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Mechanical behavior and deformation micromechanisms of polypropylene nonwoven fabrics as a function of temperature and strain rate

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ABSTRACT

The mechanical behavior and the deformation and failure micromechanisms of a thermally-bonded polypropylene nonwoven fabric were studied as a function of temperature and strain rate. Mechanical tests were carried out from 248 K (below the glass transition temperature) up to 383 K at strain rates in the range $\approx 10^{-3}\ s^{-1}$ to $10^{-1}\ s^{-1}$. In addition, individual fibers extracted from the nonwoven fabric were tested under the same conditions. Micromechanisms of deformation and failure at the fiber level were ascertained by means of mechanical tests within the scanning electron microscope while the strain distribution at the macroscopic level upon loading was determined by means of digital image correlation. It was found that the nonwoven behavior was mainly controlled by the properties of the fibers and of the interfiber bonds. Fiber properties determined the nonlinear behavior before the peak load while the interfiber bonds controlled the localization of damage after the peak load. The influence of these properties on the strength, ductility and energy absorbed during deformation is discussed from the experimental observations.

1. Introduction

Textile materials have greatly benefited from the advances in fiber technology. Woven textiles are the natural choice when design specifications require high performance in terms of strength and stiffness. Moreover, their regular pattern makes it easier to model the relationship between the microstructure and the macroscopic behavior. Recent investigations (Lomov et al., 2007; Boubaker et al., 2007; Cao et al., 2008; Badel et al., 2008; Khan et al., 2010; Durville, 2010) have contributed to a deeper understanding of the mechanical behavior of woven textiles. Nevertheless, knitted and nonwoven fabrics provide better performance if the goal is deformability and energy absorption. Knitted materials also exhibit a regular structure based on loops and knots which leads to costly manufacturing processes. Processing of nonwoven fabrics (or simply nonwovens) is significantly cheaper, since they are manufactured from disordered fibers which are consolidated by means of chemical binding, local thermal fusion or mechanical entanglement. The variability in fibers and bonding techniques leads to a wide range of properties and microstructural randomness accounts for a distinctive complex mechanical behavior. An increasing number of applications take advantage of the versatileness of nonwovens, including filters, geotextiles, fuel cell membranes or fabrics for ballistic protection, to name but a few (Russell, 2007).

Despite of the complexity of the deformation and damage mechanisms in nonwovens (or perhaps due to this factor), several models of the mechanical behavior have been recently developed. They address different

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micromechanisms of deformation and fracture typical of nonwovens, such as straightening of curved fibers, large deformations and extensive fiber rotation, topology changes due to bond breakage, fiber sliding and fracture, etc. (Hou et al., 2009, 2011; Ridruejo et al., 2010, 2012; Silberstein et al., 2012; Kulachenko and Uesaka, 2012; Wilbrink et al., 2013). However, experimental studies that relate the microstructure with the failure micromechanisms and properties have been limited to paper (Bronkhorst, 2003; Hägglund and Isaksson, 2006; Isaksson et al., 2006, 2004). In fact, most of the available experimental information of the mechanical behavior of nonwovens comes from the manufacturers' data sheets, which typically emphasize performance and provide very limited information about the fabric structure and its deformation and fracture mechanisms. Experimental studies focused on the characterization of the micromechanisms of deformation and fracture of nonwovens appeared only very recently (Rawal et al., 2008; Isaksson and Hägglund, 2009; Ridruejo et al., 2010, 2011; Isaksson et al., 2012), and they often use state-of-the-art characterization techniques (e.g. *in situ* testing within the scanning electron microscope, X-ray microtomography, digital image correlation) to establish the sequence of deformation and fracture events at the μm level.

