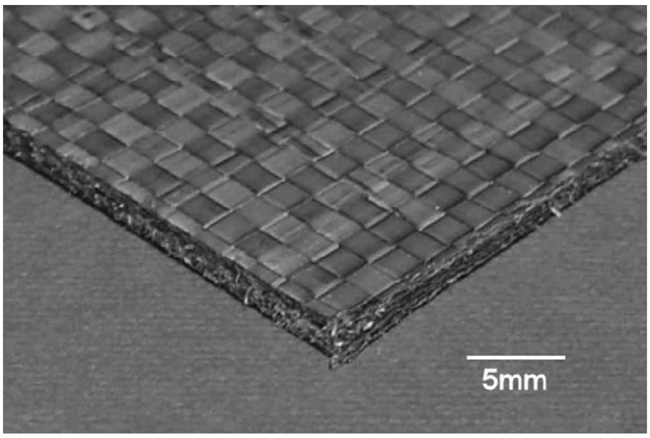

Fig. 4. Photograph of an all-PP composite laminate, in which the plain weave of the fabric is clearly visible on the upper surface of the laminate. Although manufactured from woven highly oriented PP tapes, these tapes are easily fibrillated, and the fibrillar nature of the tapes is clearly visible on the edge of the laminate.

In applications in which high stiffness or strength are required, it is desirable to have the copolymer skin layer as thin as possible while achieving a high interfacial strength. However, a relatively poor interface strength has been shown to result in superior impact resistance since damage mechanisms become much less localised [7]. This means that all-PP composites which are optimised for tensile strength or stiffness (i.e. strong interfacial bonding) are not necessarily optimised for impact resistance. Similarly, all-PP composites optimised for impact resistance may not possess adequate interfacial strengths to make them viable structural components. Thus the choice of processing parameters controls the interfacial and mechanical properties of the final composite, allowing all-PP composites to be tailored for specific applications.

2.2. Falling weight penetrative impact testing

Falling weight penetrative impact tests were performed as described by ASTM 5628-96, on a range of 2 mm thick woven all-PP composite laminates. In order to determine the effect of strain rate and temperature, falling weight penetrative impact tests were performed at a range of discrete temperatures in the range −40 °C to 120 °C, to determine the effect of temperature on the impact strength of woven tape composite plates. Plates were produced at a compaction pressure of 4 MPa and a temperature of 140 °C. These processing conditions were selected for these specimens as they yielded composite laminates with a balanced combination of good mechanical properties and good falling weight penetrative impact resistance [7], such that would make the material suitable for more general applications, unlike ballistic resistant materials which are often designed purely for ballistic impact resistance. Impact tests were performed using a servo-hydraulic Zwick Rel tensile testing machine fitted with an environmental chamber and an impact striker containing a force transducer, with a striker radius of 5 mm and a specimen holder aperture of 20 mm diameter (see Fig. 5). The tests were performed at impact speeds of 10, 4, 1 and 0.1 m s^{-1}, to determine the effect of impact speed on the absorbed falling weight penetrative energy. The environmental chamber was heated by an air-circulation oven and cooled by liquid nitrogen. The impact striker, mounted on the crosshead of the tensile testing machine, is pushed through the specimen at constant speed to simulate a weighted striker free-falling from a given height. The penetration energy is defined as the total energy absorbed during impact, which is the integral of the force–time curve measured by the striker during penetration.

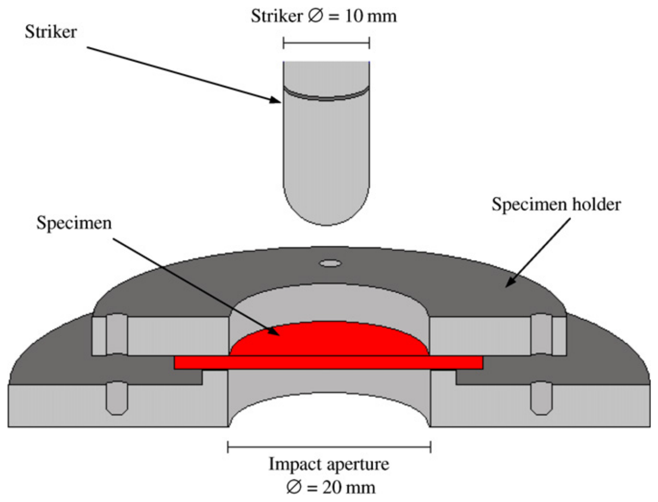

Fig. 5. Schematic of falling weight impact test set-up showing impact striker, specimen and specimen holder.

