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Mechanical behaviour of nonwovens: Analysis of effect of manufacturing parameters with parametric computational model

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ABSTRACT

A deformation behaviour of, and damage in, polymer-based thermally bonded nonwovens was studied with a parametric finite-element model. Microstructure of the studied nonwoven was modelled by direct introduction of fibres and bond points, employing a subroutine-based parametric technique. This technique helped to implement variations in dimensional characteristics of structural entities related with manufacturing of these materials. Following experimental observations, a realistic orientation distribution of fibres and single-fibre failure criteria were included into the model. The developed model was demonstrated to be a very useful tool not only for predicting effects of parameters related to manufacturing of nonwovens or of specimen's size on a macroscopic response of the nonwoven but also for getting an insight into deformation mechanisms and damage localization in its structure.

1. Introduction

Nonwovens are engineered fabrics manufactured from a set of disordered fibres consolidated together by localized melting or by the use of chemicals. Simple entanglement of fibres is also possible by means of mechanical pressure using water or cold calendering. Nonwovens and their combinations with other materials are used in numerous applications, including geotextiles for soil reinforcement as well as products for medicine, filtration and aerospace industry [1]. Regardless of the application area of nonwovens, understanding of relationships between their micro/macro mechanical properties and manufacturing parameters is needed for tailoring their properties and performance.

Thermal bonding is the most commonly used technique for the manufacturing of nonwovens [2,3]. In thermally calender-bonded nonwovens, a fibrous web is passed through a hot calendar with an embossed pattern. Bonding mainly occurs at calender's raised areas resulting in bonded spots called "*bond points*". Other parts of the web, which were not in contact with the hot engraved pattern, remained unaffected and form the permeable part called *fibre matrix* that acts as a link between the bond points. The structure of resulting thermally bonded nonwoven (shown in Fig. 1) is a combination of continuous and discontinuous regions, thanks to which the material exhibits a unique and complex mechanical behaviour. This behaviour is highly affected by the variation in manufacturing parameters such as size, shape and pattern of bond points and orientation distribution of fibres as well as temperature and pressure variations. Generally, optimal bonding is implemented during manufacturing of nonwovens using pre-defined, fixed levels of bonding temperature, pressure and speed [4]. Therefore, the effects of temperature and pressure variations on mechanical performance of the fabric are not studied here.

Previously, several models employing various approaches were developed to simulate the mechanical behaviour of nonwovens [5–9]. All of the simulations regarding mechanical performance of nonwoven available in literature are limited to a particular type of nonwoven with fixed values of size, shape and pattern of bond points. To author's knowledge, the only simulations predicting the effect of various manufacturing parameters on mechanical behaviour of nonwovens were presented in [10]. However, the results were limited to initial deformation of the fabric without any analysis of the damage behaviour of the fabric. Moreover, the effects of orientation distribution of fibres on mechanical behaviour of the fabric in terms of stress/strain distribution in fibres were not studied. Additionally, that model does not account for structural evolution as a result of progressive failure of fibres since the fibre failure criteria were not incorporated in it. This information is important for analysis of mechanical performance and structural evolution of these materials during deformation and damage.

This study is aimed at the effects of dimensional and shape variability of bond points and specimen sizes on deformation and damage of low-density thermally bonded nonwovens based on monocomponent polymer fibres. Additionally, the role of

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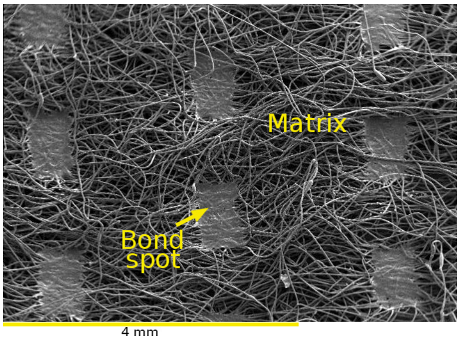

Fig. 1. Microscopic image of thermally bonded nonwoven.

orientation distribution of fibres in defining the mechanical performance of the fabric was investigated. The first part of this paper describes the suggested parametric technique used for development of a finite-element model [11,12]. The statistical parameters that define the fabric's microstructure as well as mechanical properties such as single-fibre behaviour and failure criteria, investigated experimentally [13], were used for the development of a realistic fabric's models. Mechanical performance of nonwovens was simulated using the developed models and validated with experimental data. Finally, conclusions based on the obtained results and applicability of the model to design nonwoven for specific application requirements are discussed.

