Numerical micro-scale modelling of the mechanical loading of woven fabrics equipped with particles

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Abstract The equipping of polyester multifilament fabrics with functionalized micro particles for partial and targeted reduction of the size of continuous inter-yarn pores in the fabric, utilizing the filtering effect of textile surfaces, has proven to be a very effective method for increasing the barrier properties of fabrics for use as surgical reusable textiles, cleanroom clothing or cleanable filter media. The objectives of this study were to understand the interrelationships of weaving parameters and fabric properties and to model the porous fabrics under loading conditions. Artificial Neural Networks were trained and tested in order to link the weaving and processing parameters with the fabric properties using the experimental data. Mean flow pore sizes and permeability values of woven fabrics under biaxial loading conditions were measured according to a method previously developed using a special sample holder connected to a conventional porosimetry. Finite element models of unit cells were developed and loaded virtually. Those models were transferred into voxel models and imported into software DNSlab, where they were virtually equipped with particles. For the simulation of the fluid flow, the Navier-Stokes equations were solved numerically by the Lattice-Boltzmann method. The experimental and numerical studies show that pore size of barrier fabrics can be tailored using the developed methods and models. Important parameters are the fabric construction parameters and the particle size.

Keywords— barrier fabric, finite element method, fluid flow, micro-scale model, particle, woven fabric

I. INTRODUCTION

The development of liquid- and particle-tight fabrics with excellent textile-physiological properties and an adjustable porosity for use as surgical reusable textiles, cleanroom clothing or cleanable filter media is of particular economic relevance. The equipping of polyester multifilament fabrics with functionalized micro particles for partial and targeted reduction of the size of continuous meso pores (i.e. inter-yarn pores) in the fabric, utilizing the filtering effect of textile surfaces, has proven to be a very effective method for increasing the barrier properties. For the design of the fabrics, realistic modelling with its pore morphology is necessary. The adjustable process parameters of the weaving machine and the yarn parameters as well as the fabric construction determine significantly the shape, size and distribution of the meso pores and micro pores (i. e. intra-yarn pores) and thus the flow behaviour of the fabrics [1,2].

Throughout the entire service life, membrane forces act on the barrier textiles. Combined loads (tension, bending and shear) lead to a deformation of the pore structure in the fabric, which can result in a change in the fabric permeability and thus an increased passage potential for contaminated particles and liquids [3]. First orienting studies on the changes of the fabric morphology induced by mechanical loading were conducted [3-5]. Complex mechanical loadings were determined on surgical textiles during operations, which are e. g. between 0.9 N/cm² and 1.2 N/cm² for elbows [6-8]. The experimental investigation and virtual simulation of these complex loading conditions based on real service loads and their effect on pore morphology is not known. Their influence on the barrier fabrics treated with particles and their durability are also still unexplored.

A numerical macro- or meso-scale approach is inadequate for an exact replication of the microporous morphology of fabrics. A micro-scale approach, in which the individual filaments are taken into account, considers not only the meso pores but also the micro pores. Methods that model the multifilament character of the yarns have proven notable accuracy in predicting the geometry of 2D and 3D woven fabrics [9-17]. Each yarn is discretized into multiple 1D element chains. Each of these element chains approximates the behaviour of
a bundle of fibres and contact models are used to capture the interactions between the element chains. This allows for simulating the interactions and low cohesion between the individual fibres.

The objectives of this study are, firstly, to understand the interrelationships of weaving parameters and fabric properties and, secondly, to model the porous fabrics under loading conditions.

II. MATERIALS AND METHODS

A. Materials

Woven fabrics made of polyester multifilament yarns were manufactured using different yarns, weave parameters and machine processing parameters (machine speed, shed closing time) on a Dornier PTS4/S EasyLeno® double rapier weaving machine (Lindauer Dornier GmbH, Germany). Fabrics were loaded with biaxial tensile stresses and porosity was measured in unloaded and loaded conditions. Artificial Neural Networks were trained and tested in order to link the weaving and processing parameters with the fabric properties using the experimental data [18].

B. Experimental

Cross-sectional images of the fabrics were taken and provided for the virtual modelling of the fabrics. For this, fabrics were cut out and embedded into epoxy resin in a sample carrier. After 8 hours of hardening time, samples were smoothened and polished with a grinding device (Struers, Germany). Cross-section images were taken with a light microscope Axio Imager M1m (Zeiss, Germany) with a 500 fold magnification. An image can be seen in Fig. 1.

Fig. 1. Microscopic picture of barrier fabric

Two plain woven fabrics with fabric index 0.64 (‘sample 1’) and 0.78 (‘sample 2’) were chosen for experimental tests. Breaking loads of the fabrics were measured with a uniaxial tensile test machine UPM 1445 (Zwick, Germany). Samples were then loaded with biaxial tensile stresses up to 30% and 50% of the breaking forces of the fabrics in a biaxial tensile test machine (Zwick, Germany). Experimental results were then considered as a reference for the virtual loading of developed models.