2.3. Ballistic impact testing

The impact velocity of the falling weight penetrative impact tests were within the range of 0.1–10 m s^{-1}, whereas ballistic impacts possess a typical impact velocity two orders of magnitude greater. In order to establish the ballistic performance of all-PP composites, plates of woven fabric plies were manufactured with a compaction pressure of 0.1 MPa and a compaction temperature of 125 °C. These processing conditions were different to those previously selected for processing falling weight test specimens, as lower processing temperature and pressure provided the optimum impact performance from a range of processing conditions previously tested in falling weight impact [7], but have inferior tensile properties to laminates processed at higher pressures and temperatures [5]. As described earlier, these lower temperature and lower pressure processing conditions were selected as ballistic materials are often designed purely for ballistic impact resistance, and so other properties, such as tensile performance are considered less vital. These plates were subjected to ballistic impact by 8 g, 9 mm parabellum projectiles and also 1.1 g FSPs, using a ballistic firing set-up at DSM High Performance Fibres, The Netherlands. The FSP used has a diameter of 5.39 mm and a length of 6.35 mm and is shown in Fig. 2. A schematic of the ballistic test set-up is shown in Fig. 6, in which the total distance from firing barrel to mounted specimen is approximately 10 m, and the distance between the specimen and the infrared gates is <1 m. The projectile is mounted in front of a charge inside the firing chamber. The 1.1 g FSP is fired in a plastic sabot which falls away from the projectile upon exit from the barrel. On firing, the projectile passes through two infrared gates that measure the velocity of the projectile from the difference in time between passing each of the gates. As these gates are very close to the specimen (<1 m), it is assumed that this velocity is equal to the impact velocity.

The ballistic test specimen is mounted on a 15 cm thick plasticine backing which catches projectiles which penetrate the test specimen, and also allows for some out-of-plane displacement of the specimen, i.e. the so-called trauma effect. A perforated impact specimen is shown in Fig. 7, in which the back surface of specimen is visible on the right-hand side of the image, next to the plasticine backing material. In the case shown in Fig. 7, all impacts have penetrated and there is a series of large deformations

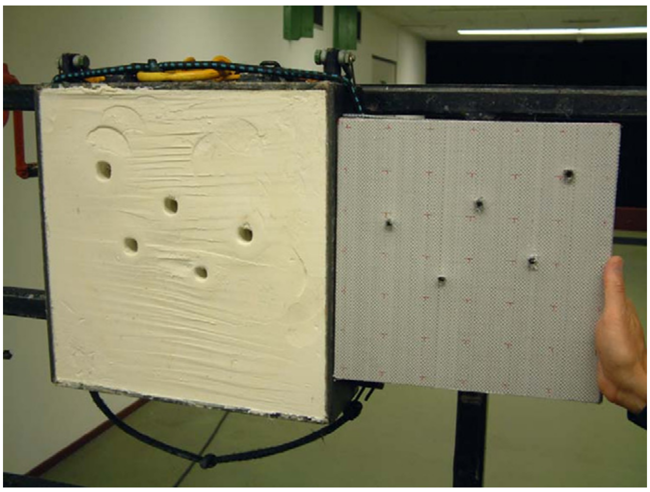

Fig. 7. Ballistic impacted all-PP plate (right) with plasticine backing (left) showing five clear perforations.