2. Modelling technique

A novel parametric finite-element modelling technique was developed to study the structure-properties relationship and the effect of various manufacturing parameters on deformation and damage of nonwovens. The parametric nature of the model allowed the introduction of variations in nonwoven's structure in a very efficient way, enabling the study of effect of various parameters on its mechanical behaviours. The details of the modelling process are given below.

2.1. Generation of microstructure

Nonwoven materials being a type of fibrous networks contain large numbers of fibres; these fibres are generally randomly oriented throughout their structure. These complexities make it difficult to develop a model of nonwoven network by explicit introduction of fibres using conventional modelling technique based on available operations with a pre-processor. Therefore, an efficient parametric modelling technique based on a subroutine was adopted in this study. In this technique, a computer builds up the model according to the instructions written in the code. The subroutine developed in this study allows reformulation of the model to incorporate variations in manufacturing parameters such as orientation distribution of fibres, size, shape and pattern of bond points and planar density of the fabric into the model with significantly reduced efforts. Thus, it is possible to generate complex models of nonwoven fibrous network in a relatively short time. The subroutine was written in Patran Command Language (PCL), which can be read by commercial software MSC. Patran.

Starting from the internal structure, the subroutine develops the model by explicit introduction of fibres according to their orientation distribution function. Before starting the modelling process, input parameters required for modelling of nonwovens, such as physical and mechanical properties of fibres, their rientation distribution, size, shape and pattern of bond points are determined by experimental characterisation of the material. The details of determination of these material properties are given in [13]. The process of development of the model starts with introduction of bond points; they are modelled according to their required shape, size and pattern. Then, the actual full length of fibres (L_a) in the area of fabric corresponding to the model is determined by using the scheme given in [14]. Then, using the information on length of individual fibres, the total number of fibres in the model is calculated. After this, their total length (L_s) is calculated by assuming a random selection of starting points for introduction of fibres. The magnitude of the actual fibre length (L_a) and the simulated fibre length (L_s) are compared. The latter value can never be greater than the former one as some parts of the fibres in the model are outside the studied area since they were introduced randomly e.g. a portion of fibre B is outside the model area (Fig. 2). Therefore, the total number of fibres to be modelled is increased one by one until $L_s = L_a$. The calculation of the number of fibres is performed before the actual modelling process is started; this reduces significantly the time required to generate the model. The discussed procedure of calculation of the number of fibres is shown in the flow chart in Fig. 3.

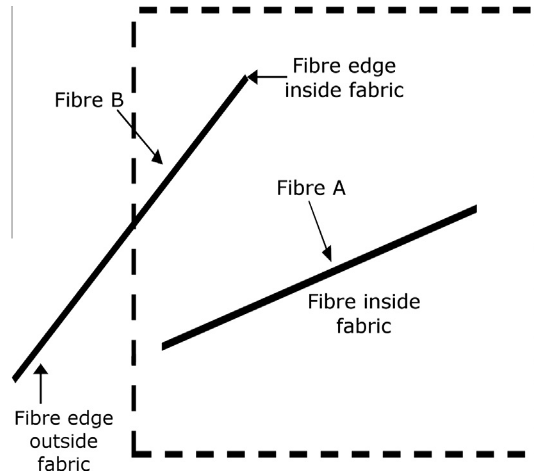

Fig. 2. Fibres inside and partially outside studied fabric area.

After calculation of the number of fibres, the process of modelling of fibres according to their orientation distribution is started and continued until the full length of the fibre is introduced into the model. The complete details of the process of development of nonwoven network are given elsewhere [13,14]. Following the morphological analysis of the fabric, the nonwoven model consists of two regions: bond points and fibrous matrix (Fig. 4). A flow chart showing the steps involved in generation of the network is given in Fig. 3.

2.2. Finite-element model

The generated model of nonwoven was discretised with finite elements. It was performed by using the subroutine, ensuring that each fibre was properly attached with the bond points at its ends to avoid convergence issues. Each fibre in the model was presented with a single truss element (Element 9 in MSC. Marc) whereas each bond point was discretised into a number of shell elements (Element 139 in MSC. Marc).

Mechanical and geometrical properties of the fibres and bond points obtained previously [13] were implemented in the developed model. The constituent fibres are made of polymer materials with nonlinear elastic–plastic and viscous properties. A single-fibre failure criterion based on experimental data [13,17] was used to simulate damage initiation and propagation in nonwovens. The