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Strength of hydroentangled fabrics manufactured from photo-irradiated poly *para*-phenylene terephthalamide (PPTA) fibres

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ABSTRACT

Photo-irradiation of poly *para*-phenylene terephthalamide (PPTA) fibre is normally associated with deterioration of physical properties. Nonwoven fabrics produced from 100% photo-irradiated PPTA fibres might therefore be expected to yield fabrics with poorer mechanical properties compared to those produced from non-irradiated fibres. To test this hypothesis, the bursting strength of hydroentangled fabrics manufactured from photo-irradiated PPTA fibres was explored. Prior to fabric manufacture, virgin PPTA staple fibres were photo-irradiated under controlled lighting conditions (xenon short arc lamp with a luminous flux of 13,000 lm) for 0, 5, 10, 20, 40, 60 and 100 h. The photo-irradiated fibres were then hydroentangled to produce nonwoven fabrics. Photo-irradiation exposure of PPTA fibre up to 30 MJ m^{-2} was not found to be detrimental to fabric bursting strength and at irradiation energies of 5–10 MJ m^{-2} a small, but statistically significant increase in fabric bursting strength was observed compared to fabrics manufactured from non-irradiated fibre. This may be linked to a change in the surface and skin properties of the PPTA photo-irradiated fibres identified by atomic force microscopy (AFM) following photo-irradiation.

1. Introduction

Poly *para*-phenylene terephthalamide (PPTA) fibres, known commercially as Kevlar (DuPont) and Twaron (Teijin) exhibit high tensile strengths (190–250 cN/tex [1]) and excellent chemical and thermal resistance [2]. This valuable combination of properties is due in part to the molecular structure in which the para position of the amide linkages allow for increased crystalline packing density. The meta position in aramid materials such as Nomex (DuPont) are associated with reduced crystalline packing, and lower tensile strength. PPTA fibres have a skin-core structure, wherein the core exhibits a more crystalline arrangement than the skin [3]. A radial order to the polymer units has also been reported [4,5]. The highly crystalline core structure contributes to the high modulus of the material in fibre form, and the tensile strength and modulus are influenced by the relative proportion of the core and skin components. A thin skin section, making way for a thick core results in very high modulus but can be detrimental to fibre tensile strength as the large crystal units can also bring about inclusions of morphological defects such as cracks [4].

Industrially, PPTA fibre is found in numerous applications including personal protection, composite reinforcement, ballistic and fire protection as well as the filtration of hot or volatile substances, amongst others. Given the valuable properties provided by the material, recycling of post-industrial PPTA waste is industrially attractive provided fibre properties do not substantially deteriorate compared to the virgin fibre. Fabrics containing recycled PPTA have been found to retain many useful properties, for example, Flambard et al. [6]. reported fabrics containing recycled PPTA with excellent cut resistance. One industrially employed method of mechanically recycling PPTA is to retrieve manufacturing waste in the form of yarn or woven fabrics including weaver's waste and off-cuts from pattern cutting. Such wastes are cut in to dimensions suitable for mechanical processing and are then shredded (pulled) to produce staple fibre recyclate suitable to be used as a raw material for the manufacture of new products. This includes production of staple yarns in which recycled PPTA may be blended with virgin fibre prior to spinning and then the production of fabrics. PPTA fibre

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recyclate is also utilised as a feedstock for nonwoven fabric manufacture. The fibre recyclate is formed in to a web before being bonded to produce a stable fabric. Of the available bonding methods, mechanical bonding by processes such as needling and hydroentangling, which rely upon fibre entanglement and friction to generate fabric strength, are particularly important because of the speed of production and the versatility of the processes.

One of the potential concerns in the use of PPTA fibre recyclate is the susceptibility of the material to photodegradation due to photo irradiation under natural and artificial light in the UV and near UV part of the spectrum (300–450 nm) [7]. Previous studies of PPTA photodegradation have mainly focused on ageing and exposing samples to artificial light exceeding 100 h of accelerated degradation [8–10]. Deterioration in fibre mechanical properties occur as well as changes in chemical composition and structure leading to embrittlement, and surface artefacts. Li et al. [11] studied the effects of shorter term UV irradiation of PPTA fibres and concluded that PPTA is highly sensitive to UV exposure even at low levels of irradiation. Changes were observed in the skin and surface morphology of PPTA fibres and an increase in surface wetting was also observed, which was attributed to greater surface roughness and the availability of oxygen-based functional groups on the fibre surfaces [11].

A potential advantage of post-industrial PPTA fibre waste utilised in the manufacture of nonwoven fabrics is that it is only likely to have received low levels of UV and light exposure compared to post consumer PPTA waste. However, the extent to which prior photo-irradiation of PPTA fibre influences final nonwoven fabric properties remains uncertain. Accordingly, in the present study, photo-irradiated and un-irradiated fibres were utilised as raw materials to manufacture nonwoven fabrics using an industrially established mechanical bonding method known as hydroentangling. The purpose was to elucidate the effects of low levels of light exposure on final hydroentangled fabric bursting strength.