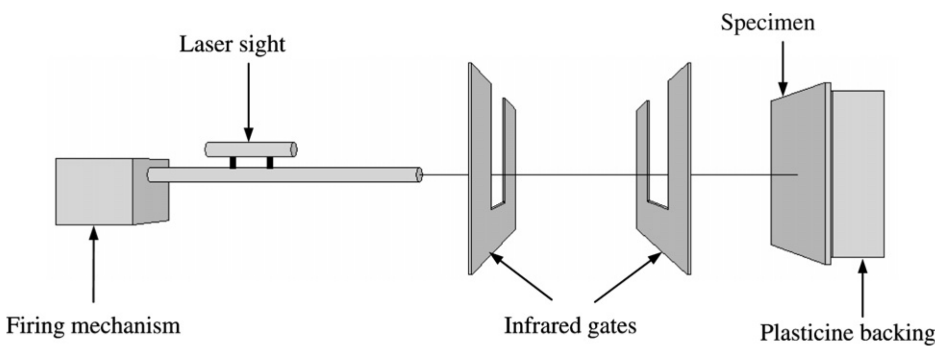

Fig. 6. Schematic of ballistic impact test set-up consisting of firing mechanism, infra-red velocity gates and impact specimen with plasticine backing (not to scale). The total distance from firing mechanism to specimen is 10 m.

in the plasticine. Although, unlike a bullet, a FSP can tumble during flight, no account is made for the orientation of the FSP as it strikes the specimen.

3. Results and discussion

3.1. Impact performance of composites at elevated temperatures

The penetration impact energy absorbed by all-PP plates, normalised for specimen thickness for a range of temperatures and strain rates is shown in Fig. 8. The effect of increasing impact temperature from −40 °C to 120 °C is much less than increasing the impact speed from 1 m s^{-1} to 10 m s^{-1}. Since the temperature range passes through the glass transition temperature (T_g) of polypropylene (onset of $T_g = -10$ °C [4]), a large difference would be expected in impact performance, since below T_g, semi-crystalline polymers have a much lower strain to failure and hence a lower resistance to crack propagation. This is normally associated with low penetrative impact energy. However, previous dynamic mechanical thermal analyses have already revealed the absence of a significant effect of the glass transition temperature on the mechanical properties of the individual tapes or all-PP composites [4,16]. The sudden decrease in modulus with increasing temperature normally seen at the glass transition temperature in semi-crystalline polymers, is due to increased micro-Brownian mobility of amorphous polymer chains. In highly oriented polymers, such as the co-extruded PP tapes used in this research, increased numbers of amorphous chains are oriented in the drawing direction (taut tie molecules). This orientation reduces molecular freedom and so the dramatic drop in modulus at the glass to rubber transition is absent [4]. Therefore, there is even a slight increase in penetrative impact energy for composites at −40 °C, but not the large decrease that would normally be associated with the brittle impact performance of a semi-crystalline polymer below T_g.

Fig. 9 shows that the effect of impact speed is much greater than impact temperature. In tensile deformation, the temperature is inversely equivalent to strain rate, and a decrease in temperature or an increase in strain rate should have a similar effect. Fig. 8 shows that decreasing temperature leads to an increase in absorbed impact energy, as does an increase in impact speed, but the effect due to increasing the impact speed is much greater. An increase in strain rate of two decades in this range leads to a 10% increase in tensile strength [4,16], but this alone cannot explain the mechanism behind the large increase in falling weight penetrative impact energy absorbed at impact speeds of 10 m s^{-1}. During falling weight penetrative impact of all-PP composites, numerous failure modes are seen to operate. On initial impact the composite is deformed in bending, which causes a tensile deformation in the constituent tapes, tape debonding and ultimately tape failure [7]. The stiffness and strength of the tapes have been considered in this analysis, but not the delamination process and it is likely that delamination at higher speeds is the cause of increased impact energy measured at higher strain rates.

