Composites: Part B 68 (2015) 327–335

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Mechanical analysis of bi-component-fibre nonwovens: Finite-element strategy

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ARTICLE INFO

Article history:
Received 18 April 2014
Received in revised form 11 August 2014
Accepted 1 September 2014
Available online 15 September 2014

Keywords:
A. Fabrics/textiles
A. Fibres
B. Mechanical properties
C. Finite element analysis (FEA)

ABSTRACT

In thermally bonded bi-component fibre nonwovens, a significant contribution is made by bond points in defining their mechanical behaviour formed as a result of their manufacture. Bond points are composite regions with a sheath material reinforced by a network of fibres' cores. These composite regions are connected by bi-component fibres — a discontinuous domain of the material. Microstructural and mechanical characterization of this material was carried out with experimental and numerical modelling techniques. Two numerical modelling strategies were implemented: (i) traditional finite element (FE) and (ii) a new parametric discrete phase FE model to elucidate the mechanical behaviour and underlying mechanisms involved in deformation of these materials. In FE models the studied nonwoven material was treated as an assembly of two regions having distinct microstructure and mechanical properties: fibre matrix and bond points. The former is composed of randomly oriented core/sheath fibres acting as load-transfer link between composite bond points. Randomness of material's microstructure was introduced in terms of orientation distribution function (ODF). The ODF was obtained by analysing the data acquired with scanning electron microscopy (SEM) and X-ray micro computed tomography (CT). Bond points were treated as a deformable two-phase composite. An in-house algorithm was used to calculate anisotropic material properties of composite bond points based on properties of constituent fibres and manufacturing parameters such as the planar density, core/sheath ratio and fibre diameter. Individual fibres connecting the composite bond points were modelled in the discrete phase model directly according to their orientation distribution. The developed models were validated by comparing numerical results with experimental tensile test data, demonstrating that the proposed approach is highly suitable for prediction of complex deformation mechanisms, mechanical performance and structure-properties relationships of composites.

1. Introduction

Thanks to their beneficial material properties, such as, high formability and improved resistance to impact, interest in application of textile composites is continuously increasing, for instance, in automotive and aerospace industry [1]. As compared to woven composites, the nonwoven composites have been getting more attention, which is evidenced by a rapidly growing number of patents in recent decades. The reason for this attention from academia and industry lies in several advantages attributed to nonwoven composites such as low cost and quicker manufacturing of nonwovens along with better control on fibres orientation-based properties [2]. Despite their importance and significant research in this field, there is no adequate design tool for nonwoven composites. One of the main challenges in developing a design tool for nonwovens is insufficient understanding of their complex mechanical behaviour [3–5] especially in thermally bonded bi-component fibre nonwovens, in which bond points behave like a composite themselves. Therefore, this research is focussed on the mechanical behaviour of such nonwovens.

Such materials can be manufactured by embedding a nonwoven web, bonded with any of three main techniques: chemical, mechanical or thermal, into a matrix to achieve a necessary combination of properties. This study is focussed on a type of nonwovens, which were thermally bonded by calendering using core-sheath type bi-component fibres as shown in Fig. 1. Thermal bonding is

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http://dx.doi.org/10.1016/j.compositesb.2014.09.003
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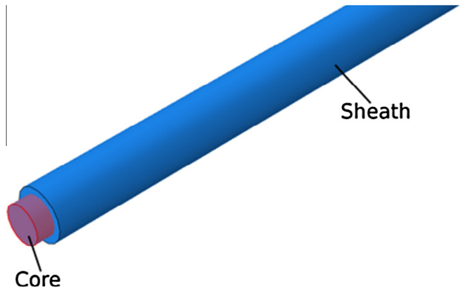

Fig. 1. Structure of core/sheath type bi-component fibre.

the most widely used technique for manufacturing of nonwovens [2,6]. During thermal bonding, fibres are passed through hot calendar rolls with smooth or embossed surface design. Bonding occurs at raised areas of the embossed calender under pressure and high temperature by partial melting and subsequent solidification of fibres. The molten sheath material that has a lower melting point acts as adhesive while core parts of the fibres remain fully intact at the bond points, thus forming them with a two-phase composite structure with matrix and fibre reinforcement. The bonding process results in two distinct regions, namely, bond points and a fibre matrix, as shown in Fig. 2. The same technique with smooth calenders can be used for the manufacturing of composite sheets using nonwovens as a precursor [7]. Therefore, this study is focussed on the mechanical behaviour calendar-bonded nonwovens.

