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EFFECT OF FIBRE TYPE ON MECHANICAL PROPERTIES OF NONWOVEN REINFORCED TPU COMPOSITES

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ABSTRACT

Nonwoven-reinforced composites were produced using both low modulus fibres (lyocell, polyethylene terephthalate, and polyamide) and high modulus aramid fibres (polyphenylene terephthalamide) in thermoplastic polyurethane (TPU) matrix. Preferentially oriented web preforms were prepared by carding and pre-needling before impregnating the nonwovens in a thermoplastic polyurethane resin matrix. Composites were prepared by compression moulding and mechanical properties were evaluated. Scanning Electron Microscopy was employed to study the fibre-to-matrix interface in the nonwoven-reinforced composites. It was found that nonwoven reinforcement provided a range of mechanical properties, mainly linked to fibre properties and orientation of fibres in the web, apparently unaffected by the mechanical properties of the web. Furthermore, all studies fibres were thoroughly embedded in the matrix.

Keywords: nonwovens, flexible, composites, fibre reinforced, mechanical properties

1 INTRODUCTION

Flexible fibre reinforced composites employ elastomeric matrix polymers with a characteristic range of deformations that are often larger than what are encountered in conventional fibre reinforced composites. Flexible composites find applications as tyres, conveyor belts, coated fabrics, inflated structures, hoses, surgical medical devices, diaphragms and reinforced membranes, amongst others. The mechanical properties of such composites can be engineered by suitable selection of fibre and matrix materials as well as by tailoring the geometric configurations of the reinforcing phase.[1, 2] The strength of fibres is dependent on the interatomic and intermolecular bonds and is a direction-dependent property. The inherent strength of fibres is employed to transmit load from matrix to fibre. In this load transfer, shear stress acts on the surface of fibre and subsequently causes tensile stress within the fibre. Hence, different fibre types can provide different levels of reinforcement in a TPU matrix.[3] High modulus fibres are commonly employed as reinforcements in composites but depending on the needs of the application, it is not always necessary to utilise such high value materials, and a lower cost alternatives can be potentially employed. The extent to which this is possible is conditional on providing an appropriate geometry and dimensions of fibres in the preform as well as adhesion between the dispersed and the matrix phases. The polymer matrix in the composite acts both as a binder for the fibre network as well as a stress transfer medium. Nonwoven fabrics can be directly made from fibres or filaments and by selecting a suitable web formation and bonding method preform properties can be adjusted. Carding and needlepunching provide a convenient means of producing a low density fibre network in which fibre orientation can be manipulated to some extent with respect to the machine and cross directions. As in most nonwoven fabrics, a planar x-y arrangement of fibres is provided in which a small proportion of fibre segments are locally deflected and reoriented through-thickness giving structural integrity to the carded web. These out-of-plane deflections impart mechanical properties in three dimensions, unlike planar textile preforms.[4] The low number of process steps and high production speeds translates in to low cost preforms with the opportunity to engineer geometric structure.[5]

Nonwovens can provide high surface area for fibre-matrix adhesion interface but this could also limit fibre volume fraction in reinforced composite[6]. The current study aims to compare the mechanical properties of nonwoven reinforced flexible composites prepared from standard textile fibres to that of prepared from high strength aramid fibre.

2 MATERIALS AND METHODS

Lyocell, polyphenylene terephthalamide (PPTA), polyethlyene terephthalate (PET), and polyamide (PA) 6,6 were carded (70 g m^{-2}, parallel-laid) and pre-needled (42 punches cm^{-2}) to form a nonwoven reinforcement. Thermoplastic polyurethane (TPU, Elastollan® A C 88 A 12, Shore hardness 88A, BASF Polyurethanes GmbH) was employed as a matrix material in the form of flat sheets (≈ 315 g m^{-2}). The aforementioned nonwoven webs were sandwiched between two layers of TPU and compression moulded at 200°C and 20 kg cm^{-2} (1.96 MPa) to achieve a nominal fibre content of 10 wt% in the composite. The estimated fibre volume fraction % for Lyocell-, PPTA-, PET- and PA-reinforced TPU composites were 8.1, 8.5, 8.8 and 10.5, respectively. To determine fibre strength, the single fibres were mounted on a card frame and strength was evaluated (ASTM D3822-14, 20mm gauge length, 12 mm min^{-1}) on a universal testing machine (Instron 5540) with pneumatic fibre grips and 5N load cell. The nonwoven webs (WSP 110.4-09, 100 mm gauge length and 50 mm wide, 100 mm min^{-1}) and tensile bars from prepared composites (ISO 527-4, 55 mm gauge length and 10 mm wide, 10 mm min^{-1}) were tested for mechanical properties on a universal testing machine (Zwick Roell Z010) with mechanical jaws. The prepared composites were cross-sectioned by freezing the samples to -20℃, stored in a laboratory freezer, and cutting with a fresh razor blade for each specimen. The cross-sections were sputter coated with gold and imaged on scanning electron microscope (Hitachi S-2600N).