3.2. Ballistic impact performance

Ballistic analysis of the all-PP plates was performed to determine the effect of high-speed impact on all-PP plates. Specimens processed for optimised falling weight penetrative impact resistance, as described in Section 2.3, were

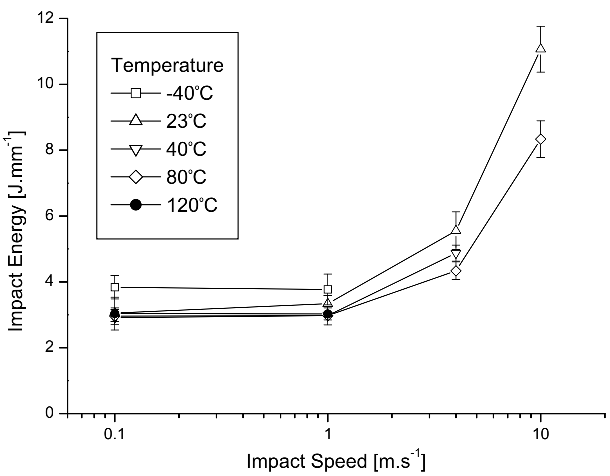

Fig. 8. Falling weight penetrative impact energy vs. impact speed for a range of impact temperatures showing the effect of increasing impact velocity and impact temperature.

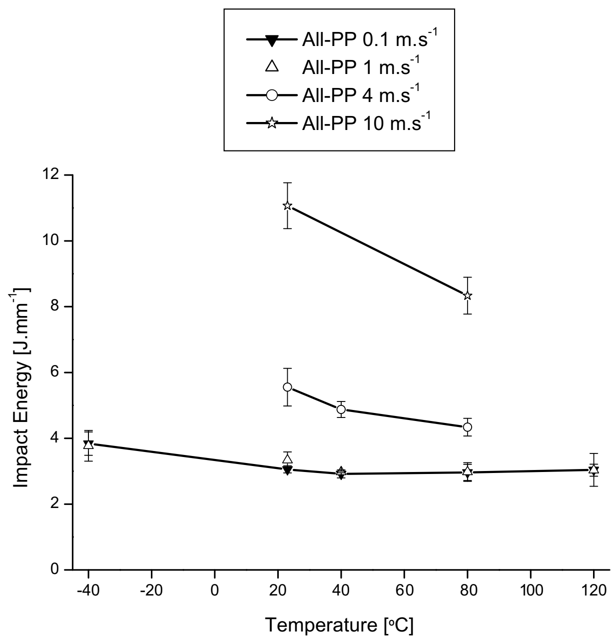

Fig. 9. Falling weight penetrative impact energy vs. impact temperatures for a range of impact speeds and temperatures, further illustrating the relatively large effect of impact velocity but rather small effect of impact temperature.

chosen for ballistic analysis. Firstly, a panel with an areal density of approximately 8 kg m^{-2} (~12 mm thick) was tested with a 1.1 g FSP to establish a V50 rating for this plate. The mechanics of penetration have been investigated for FSP penetration of a nylon/EVA composite system [18] and showed that failure in this system was mostly due to fibre breakage and shear 'cutting'. For all-PP systems, it was apparent from the post-impact specimens the energy absorption mechanism depends on the processing conditions. In the case of all-PP composites with high compaction temperature and pressure it has also been proposed that impact energy is almost solely absorbed by tape failure [7]. This agrees with studies on UHMW-PE fibre reinforced epoxy composites, in which the energy absorption during impact was reported to be mainly due to fibre fracture [45].

However, all-PP specimens with lower compaction temperatures and pressures (and so also a weaker interfacial strength) showed larger energy absorption by delocalised delamination [7]. On this basis, the all-PP specimens created for the ballistic testing reported here were based on lower compaction temperature and pressure (125 °C and 0.1 MPa) than the all-PP specimens created for the falling weight penetrative impact testing in Section 3.1.

The result of the V50 test for these specimens can be seen in Fig. 10. The V50 velocity for the FSP is the average velocity of the final four values shown in Fig. 10; two of which fully penetrated the specimen and two of which that did not. The V50 value is 504 m s^{-1} and the energy absorbed per areal density is approximately 17 J kg^{-1} m^{2}. A similar V50 test was performed with a 9 mm (8 g) FMJ bullet. Because of the greater kinetic energy of the 9 mm FMJ, a thicker plate is required to prevent penetration, but energy/areal density is also greater, at 44 J kg^{-1} m^{2}. This performance is specific to the processing conditions for the all-PP composite, as the impact performance is expected to vary for ballistics as it does for falling weight penetrative impact resistance. All of the V50 values will be slight underestimates as they do not consider the cumulative damage effect of numerous impact in the same test panel, although damage appears to be rather localised (see Fig. 7). Thus the mechanisms of energy absorption which operate to give less well consolidated all-PP composites a large impact resistance in slower impacts with larger strikers [7], i.e. highly delocalised delamination and tape debonding, are not witnessed in the very localised failure seen in ballistic impacts.