Due to the multi-scale nature of nonwovens, both continuous and discrete modelling approaches to their analyses were used in the literature. Continuous phase models offer the benefit of using a standard finite element method. Still, they provide a macroscopic response of the material without sufficient information about underlying mechanisms defining their mechanical behaviour [8–10]. In contrast to continuous phase models, discrete phase models of nonwovens were applied at the unit cell level in combination with a homogenization approach [11,12]. These models do not represent the microstructure realistically and cannot be used to understand the structure-properties relationship of nonwovens. Other discrete phase models developed by the authors employ direct introduction of individual fibres according to the experimentally measured orientation distribution [13–17]. These models incorporate the microstructural randomness of nonwovens into the model to predict their anisotropic behaviour. As a result, they are capable of providing information about structural evolution and other main aspects of the fabric's mechanical behaviour. All these models were either developed to deal with mono-component fibre nonwovens or based on a traditional continuous phase modelling technique, which could predict only a macroscopic response of the composite fabrics. To the authors' knowledge, none of the model in the literature based on discreet modelling deal with thermally bonded bi-component fibre nonwovens, which contain special type of structures consisting of composite domains connected by a network of fibres.

In this paper, a novel modelling strategy based on a discrete phase modelling approach is presented to characterise the mechanical behaviour of textile composite nonwovens formed by bi-component fibres. The modelling process starts by determining morphological and mechanical properties of the fabric and its constituent fibres. Bond points were modelled as a continuous structure, with their mechanical properties obtained by a special developed in-house algorithm. Fibres between the bond points were modelled directly according to their orientation distribution forming the discontinuous part of the model. This approach is compared with simulations employing a traditional FE model.

2. Experimentation

2.1. Fabric behaviour

The morphological features and mechanical behaviour of a 35 g/m^2 bi-component fibre nonwoven, which is the focus of our study, were obtained by performing various analysis and tests. The fabric was scanned with X-ray Micro Computed Tomography (μCT) and observed with SEM to acquire the information about its microstructure. The data about the size, shape and pattern of bond points and thickness of fibrous matrix and bond points were collected directly from the captured images. The bond points of the fabric were similar to those in Fig. 2. Table 1 provide information about the measured size, shape and pattern of bond points. In the images of the fabric at micro level, it was observed that the diameter of the fibres was not constant along their length; this variation is a result of the manufacturing process.

Mechanical characterization of the fabric was implemented employing uni-axial tensile tests on rectangular coupons of the fabric 15 mm × 10 mm in size using cut-strip grab test method [18]. In order to capture anisotropy of the material, tensile tests were performed in MD and CD directions. The results of uni-axial tests in terms of force–displacement curves are given in Fig. 3 demonstrating a scatter in experimental results due to the random microstructure of the fabric. The deformed shape of the fabric at extension of 50% is shown in Fig. 4. At this level of fabric's extension, misalignment of bond points e.g. breaks of bond points lines in the initial pattern can be observed. The reason for this is a random orientation distribution of fibres. One of the main deformation processes of a nonwoven is re-orientation of fibres towards the loading direction during extension [16,17], and their final

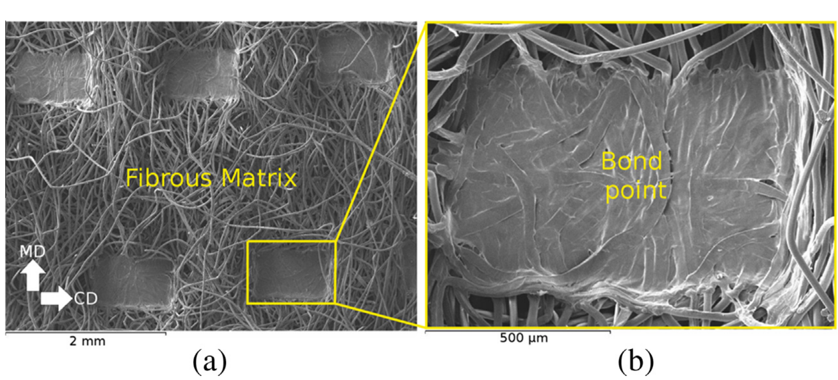

Fig. 2. SEM images of bi-component fibre nonwoven fabric composed of composite bond points (b) and fibrous matrix (a).