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Application of dynamic recursive splitting to estimate fibre entanglement in simulated nonwoven fibrous assemblies

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ABSTRACT

Fibrous nonwovens comprise of fibres or filaments bonded by various methods. Depending on the mode of fabric formation these fibres may be entangled; this affects the physical properties of the bulk structure. Estimating the degree of entanglement based on relative fibre arrangement in such structures is highly challenging. In this paper, fibre-to-fibre interactions within simulated fibrous assemblies are analysed using topological and geometrical principles as a means to quantify entanglement. The underlying theoretical framework in which splitting number is used to characterise entanglement has been previously described [1]. A detailed algorithm and its practical application for the estimation of fibre entanglement are reported based on Dynamic Recursive Splitting (DYRES).

1. Introduction

The geometric arrangement of fibres in a general fibrous assembly is a defining parameter of the structure. Together with the mode of bonding and the physical properties of the fibres it has a direct and decisive effect on the properties of the assembly. The mechanical behaviour of fibrous assemblies such as webs and nonwovens including electrospun structures can be modelled by micromechanical and phenomenological approaches. A limitation of phenomenological approaches is that they commonly fail to provide a link between parameters of the model and the actual assembly [2]. Micromechanical studies of general fibrous assemblies including those pioneered by Van Wyk [3] and Cox [4] have provided fundamental insights into structure–property relationships. Fibre-to-fibre contact points, mean fibre length between contact points, fibre orientation and pore size distribution have been considered vital for characterising the mechanical behaviour and physical properties of fibrous assemblies [5,6]. Following the same principles, compression properties [7], shear properties [8], compression hysteresis [9] and the tensile behaviour of nonwoven structure [10] have been studied. The mechanics of fibrous assemblies have also been approached using energy methods wherein unnecessary assumptions and approximations can be removed to simplify the analysis [11]. A detailed review of two-dimensional [12] and three-dimensional [2] mechanical models can be consulted for further interest. Computer simulations and algorithms have been used for predicting mechanical properties [13–16] and structural features [17–19] of fibrous assemblies, respectively.

Nonwovens are fibrous assemblies bonded by various means; in mechanically bonded nonwovens, crossings of fibres with other fibres as well as around themselves provide structural integrity as shown in Fig. 1. Intuitively it can be understood that a higher degree of entanglement should provide better mechanical interactions between the fibres and thus improve the mechanical integrity of the whole assembly. However, if a nonwoven fabric or web requires high tensile strength in one particular direction then a very high degree of entanglement may lead to a large variation in the fibre orientation and a decrease in the strength. This raises a general question of an optimal fibre entanglement which is the best for the specified application.

The direct characterisation of fibre interactions to quantify entanglement has been described in a recent paper based on a combination of topological and geometrical principles [1]. This approach requires the nature of fibre crossings in the assembly to be analysed for each individual fibre within the network. In the present paper, the basic method is further developed and applied to enable the degree of entanglement in a nonwoven fabric to be estimated based on its topological and geometric features. This estimation is based on splitting number, which is associated with the degree of entanglement of the structure, where a higher splitting number means a more entangled structure.

The degree of splitting, S, of a fibre assembly $\boldsymbol{F}$ of m fibres can be described in terms of the number and type of crossings present in the structure. S is defined as the minimum number of crossings which have to be switched in order for the assembly $\boldsymbol{F}$ to be split into a maximum of m disentangled subsets $\boldsymbol{L}_k$, $k = 1,2,\ldots,m$, where

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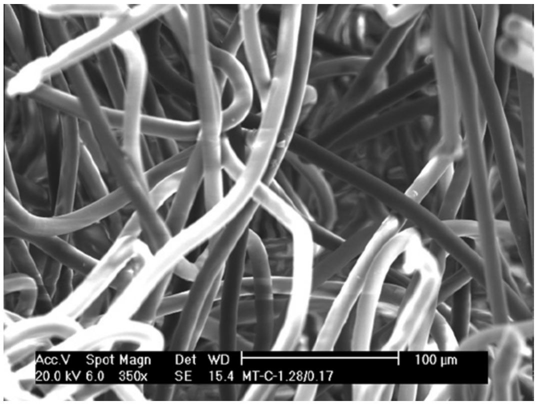

Fig. 1. SEM micrograph of 200 g m^{-2} PET-Glass fibre hydroentangled nonwoven fabric.

fibres in each subset $\boldsymbol{L}_k$ are not entangled with one another [1]. Each individual fibre in each subset $\boldsymbol{L}_k$ may or may not be knotted with itself. Using this approach it can be demonstrated that the degree of entanglement of a fibre assembly is zero or $S = 0$ when fibres do cross one another but lie in disjointed parallel layers such that they are not entangled. The aim of this paper is to develop a method to calculate the value of S in a general fibre assembly based on Dynamic Recursive Splitting (DYRES).