Fig. 11 compares the energy per areal density of all-PP with some alternative commercial polyolefin ballistic composites. Dyneema® UDHB25 (DSM High Performance Fibres BV, Netherlands) is a composite based on unidirectional plies of high modulus polyethylene fibres. Dyneema® UD66 is a similar product which has been tested independently [14] and shows the same trend in behaviour as the data presented by DSM for UDHB25. These composites are rigid plates rather than loose fabrics and are often designed to prevent penetration by small bullets (such as 9 mm FMJs). Dyneema® Fraglight is a felt made up of the same Dyneema® yarn but is an unconsolidated, flexible textile which is optimised to prevent penetration by FSPs.

In order to prevent penetration by low mass FSPs, such materials are often designed as loose fabrics which can absorb energy by large deformations out of the plane of the material, rather than solely fibre breakage and delamination in the fabric plane [17,46]. However, employing large out-of-plane deformation as an energy absorbing mechanism imposes limitations on the applications of such a material, if the aim is to use the material as a protective shield. Even if a projectile is prevented from penetrating the shield, a large deformation will still inflict trauma on whatever is directly behind the shield. A large out-of-plane

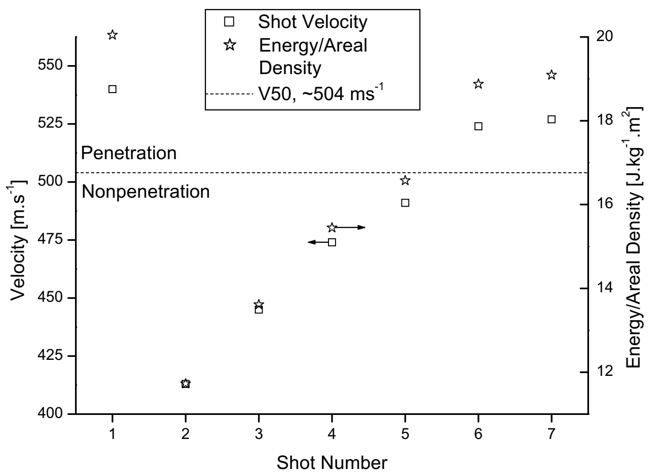

Fig. 10. Ballistic V50 determination of an all-PP composite plate giving a V50 value (the velocity at which, statistically, the probability of perforation is 50%) of 504 m s^{-1}. It must be stated that this V50 value is specific to the particular plate and projectile being investigated, in this case a 1.1 g FSP.

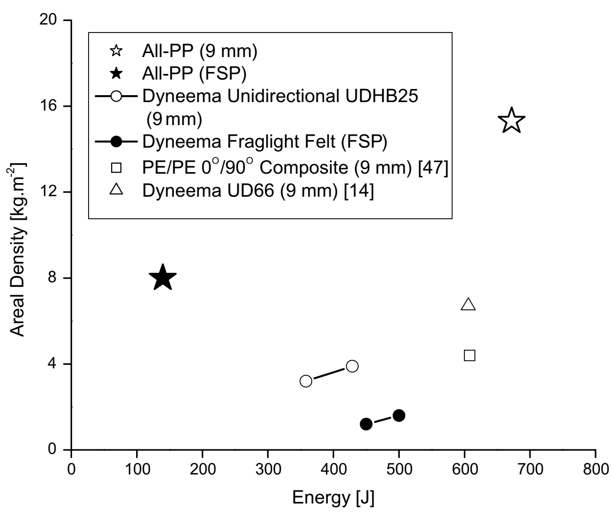

Fig. 11. Comparison of different polyolefin structures for ballistic impact resistance showing that all-PP composite laminates require a much greater areal density to absorb the energy of ballistic impacts when compared to polyethylene alternatives.

deformation mechanism is not possible in the all-PP plates used here because the inherently low density of these plates results in a high thickness, leading to an increased flexural strength as can be seen in the tested specimen shown in Fig. 7. Also shown in Fig. 11 is a polyethylene/polyethylene composite which has been investigated for possible ballistic applications [47]. This material is composed of unidirectional Dyneema® fibres consolidated between films of high density polyethylene. Such polyethylene/polyethylene composites have a fibre volume fraction of 72%, and like all-PP composites, should be easily recyclable.