3 RESULTS AND DISCUSSION

The mean single fibre strength values for each reinforcing material are given in Figure 1 and the corresponding tensile strength of the pre-needled nonwovens made from each, both in the machine- and cross-directions, is shown in Figure 2. It is apparent that the trend in fibre strength does not directly translate in to fabric strength. Despite the same needling density, the webs exhibited different mechanical properties owing to the inherent low stress mechanical properties of the fibres and the effect of this on fibre friction and entanglement. The capstan effect and contact pressures are key parameters during fibre-fibre interactions. The capstan effect is introduced at fibre crossings and contact pressure is applied by looping of a fibre around other fibres. This restricts the displacement of fibres and results in resistance to slippage.[7] Furthermore, the surface characteristics of fibres are also important. The bending stiffness of a circular fibre is linearly proportional to the Young's modulus of the fibre, and increases as a function of the fourth power of fibre diameter and an inverse power of the fibre length.[8, 9] Note also the difference in strength in the MD and CD, which is due to preferential orientation of fibres in the machine direction. Despite the high strength of the PPTA fibres, the lyocell fibres produced the strongest nonwoven fabrics under fixed process conditions, owing to the higher fibre entanglement and resistance to frictional slippage developed during web formation and pre-needling.

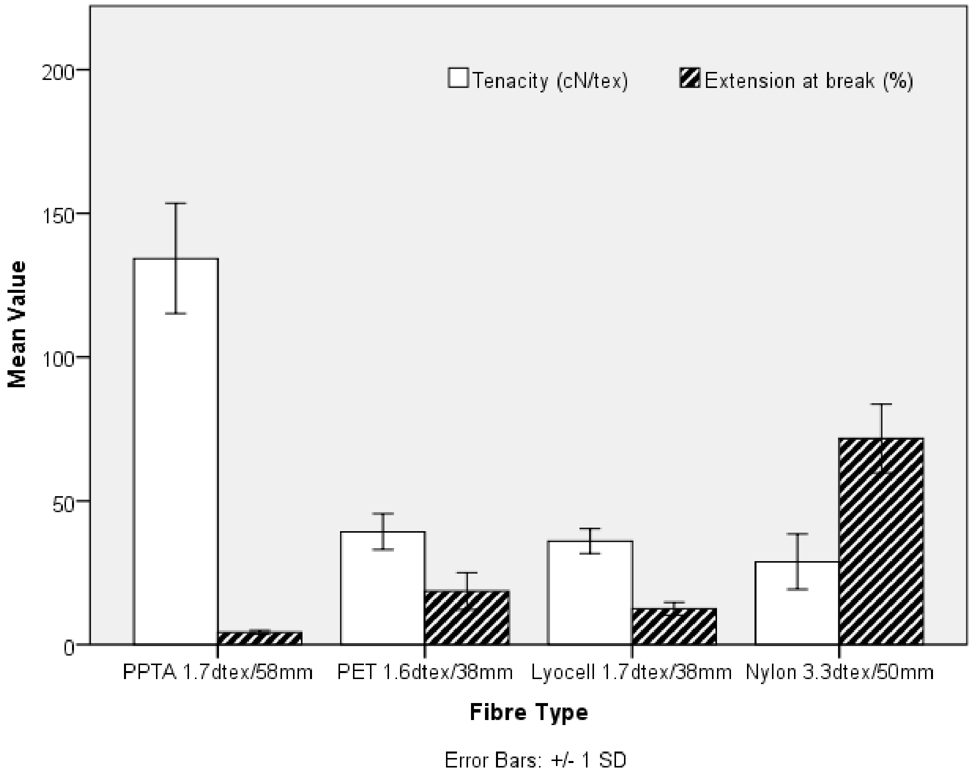

Figure 1. Tensile strength of single fibres

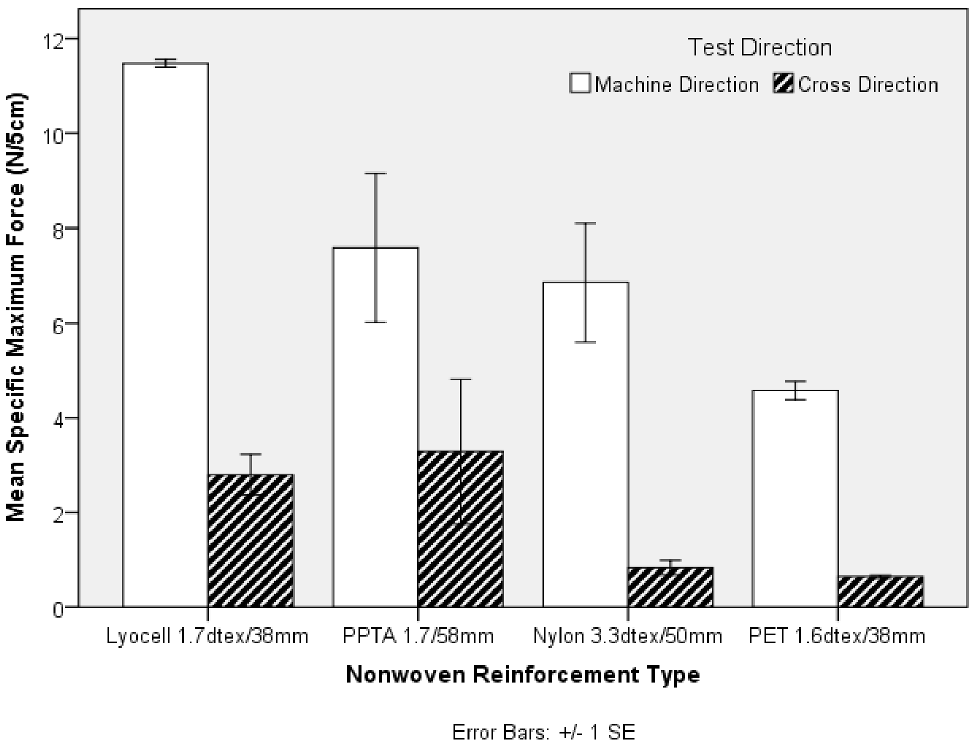

Figure 2. Tensile strength of pre-needled nonwoven-reinforcements in machine- and cross-direction.