It is obvious that further optimization of nonwoven textiles as well as validation of models require a deeper understanding of the microstructure-mechanisms-properties relationship and this was the main goal of this investigation. The material selected was a thermally-bonded polypropylene nonwoven, commercially available as a geotextile. This class of materials stands out because of its excellent strength and energy absorption capability (Rawal et al., 2010; Ridruejo et al., 2011; Farukh et al., 2013). Mechanical characterization was carried out at temperatures above and below the glass transition temperature and near to the melting point to assess the influence of fiber properties on the mechanical behavior and at strain rates in the range 10^{-3} to 10^{-1} s^{-1}. Different experimental techniques (including *in situ* testing within the scanning electron microscope and digital image correlation) were used to analyze the deformation and damage mechanisms as a function of temperature and strain rate. Individual fibers, extracted from the nonwoven fabric, were also tested under the same conditions. The result of this comprehensive characterization provided a detailed picture of the dominant deformation and fracture mechanisms as a function of the temperature and strain rate and their influence on the macroscopic properties (namely strength and energy absorption). Moreover, this comprehensive characterization of the mechanical behavior at different strain rates and temperatures can be used as a benchmark for the calibration of constitutive models for this type of materials.

2. Material and experimental techniques

2.1. Polypropylene nonwoven fabric

The nonwoven material under study was a geotextile made of polypropylene fibers (commercial trade name Typar SF32) manufactured by Du Pont de Nemours. The isotactic polypropylene (PP) fibers were extruded and then stretched to increase crystallinity, resulting in fibers of 40–60 μm in diameter, 0.91 g/cm^3 of density, 48% crystallinity and 438 K of melting temperature (Fig. 1) Ridruejo et al., 2011; Jubera, 2013. The continuous spun fibers were laid down randomly on a flat surface producing an isotropic fiber web sheet which was then bonded by the simultaneous application of pressure and heat. The fibers typically appear as isolated, although bundles of 2–5 fibers were often found (Fig. 1). Partial fusion between fibers at the entanglement points was normally observed. Differential scanning calorimetry tests confirmed that the melting temperature and the crystallinity of the PP in the thermal bonds were below that of the fibers. The processing route leads to a nonwoven with a random fiber distribution and isotropic properties (Ridruejo et al., 2011; Jubera, 2013).

2.2. Fiber mechanical characterization

Individual fibers were extracted from the nonwoven fabric by carefully pulling with tweezers. Fibers with a gage length of in the range 4.9 to 6.1 mm were stitched on a cellulose acetate frame, which was fixed to a mechanical testing machine for the tensile tests. The load was exerted on the fiber after cutting the cardboard. The experimental set-up was located within an environmental chamber and mechanical tests were carried out at 248, 298 and 383 K. The temperature of 248 K was selected because it was well below the glass transition temperature of the PP, which was found to be around 283 K by differential scanning calorimetry Jubera, 2013. The fiber temperature during the tests was measured with a thermocouple very close to the fiber.

Tensile tests were carried out at constant cross-head displacement. Fiber elongation was determined as the cross-head displacement, since the machine compliance was negligible as compared with the fiber. Tests were carried out at three different strain rates of 8.0×10^{-4}, 8.0×10^{-3} and 10^{-1} s^{-1}. The load carried by the fibers was measured by using a load cell with ±1 mN resolution.

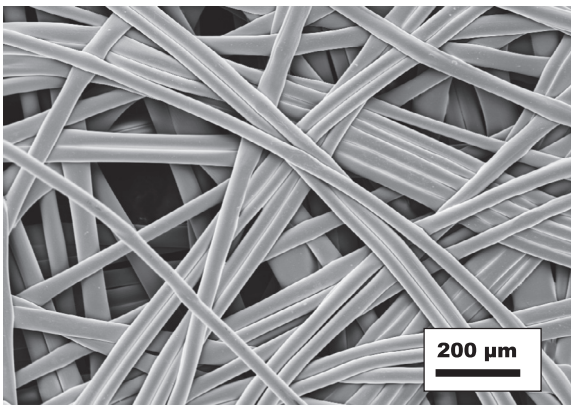

Fig. 1. Scanning electron micrograph of the PP nonwoven fabric Typar SF32, manufactured by Du Pont de Nemours.