Since the ideal ballistic material would absorb most energy while having the lowest areal density, the performance of all-PP is slightly better against the 9 mm FMJs than the FSPs, but it is clear that all of the alternative polyolefin materials considered here easily out-perform this specific all-PP plate in these ballistic applications. This is illustrated in Fig. 1, and is due to the greater moduli achievable in polyethylene fibres with only a slight increase in density compared to polypropylene. Solution (gel) spun UHMW-PE fibres with moduli of over 120 GPa and density of 0.97 g cm^{-3} have been reported [48], while gel-spun UHMW-PP fibres have been produced with moduli of 36 GPa and density of 0.91 g cm^{-3} [15]. Even though gel-spinning of polymer fibres is an expensive process, melt processed HDPE fibres have been reported [49–51] possessing properties which can still outperform PP fibres with moduli similar to those based on the calculated modulus of the PP crystal [52].

It is also worth noting that all the other composite systems compared so far in this research are stacked UD layers rather than the woven plies which are used in all-PP. Stacked unidirectional plies possess greater energy absorbing potential because delaminations can more easily spread through the composite allowing a large damage area and so large energy absorption. This is partly due to the absence of crimping in stacked UD composites, and also partly due the increased interply plasticity of woven composites [8,53–55]. This effect gives stacked UD composites a more suitable architecture for ballistic applications, before any consideration for actual material property is considered. A comparison of Dyneema® UDHB25 compared to a woven Dyneema® fabric composite showed an increase in energy absorption of 2.85 g FSPs, which maybe due simply to the composite architecture [9]. By just considering the mechanical performance presented here all-PP composites cannot compete with UHMW-PE alternatives solely on ballistic performance due to their inferior modulus and strength. However, there may be a significant cost/performance factor which would make all-PP plates a viable cost-effective option for some types of ballistic impact since melt processing of polymer tapes can be considerably cheaper, cleaner and more efficient than solution (gel) spinning.

The main advantages of using tape geometry for the reinforcement phase in composite materials rather than multi-filament yarns are the reduced crimp in woven tape fabrics and the higher volume fractions of reinforcement possible while still retaining good interfacial properties. While this woven tape geometry clearly has advantages over circular cross-section fibres of bundles of multifilament yarns, the potential of all-PP composites for ballistic applications is reduced by the limited maximum achievable modulus and strength of oriented PP. Therefore, it is clear that there is a great potential for an all-polymer composite based on polyethylene, which combines the advantages of:

(i) the high modulus and high strength achievable in oriented PE,
(ii) the geometrical advantages of using woven tape fabrics, and
(iii) the high volume fraction reinforcement and user-definable interfaces achieved by using the co-extrusion technology presented here.

A likely application of all-PP composites is as a cost effective addition to traditional ballistic resistant alloys or ceramics. This type of application inherently undermines the desire to construct single component composite systems, but due to the high production standards and relatively low production volumes of ballistic materials, it is unlikely that the recyclability of such materials will be a major concern. All-PP composites may find applications as low-cost alternatives to current rigid ballistic protection materials which are aimed at protection from impact by small fragments.

4. Conclusions

The impact performance of all-PP composite materials has been analysed at a range of temperatures and strain rates through penetrating impact by falling weight impact testing and ballistic impact testing. The normal glass transition temperature which results in a significant decrease in impact resistance of isotropic PP at low temperatures (<0 °C), is absent in all-PP composites leading to high impact energy absorption even below T_g.

Since the impact resistance of all-PP composites depends on the interfacial strength of the composite and hence the composite processing conditions, all-PP composites possess the versatility to be tailored for specific application during processing.

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