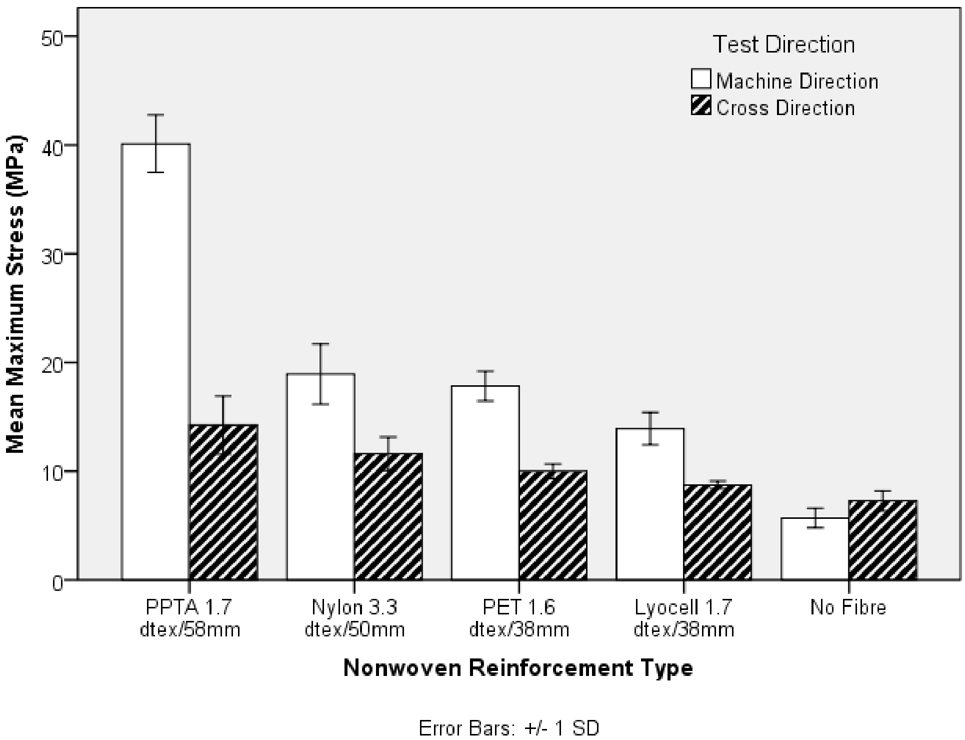

Figure 3. Tensile Strength of nonwoven-reinforced TPU composites

The stress at break values of the nonwoven-TPU composites in the machine direction is shown in Figure 3. Following compression moulding it is evident that the initial strength of the precursor fabrics is not critical and the matrix to fibre load transfer occurs during the application of tensile force. Compared to that of the homogenous TPU sheet, significant improvements in mechanical properties were achieved for all nonwoven-reinforced composites, depending on the inherent properties of the selected reinforcing fibre. The geometrical arrangement of fibres in the nonwoven is important as it results in anisotropy of mechanical properties. Hence, the fibre segment orientation in the nonwoven web can be controlled to engineer desired mechanical properties in the composite.

The unreinforced TPU displayed the lowest and the aramid reinforcement created the composite with the highest Young's Modulus. An increase in Young's Modulus occurs in the matrix TPU polymer as a result of the addition of nonwoven reinforcement (Figure 4). Though the polyamide-based nonwoven composites exhibited higher maximum strength, a lower Young's Modulus was observed compared to reinforcements composed or either PET or