2. Dynamic Recursive Splitting (DYRES) method

An algorithm is required to find the minimum possible number of crossings that have to be switched in order for the whole structure to become a disjointed collection of fibres lying in parallel planes. Each individual fibre in this resultant assembly may be knotted with itself. This algorithm implements a Search-Switch-Remove procedure (SSR-procedure) by searching for fibres in $\boldsymbol{F}$ that are least entangled either at the top or at the bottom of the assembly. Each time, if necessary, the SSR-procedure switches the minimum possible number of crossings of such fibres and then removes them from the assembly. In some cases, if the fibres are not entangled with the rest of the assembly, they can be removed without switching. This dynamically changes the structure of the assembly by reducing its entanglement thus generating a new subset of the least entangled fibres that will be analysed in the next step. This algorithm also calculates the number of layers into which the structure can be split.

In the course of calculations each switched crossing increases the splitting number being calculated by one. Each completed step of fibre removal, which sometimes involves several fibres, increases the number of layers being calculated by one. In some cases there may be several fibres in the current structure with the same number of crossings to be switched. Switching crossings of one such fibre may lead to a different structure in comparison to that obtained by switching a different fibre. It is therefore necessary to examine all such cases and select the sequence of switching that provides the minimum splitting number. This analysis can be done by employing a recursive search which explores all possible cases, compares the splitting number achieved at each case, and selects the sequence of switches and removals that yields the minimum splitting number.

A simplified description of the main steps of this approach is given below.

1. Identify and number all fibres in the assembly $\boldsymbol{F}\{f_1,f_2,\ldots,f_m\}$ in an arbitrary way.
2. Identify the orientation of all fibres in $\boldsymbol{F}$ in an arbitrary way.
3. Identify the fibre crossings $\boldsymbol{C}\{c_1\{c_{1i},c_{1j},c_{1k},\ldots\}, c_2\{c_{2i},c_{2j},c_{2k},\ldots\}\ldots,c_m\{c_{mi},c_{mj},c_{mk},\ldots\}\}$ as positive or negative, where $c_{ij} = j$, if f_i is above f_j; $c_{ij} = -j$, if f_i is below f_j.
4. Set the number of layers $n_L = 0$ and splitting number $S = 0$.
5. Calculate the number of positive and negative self-crossings for each fibre:

$$p_i^s = \sum_{j=1, j=i, c_{ij}>0}^{m_i} sign(c_{ij}),$$

$$n_i^s = \sum_{j=1, j=i, c_{ij}<0}^{m_i} sign(|c_{ij}|),$$

where $i = 1, 2,\ldots,m$ and m_i is the number of crossings of fibre f_i with other fibres in $\boldsymbol{F}$.

Note that the number of positive and negative self-crossings will not change in the calculations that follow.

6. Calculate the total number of positive, $p_i^t = \sum_{j=1,c_{ij}>0}^{m_i} sign(c_{ij})$, and negative, $n_i^t = \sum_{j=1,c_{ij}<0}^{m_i} sign(|c_{ij}|)$, crossings for each fibre i in $\boldsymbol{F}$ including self-crossings.

Fig. 2. Fibre assembly for Example 1.

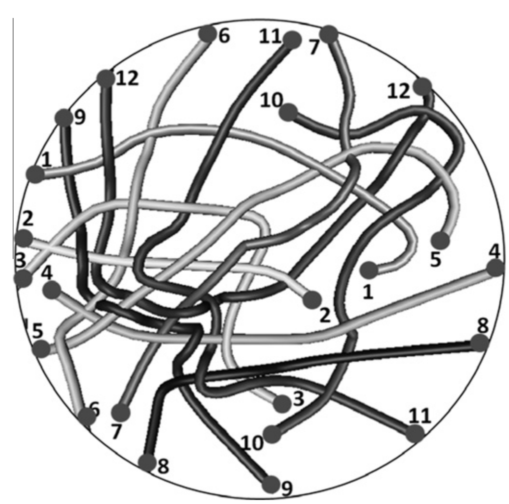

Fig. 3. Fibre assembly for Example 2.