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Finite element modelling of thermally bonded bicomponent fibre nonwovens: Tensile behaviour

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ABSTRACT

Nonwovens are polymer-based engineered textiles with a random microstructure and hence require a numerical model to predict their mechanical performance. This paper focuses on finite element (FE) modelling the elastic–plastic mechanical response of polymer-based core/sheath type thermally bonded bicomponent fibre nonwoven materials. The nonwoven fabric is treated as an assembly of two regions having distinct mechanical properties: fibre matrix and bond points. The fibre matrix is composed of randomly oriented core/sheath type fibres acting as load-transfer link between bond points. Random orientation of individual fibres is introduced into the model in terms of the orientation distribution function (ODF) in order to determine the material's anisotropy. The ODF is obtained by analysing the data acquired with scanning electron microscopy (SEM) and X-ray micro computed tomography (CT). On the other hand, bond points are treated as a deformable bicomponent composite material composed of the sheath material as matrix and the core material as fibres having random orientations. An algorithm is developed to calculate the anisotropic material properties of these regions based on properties of fibres and manufacturing parameters such as the planar density, core/sheath ratio and fibre diameter. Having distinct anisotropic mechanical properties for two regions, the fabric is modelled with shell elements with thicknesses identical to those of the bond points and fibre matrix. Finally, nonwoven specimens are subjected to tensile tests along different loading directions with respect to the machine direction of the fabric. The force–displacement curves obtained in these tests are compared with the results of FE simulations.
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1. Introduction

In contrast to composites and woven fabrics, nonwoven materials have a unique web structure which is composed of randomly oriented polymer fibres bonded in a pattern by mechanical, thermal or chemical techniques. The type of nonwovens studied in this paper is a thermally bonded one with bicomponent fibres. The bicomponent fibres have a core/sheath structure with outer layer (sheath) having a lower melting temperature than that of the core (Fig. 1). In thermal bonding of such fibres, as the hot calender with an engraved pattern contacts the fibre web, bond spots are formed by melting of the sheath material [1]. Molten sheath material acts as an adhesive while core parts of the fibres remain fully intact in the bond spots. On the other hand, web regions, which are not in contact with the hot engraved pattern, remain unaffected and form the fibre matrix that acts as a link between the bond points. The structure of the resulting thermally bonded bicomponent fibre nonwoven is shown in Fig. 2. Having two distinct regions, namely bond points and fibre matrix with different structures, nonwovens exhibit a unique deformation behaviour.

The deformation behaviour of thermally bonded bicomponent fibre nonwovens is complicated due to the fact that random fibrous structure leads to their anisotropy [1,2] while polymer-based constituents are characterised by a temperature dependant large-strain elastic–plastic behaviour including viscous effects [3]. Several studies were performed to predict the mechanical response of such materials regarding fibre arrangements [4], curliness of the fibres [5], orientation distribution of the fibres [6,7] and bonding temperature [1,8]. However, these studies offer only partial solutions for prediction of the mechanical response of these materials to loading.

In order to assess the mechanical behaviour of nonwoven materials, a comprehensive numerical model, which considers physical and manufacturing parameters, is necessary. Only a few studies were performed to construct a numerical model for the prediction of the mechanical response of nonwoven fabrics. To author's knowledge the only finite element (FE) models were proposed only in [9] and [10]; they treat the nonwoven material as a 2D structure composed of truss elements representing fibre matrix and isotropic planar elements representing bond spots. Those models are appli-

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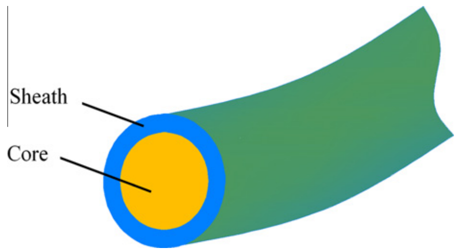

Fig. 1. Structure of core/sheath type bicomponent fibre.

cable to planar fabrics with small dimensions including a few bond spots. However, these models cannot be used for real 3D fabric shapes and unable to represent their low bending stiffness as well as buckling phenomena. Furthermore, they require a long computation time due to a large number of elements necessary to simulate the fabric structure. The FE model developed in this paper eliminates these crucial disadvantages by employing orthotropic shell elements for simulating the behaviour of bond spots and fibre matrix. The mechanical properties of these regions are derived using the manufacturing parameters, microstructural character of the nonwoven as well as the behaviour of a single fibre employing computational approaches used for composites.

