Parametric 3D modelling of nonwovens for mechanical and filtration properties

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Parametric 3D Modelling of Nonwovens for Mechanical and Filtration Properties

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Motivation

What does happen to nonwovens under tension and compression?
Does microstructure change?
Does this affect mechanical, filtration and absorption properties?
Outline

- Motivation
- Objectives
- Material and microstructure
- Experiments
- Tensile Performance
- Out-of-plane Loading
- A New Parametric 3D Computational Model
- Flow Simulations
- Summary and conclusions
Objectives

i. To predict tensile, compression and filtration performance of nonwovens with computational models.

ii. To develop a new 3D parametric model to simulate compression of nonwovens and its effects on flow properties.

iii. To optimize available nonwovens by means of this new parametric model to enhance filtration and absorption performances.

Figure 1: Thermally bonded nonwovens
Material and Microstructure

- Highly complicated materials due to material and microstructural properties

- Fiber curvature
- Fiber-to-fiber interactions
- Random orientation
- Deep-grooved fiber cross-section

200µm

Bond point
## Experiments

<table>
<thead>
<tr>
<th>Test</th>
<th>Instrument</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanning electron microscopy (SEM)</td>
<td>Carl Zeiss, Leo, 1530VP FEGSEM</td>
<td>Fabric characteristics (bond pattern, shape…etc.)</td>
</tr>
<tr>
<td>X-ray micro computed tomography (CT)</td>
<td>XTEK XT-H 160Xi</td>
<td>3D image, ODF, bond pattern, shape and dimensions…etc.</td>
</tr>
<tr>
<td>Fiber tensile tests</td>
<td>Intron Micro Tester 5848</td>
<td>Elastic properties and rate-dependent flow curve</td>
</tr>
<tr>
<td>Creep tests</td>
<td>Intron Micro Tester 5848</td>
<td>Viscous properties</td>
</tr>
<tr>
<td>Relaxation tests</td>
<td>Intron Micro Tester 5848</td>
<td>Viscous properties</td>
</tr>
<tr>
<td>Fabric tensile tests</td>
<td>Hounsfield Benchtop Tester</td>
<td>Mechanical response</td>
</tr>
</tbody>
</table>
Fiber Orientation Distribution:
- Grey-scale 2D images using a Hough-transform-based image processing algorithm

(Demirci, 2011)
Experiments - Single Fiber Tests

- Individual fibers extracted from nonwovens and tested under a tensile tester with a ±5N load cell

- Fibers exhibit highly time-dependent material behaviour.

- Tensile tests with various strain rates

- Relaxation tests
Tensile Performance - Deformation and Damage Mechanisms

- Discontinuous models

- Continuous models
Out-of-plane Loading - a Falling Ball

Equivalent von Mises (MPa)

1.62 mm

1.7 mm
New Parametric 3D Computational Model

50 gsm through air bonded nonwoven model

- Modelling of nonwoven network using fiber deposition and FE methods.
- Multiple fiber types can be generated in the same model (For instance, main and binder fibers)
New Parametric 3D Computational Model-Capabilities

Short Fibers

Continuous Fibers

Various fiber cross-sections: rectangular hollow, round, trilobal, 4DG, etc
Flow Simulations – a Case Study

- A through-air bonded nonwoven (90gsm, PP/PE 60:40)

*SEM images

- ODF

- Star CCM+
- Laminar air flow
- No heat transfer, only continuity equations
- 8-10 millions cells (Polyhedral, tetrahedral elements)
- Inlet velocities: 0.1, 0.25, 0.5, 1.0 m/s
- No-slip on fibers
Flow Simulations – a Case Study

- A section in the middle along the flow direction
- A line of probes marked for calculations
- Nonwoven network was compressed 50% in FE software and flow simulations were repeated.
Flow Simulations – Pressure Drop

Pressure Distribution along Through Thickness Direction

Zero Compression

Pressure Drop without/with Compression

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>No Compression</th>
<th>%50 Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.64</td>
<td>2.12</td>
</tr>
<tr>
<td>0.25</td>
<td>4.23</td>
<td>5.50</td>
</tr>
<tr>
<td>0.5</td>
<td>9.09</td>
<td>11.78</td>
</tr>
<tr>
<td>1</td>
<td>20.86</td>
<td>26.69</td>
</tr>
</tbody>
</table>

50% Compression

Air Permeability (Darcy Law)

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>No Compression</th>
<th>%50 Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.17728E-09</td>
<td>8.40586E-10</td>
</tr>
<tr>
<td>0.25</td>
<td>2.11155E-09</td>
<td>8.11804E-10</td>
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<tr>
<td>0.5</td>
<td>1.96376E-09</td>
<td>7.57353E-10</td>
</tr>
<tr>
<td>1</td>
<td>1.71123E-09</td>
<td>6.68731E-10</td>
</tr>
</tbody>
</table>
Summary and Conclusions

- A material characterization process in micro and macro scales is necessary to obtain material and geometric properties of nonwovens.
- Tensile performance of nonwovens strongly depends on material properties of fibers and their orientation distributions (ODF’s).
- Two dimensional continuous and discontinuous FE models, in which ODF was incorporated into, were presented. Their uses in simulating deformation, damage and out-of-plane loading were shown with sample cases.
- A new parametric 3D finite-element model with fiber curvature and fiber-to-fiber interactions was introduced.
- Based on the new parametric model, flow simulations on an uncompressed and 50% compressed nonwoven were conducted. Pressure drop and permeability calculated.
- By compressing nonwovens, a significant increase in pressure drop and a decrease in air permeability were observed.
Future Work – Compression of Nonwoven due to Fluid Flow

Coupling of Structural Analysis with Computational Fluid Dynamics

- **Method**: Computational Fluid Dynamics (CFD)
- **Domain**: Fluid Flow in Pores around Fibers

- **Investigated Properties**:
  - Flow Velocity
  - Pressure Field
  - Permeability
  - Filtration
  - Performance

- **Structural Analysis**
- **Nonwoven Geometry with all Fiber Interactions**

- **Displacement Field**
- **Strain Field**
- **Stress Field**

At initial state: $h_0$
At deformed state: $h_1$

$h_0 > h_1$
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