Mean flow pore sizes and permeability values under biaxial loading were measured according to the method developed in [19] using a special sample holder connected to the conventional porosimetry PSM 165 (Topas, Germany). Software PSMWin enables the recording of permeability values of the porosity tests which were performed under biaxial loading.

C. Numerical

For the second part of the study, numerical models on a unit cell level were developed. The models were generated according to the method provided in [9] using digital elements and the weave parameters determined from real fabrics (Fig. 1 and Fig. 2). Fabrics were then virtually loaded in LS-Dyna (Livermore Software Technology Corporation, USA) using finite element method. Finite element models were transferred into voxel models and imported into software DNSlab (IT for Engineering (tt4e) GmbH, Germany), where they were virtually equipped with particles applying Lattice-Boltzmann method.

Fig. 2. Micro-scale model of plain woven fabric
III. RESULTS AND DISCUSSION

A. Artificial Neural Networks

Neural networks have learned well the underlying interaction between training inputs and output variables. The mean pore size of fabrics was decreased by increasing the weave density (Fig. 3). An opposite trend was observed with weft filament fineness (Fig. 4). Weave process parameters only have a minor influence on pore size. The model findings were in agreement with the experimental results, which suggest that the ANN has simulated well the input-output relationship.

B. Experimental

Fig. 5 shows the force-elongation diagrams of each axis for the woven sample 1 as an example after biaxial tensile loading. It was observed that sample 1 elongates up to ca. 1.1% in the warp direction and up to 1.3% in the weft direction at 50% biaxial loading. This elongation value is up to 0.7% in the warp direction and up to 0.9% in the weft direction at 30% biaxial loading. Sample 2 showed an elongation value up to 0.9% in the warp direction and up to 0.8% in the weft direction at 30% biaxial loading. At 50% of biaxial loading, these values became 1.4% in the warp direction and 1.6% in the weft direction.
Fig. 5. Force-elongation diagrams of woven sample 1 for each axis: a) axis 1 – warp direction, b) axis 2 – weft direction, c) axis 3 – warp direction, d) axis 4 – weft direction

Permeability values were also recorded during porosity measurements under biaxial loading. Fig. 6 illustrates the permeability of woven samples without loading and under 30% and 50% biaxial loading depending on the pressure difference.

Fig. 6. Permeability of woven samples without loading and under 30% and 50% biaxial loading conditions: a) sample 1, b) sample 2

It was observed that permeability tendencies of sample 2 showed reduced permeability values comparing to sample 1. The reason for this is the fabric index; increased fabric indices reduced permeability values [18]. Woven samples under biaxial loading showed increased permeability values compared to samples without loading. Permeability value of sample 1 changes from ca. 22 to 38 l/(m²s) at a pressure difference of 200 Pa depending on the loading. This interval becomes smaller in sample 2 as from ca. 14 to 16 l/(m²s) at a pressure difference of 200 Pa.

C. Numerical

To observe the behaviour of the barrier fabrics under loading conditions on a virtual level, the microscale models were used in a numerical loading simulation according to the introduced uniaxial and biaxial tensile experiments. The detailed fabric models (Fig. 2) are symmetric and periodic boundary conditions were applied to account for the unit-cell deformation character. The loading conditions for the uniaxial and biaxial load cases are in accordance to the conducted experiments. The stiffness behaviour of the single filaments, which are regarded as tension-only threads according to the digital-element approach, was obtained by single filament tensile tests. The results of the periodic deformation under uniaxial and biaxial load can be seen in Fig. 7a and 7b. The result of a virtual shear deformation is shown in Fig. 7c.
The simulation of the particle suspension flow across a woven fabric was conducted with DNSlab, where the unloaded or loaded model was imported from LS-Dyna. For the simulation of the fluid flow, the Navier-Stokes equations are solved numerically by the Lattice-Boltzmann method. The particle transport and deposition can be modeled either by a simplified Euler-Lagrange approach, where the effect of the particles on the fluid flow is neglected, or by highly resolved 4-way CFD-DEM coupling, which includes all fluid-particle and particle-structure interactions but demands more computational power. Figs. 8 - 11 show a particle deposition simulation with the Euler-Lagrange approach, where a cross-flow velocity of 0.1 m/s, a pressure difference of 300 Pa and a particle size of 15 µm were applied.
IV. CONCLUSIONS

The findings suggest that it is plausible to predict fabric properties of PES multifilament fabrics using yarn, fabric construction and processing parameters with excellent accuracy by means of ANN. Numerical studies show that pore size of barrier fabrics can be tailored using the developed models. Important parameters are the fabric construction parameters and the particle size.