lyocell, owing to higher elongation at break of the polyamide fibres compared to that of PET and lyocell (Figure 1). Hence, as expected modulus is important and stress-strain characteristics can be used to control the stiffness and load bearing properties of the ultimate nonwoven reinforced composite part.

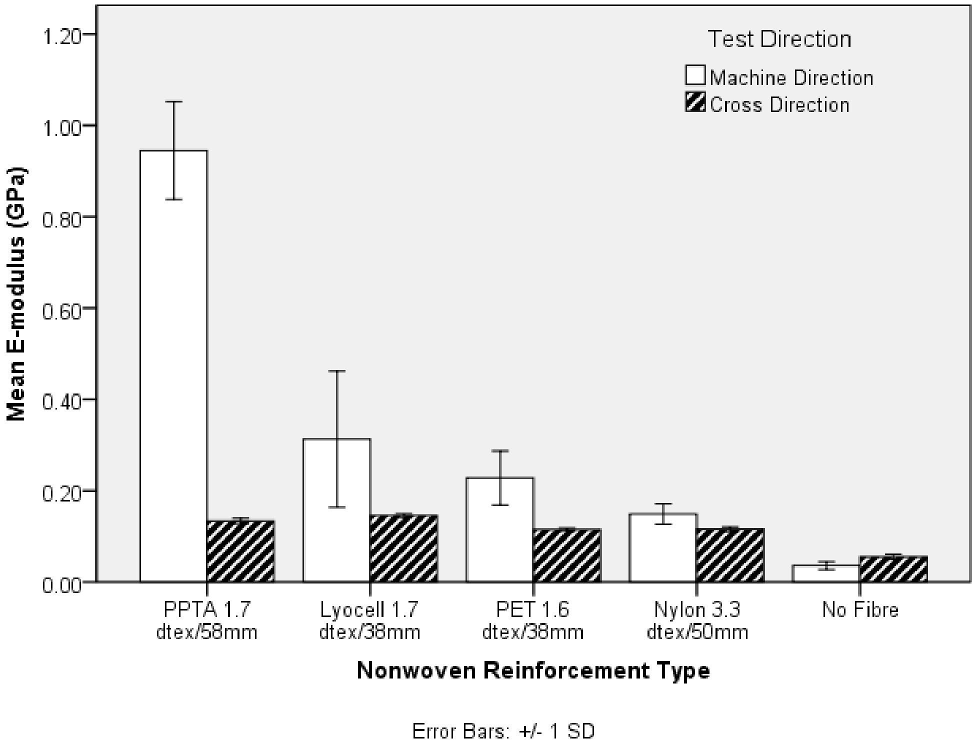

Figure 4. Tensile modulus of studied flexible composites

The mechanical behaviour of composites depends on other factors such as solid volume fraction and adhesion between the fibre and matrix components. Cross-sectional SEM images of the composite parts revealed all fibres to be thoroughly embedded in matrix despite different surface chemistries and morphologies due to fibre type (Figure 5a-d). Most of the fibres appeared circular, confirming preferential orientation of fibres in the machine direction. The razor blade sectioning technique could not satisfactorily cut the high strength PPTA fibre leading to a characteristic fracture morphology displaying some fibrillation and pull-out from the composite (Figure 5b). The different type of employed fibres are expected to inherently possess different surface energies but it is likely that the employed temperature and pressure overcame any such differences and fibres exhibited good adhesion with the matrix.