2. Methodology

2.1. Raw materials and web manufacture

All experimental work was conducted using industrially available virgin PPTA staple fibre (Teijin Twaron 1078; 1.7 dtex; mean fibre length 58 mm; crimped) as the starting material. To ensure uniform photo-irradiation of the fibres prior to hydroentangling, virgin PPTA fibre was first formed in to carded batts and mechanically stabilised by pre-needling. Carded webs were prepared with a basis weight of 55 g m^{-2}, the webs were prepared on a 0.5 m wide Tatham worker-stripper nonwoven sample carding machine. Webs were parallel-laid using a 0.5 m wide lapper, to produce batts with an area of roughly 0.25 m^2. This relatively lightweight batt was formed to ensure uniform photo-irradiation during the subsequent ageing procedure. To facilitate ease of handling, the batts were lightly pre-needled using a needle penetration depth of 12 mm and a very low punch density of 5.4 punches cm^{-2} using regular three-barbed needles (Specification: 15-18–42; Foster needle, USA). This loosely bonded fibrous assembly is referred to as a lightly pre-needled fabric.

2.2. Photo-irradiation procedure

Samples of the PPTA pre-needled fabric were then irradiated for different time periods of 0, 5, 10, 20, 40, 60 and 100 h using a XBO 450 w/4 xenon short arc lamp with a luminous flux of 13000 lm. The configuration of the irradiation chamber allowed for an incident energy of 210 W m^{-2}, roughly equivalent to a medium to high level of irradiation incident on the earth provided by the sun (the world meteorological organisation defines time of "sunshine" as the time that the surface receives at least 120 W m^{-2}) [12]. The XBO lamp spectrum is given in Fig. 1, this spectrum was used as it is a close approximation of a D65 daylight spectra. The irradiation energy levels (MJ m^{-2}) were determined (0–76 MJ m^{-2}) based upon the sample dimensions, geometric position from the light source and the emitted energy. A non-irradiated PPTA pre-needled fabric was retained as a control sample and all samples were stored in black bags in a dark storage area prior to hydroentangling to minimise any extra environmental irradiation.

The irradiation energy (MJ) received by the PPTA was calculated by first calculating the light energy incident on the material in Lumens (lm), i.e. candela steradians (cd x Sr), which are given by the manufacturer and physical dimensions of the experiment for candela and steradians respectively. Lux was then calculated using Equation (1).

$$Lux = \frac{lm}{a} \quad (1)$$

Where, lm is lumen and a is the area, this value is then converted to Watts.m^{-2} using the conversion factor of 0.00146 and finally multiplied by the exposure time to give the total energy in J m^{-2}.

2.3. Bonding of fibre web samples by hydroentangling

The photo-irradiated PPTA pre-needled fabrics were hydroentangled using a 0.5 m wide pilot-line (STL Hydrolace) using the operating conditions in Table 1. Hydroentangling subjects the fibres in the web to kinetic energy delivered by an array of columnar, high-velocity water jets issuing from a row of small diameter, cone-capillary shaped nozzles.

Each web sample was hydroentangled sequentially on the face and back to promote uniform fibre entanglement throughout the structure. The fabrics were then dried for 5 min in a through-air oven at a temperature of 100 °C.

2.4. Single fibre tensile testing

Single PPTA staple fibres were photo-irradiated up to a total irradiation energy of 9.3 MJ m^{-2} with an irradiation power of 107.6 W m^{-2} using an XBO 450 w/4 xenon short arc lamp operating with a luminous flux of 13000 lm. The fibres were mounted on small 20 mm × 20 mm square cardboard frames and glued at either end to hold them in place. The frames were then placed on a large plastic holder before being irradiated by the Xenon arc lamp irradiation box for time periods of t = 0, 4, 8, 16 and 24 h equating to 0, 1.55, 3.1, 6.2 and 9.3 MJ m^{-2} irradiation energy. Short exposure times were selected to gain a better understanding of any progressive change in fibre mechanical properties that might influence the way in which PPTA fibres respond during hydroentangling.

Tensile testing was based on BS EN ISO 13895:2003 using an Instron 1026 with a crosshead speed of 50 mm min^{-1} and a gauge length of 20 mm. The specimens, retained in cardboard windows were mounted in the pneumatic jaws of the Instron. Once in position, the vertical sides of the windows were cut and the test was started. Twenty specimens for each sample were tested.

2.5. Atomic force microscopy (AFM)

All AFM experiments were carried out using an Asylum Research MFP-3D (Santa Barbara, CA) using AC160TS Olympus silicon cantilever probes with a tip radius (R_{tip}) of 25 nm and a half cone angle of $\theta = 36°$, which were independently verified by scanning a standard calibration grid. The spring constant of the