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REFERENCES

[1] H. Gooijer, M.M.C.G. Warmoeskerken, J. Groot Wassink, “Flow resistance of textile materials”, Textile Research Journal, vol. 73 no. 6, pp. 480–484, 2003.
[2] R. B. Turan, A. Okur, “Investigation of pore parameters of woven fabrics by theoretical and image analysis methods”, The Journal of The Textile Institute, vol. 103, no. 8, pp. 875–884, 2012.
[3] K. Pietsch: Untersuchungen zur Reproduzierbarkeit der Struktur-Eigenschaftsrelation von Operationsschutztextilien unter Gebrauchsbedingungen. PhD Thesis, Technische Universität Dresden, 2010.
[4] P. D. Dubrovskii, M. Brezočnik, “The usage of genetic methods for prediction of fabric porosity”, In: Genetic programming - New approaches and successful applications, S. Ventura, Ed., Rijeka: InTech, 2012, pp. 171–198.
[5] M. Havlová, “Air permeability and constructional parameters of woven fabrics”, FIBRES & TEXTILES in Eastern Europe, vol. 21, no. 2, pp. 84–89, 2013.
[6] K. W. Altman, J. H. McElhaney, J. A. Moylan, K. T Fitzpatrick, “Transmural surgical gown pressure measurements in the operating theater”, American Journal of Infection Control, vol. 19, no. 5, pp. 147–155, 1991.
[7] J. W. Smith, R. L. Nichols, “Barrier efficiency of surgical gowns: Are we really protected from our patients’ pathogens?”, Archives of Surgery, vol. 126, no. 6, pp. 756–763, 1991.
[8] J. W. Smith, W. A. Tate, S. Yazdani, R. Y. Garcia, A. C. Muzik, R. L. Nichols, “Determination of surgeon-generated gown pressures during various surgical procedures in the operating room”, American Journal of Infection Control, vol. 23, no. 4, pp. 237–246, 1995.
[9] O. Döbrich, T. Gereke, C. Cherif, “Modelling of textile composite reinforcements on the micro-scale”, Autex Research Journal, vol. 14, no. 1, pp. 28–33, 2014.
[10] O. Döbrich, T. Gereke, C. Cherif, “Modeling the mechanical properties of textile-reinforced composites with a near micro-scale approach”, Composite Structures, vol. 135, pp. 1–7, 2016.
[11] G. Zhou, X. Sun, Y. Wang, “Multi-chain digital element analysis in textile mechanics”, Composites Science and Technology, vol. 64, no. 2, pp. 239–244, 2004.
[12] D. Durville, “Simulation of the mechanical behaviour of woven fabrics at the scale of fibers”, *International Journal of Material Forming*, vol. 3 (SUPPL. 2), pp. 1241–1251, 2010.

[13] Y. Mahadik, S. R. Hallett, “Finite element modelling of tow geometry in 3D woven fabrics”, *Composites Part A: Applied Science and Manufacturing*, vol. 41, no. 9, pp. 1192–1200, 2010.

[14] B. El Said, S. Green, S. R. Hallett, “Kinematic modelling of 3D woven fabric deformation for structural scale features”, *Composites Part A: Applied Science and Manufacturing*, vol. 57, pp. 95–107, 2014.

[15] N. Naouar, E. Vidal-Sallé, J. Schneider, E. Maire, P. Boisse, “Meso-scale FE analyses of textile composite reinforcement deformation based on X-ray computed tomography”, *Composite Structures*, vol. 116, no. 1, pp. 165–176, 2014.

[16] L. Daelemans, J. Fues, S. Allaoui, G. Hivet, M. Dietrick, “Finite element simulation of the woven geometry and mechanical behaviour of a 3D woven dry fabric under tensile and shear loading using the digital element method”, *Composites Science and Technology*, vol. 137, pp. 177–187, 2016.

[17] S. Joglekar, M. Pankow, “Modeling of 3D woven composites using the digital element approach for accurate prediction of kinking under compressive loads”, *Composite Structures*, vol. 160, pp. 547–559, 2017.

[18] S. A. Malik, R. T. Kocaman, H. K. Kaynak, T. Gereke, D. Aibibu, O. Babaarslan, C. Cherif, “Analysis and prediction of air permeability of woven barrier fabrics with respect to loom dynamics, fabric construction and material parameters”, *Fibers and Polymers*, vol. 18, pp. 2005-2017, 2017.

[19] R. T. Kocaman, S. A. Malik, D. Aibibu, C. Cherif, “In situ determination of pore sizes of high density polyester woven fabrics under biaxial loading”, *IOP Conference series: Materials Science and Engineering*, vol. 254, pp. 142011, 2017.