4 CONCLUSIONS

Nonwoven, fibre reinforced flexible TPU composites were manufactured by employing standard textile fibres and PPTA and then characterised in terms tensile failure. A range of stiffness and tensile strength values can be engineered by selection of appropriate fibre and nonwoven fabric properties. The degree of initial frictional bonding in the nonwoven fabric prior to matrix impregnation, did not affect the final mechanical properties of the composite part, but fibre orientation was influential in determining the anisotropy of mechanical properties. The tensile modulus of the composites produced was linked to both tensile strength and elongation at break of the reinforcing fibres. Cross-sectional analysis of the composite parts, revealed embedding of all fibres in the TPU matrix both for the hydrophilic (lyocell) and hydrophobic (PA, PET, PPTA) fibre reinforcements.

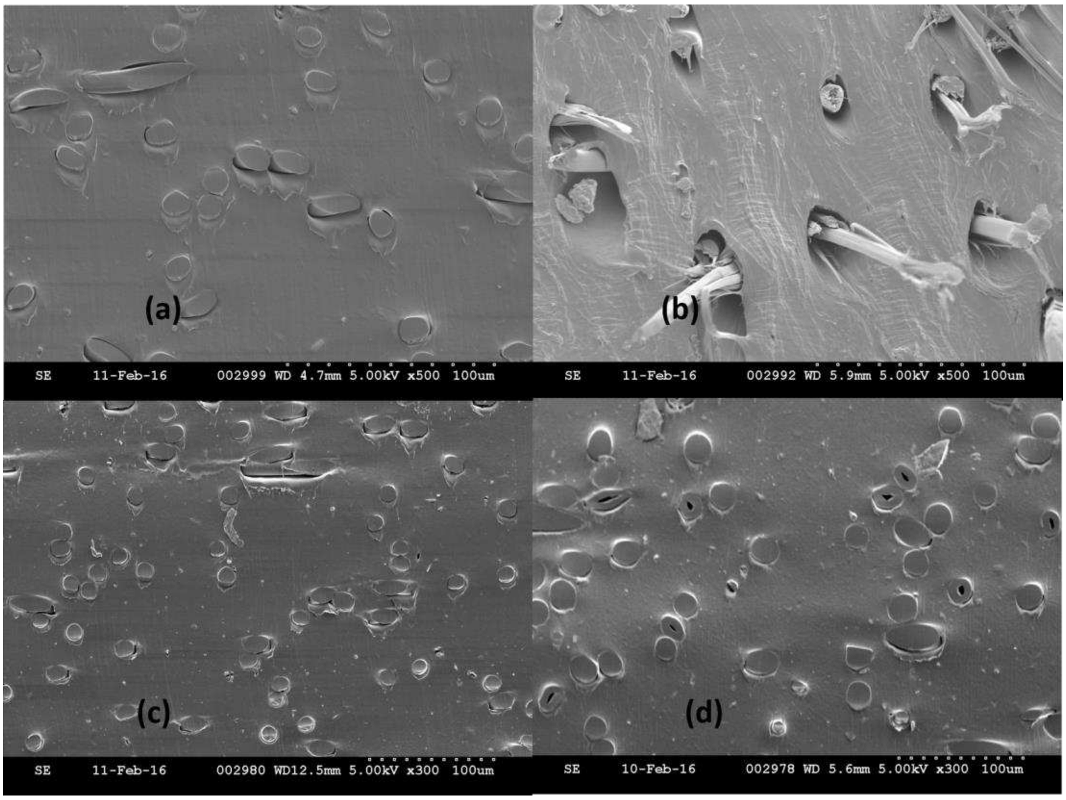

Figure 5. Scanning Electron Microscope (SEM) cross-sectional images of nonwoven-reinforced composites in machine direction (a) Lyocell (b) PPTA (c) PET (d) PA.

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For further details about the "Sports Infinity" project, please visit following website:
http://www.adidas-group.com/en/magazine/stories/specialty/farewell-recycling-infinity-cycling/

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