This study aims to introduce a practical 3D numerical model for predicting the mechanical response of thermally bonded bicomponent fibre nonwoven fabrics to loading in order to eliminate costly and time-consuming product development. The development of the model starts with determining the behaviour of a single fibre constituting the fabric, then computing the anisotropy in the structure and the mechanical properties of the bond points and matrix. Finally, the FE model of the nonwoven fabric is generated using the calculated mechanical properties of the regions and then experiments are conducted to verify the numerical model.

2. Single fibre behaviour

Fibres are the basic constituents of a nonwoven fabric and play an important role in determination of its mechanical properties. The type of fibres focussed on this study is a core/sheath bicomponent one composed of a sheath material having a lower melting temperature than that of the core material. For bicomponent fibres, polyethylene (PE) is frequently used as sheath material, whereas polypropylene (PP), polyamide 6 (PA6) and polyester (PET) are the most commonly used polymers as core material [11]. The polymers used for the core region have higher values of the elasticity modulus than the ones used for the sheath region, and the cross-sectional area of the core is always larger than that of sheath.

As a starting point for computation of the mechanical properties, elastic–plastic behaviour of a single fibre constituting the nonwoven fabric, should be obtained. There are two ways to do this; either the Rule of Mixture (RoM) is applied to determine the mechanical behaviour of the bicomponent fibre from the behaviour of its core and sheath regions or tensile testing of the fibres is performed to obtain their mechanical properties. The use of RoM is not appropriate since the mechanical behaviour of the polymeric bicomponent fibre is affected by its temperature history linked to the manufacturing stage. The interface between the core and sheath is characterised by temperature variations throughout the manufacturing process by diffusion, which affects the overall mechanical response of the fibre. Therefore, rather than applying RoM, bicomponent fibres constituting the nonwoven fabric are tested to determine their elastic–plastic mechanical properties.

As a typical example, PA6/PE core/sheath bicomponent fibres having 15 μm diameter, extracted from the free edge of a 150 g/m^2 thermally bonded nonwoven fabric, are tested (Fig. 3). The PA6-based core region forms 75% of the cross-sectional area of these bicomponent fibres and PE-based sheath region does 25% of that. Tensile tests are performed using Instron® Micro Tester 5848 test rig having a ±5 N Instron® load cell.

Fig. 3 shows that the bicomponent fibre tested at different strain rates exhibits a typical polymer behaviour characterised by the high level of strain and nonlinearity. The deformation of fibre consists of reversible (elastic) and irreversible (plastic) stages, but is mainly governed by the plastic stage because the yield strain is approximately 0.005. The slight difference between the curves is due to strain-rate sensitivity linked to viscous effects in the material. Moreover, the stress–strain curves indicate that hardening, i.e. material's strengthening with plastic deformation, occurs throughout the whole deformation range.

The parameters, which are related to a single fibre and necessary for computing the mechanical properties of the nonwoven fabric, are the flow curve (plastic strain vs. stress) and modulus of elasticity. If the fibre exhibits nonlinear large-strain elasticity, instead of a single value of the modulus of elasticity, the tangential modulus vs. elastic strain curve could be used to define the elastic behaviour. Generally, for bicomponent fibres, the energy stored in the elastic range is very small with respect to the toughness for continuous loading without unloading. Due to this reason, the elasticity could be assumed as linear, in order to simplify the model and reduce the computation time.

3. Mechanical behaviour of fabric

The mechanical performance of 150 g/m^2 thermally bonded nonwoven fabric manufactured with PA6/PE bicomponent fibres forms our case study. The bond pattern of the fabric is identical

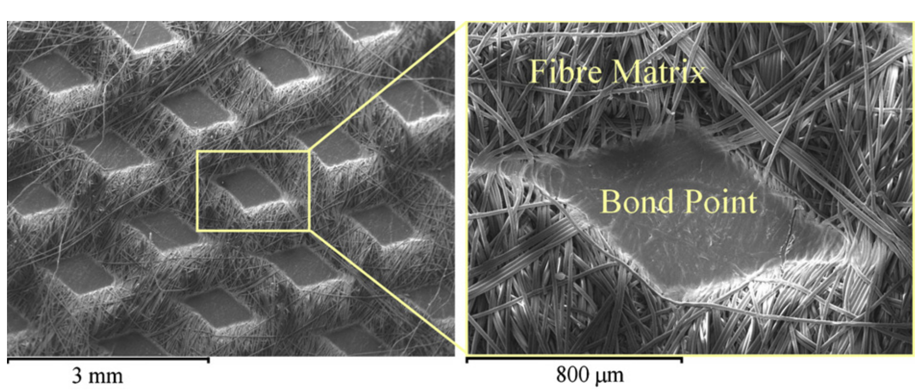

Fig. 2. SEM images of bicomponent fibre nonwoven fabric composed of bond points and fibre matrix.

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