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Examination and modeling of porosity in polyester twisted fibrous structures
PhD dissertation

THESES

1 I drew the following conclusions with the help of the microscopic examinations carried out on the yarn cross sections of the examined carded and ring spun polyester yarn samples (of the same linear density and made of the same material but composed of fibers of different shapes of cross sections):

1.1 I developed a method that uses yarn cross section data determined with image analysis and I also supported it by a mathematical algorithm. This process can be applied to describe the fiber packing and pore sizes of yarns as a function of yarn radius.

1.2 I calculated the packing density of the examined yarn core and in average it turned out to be around 0.6 (60%).

1.3 I found that in the examined cases the average pore sizes obtained with the quadratic and hexagonal lattice models are in the range of 5.87 – 9.55 µm and 4.15 – 6.75 µm, respectively.

2 I came to the following conclusions concerning mercury porosimetry measurements carried out on carded and ring spun polyester yarn samples (of the same linear density and made of the same material but composed of fibers of different shapes of cross sections):

2.1 I verified that the simplified form of the pore size distribution based on the Poisson type short fiber layers and the cylindrical layer yarn model can be applied to describe the size distribution of intrayarn (within a yarn) and interyarn (in a yarn bundle) pores (if $r > 0$).

$$F(r) = 1 - \exp\left(-K\left[\left(\frac{r}{\eta} \right)^2 \pi + 2\frac{r}{\eta}\bar{l} \right] \right)$$

where K denotes the two dimensional fiber centroid density, r is the pore radius, $\bar{l}$ is the average fiber length and η is the modified pore correction factor.

2.2 I found that the differential pore size distribution obtained for the bundles of the examined yarns can be divided into three parts, and these three peaks can be assigned to the following pore types: pores within an elementary fiber, pores within a yarn (= among elementary fibers) and pores among yarns (within a yarn bundle). I obtained 25.1 – 41.4 µm for the dominant pores among yarns , 5 – 6.3 µm for pores within yarns and 0.11 – 0.77 µm for pores within elementary fibers.

2.3 I proved that the measured pore distribution can be approximated with a weighted sum of three, $V_\infty \frac{r^4}{\overline{r^3}} f(r)$ type (where V_∞ denotes the sum of the pore volumes), $f(r) = F'(r)$ density functions (where F' is the derivative of distribution function F). I determined that the pores within yarns are the dominant ones with a weight factor of 57 – 70% after I decomposed the measured pore distribution mixture. I found that weighting was also influenced by the different cross section shapes: in case of hollow fibers the weight of pores within fibers is the highest (α_3=0.3), while this value is only around 0.1 in the other cases.

3 I drew the following conclusions based on my capillary liquid uptake measurements with device Krüss K12 on the examined carded and ring spun polyester yarn samples (of the same linear density and made of the same material but composed of fibers of different shapes of cross sections):

3.1 I developed an explicit solution (exact in $t \rightarrow 0$ and $t \rightarrow \infty$ asymptotic cases) for the Lukas-Washburn equation and this formula approximates the measured liquid uptake curves well (the error of approximation is below 2.5% throughout the whole range):

$$m(t) = m_\infty \left[1 - e^{-\left(\frac{2a}{m_\infty} t \right)^{\frac{1}{\sqrt{2}}}} \right]^{\frac{1}{\sqrt{2}}}$$

where $m(t)$ denotes the mass of absorbed water as a function of time, m_∞ the mass of absorbed water in equilibrium (in case $t \rightarrow \infty$), and a is defined with the following equation: $a = \frac{r^2 \rho g}{8 \eta_D}$ (where r is the average capillary radius, g gravitational acceleration, γ is the surface tension of the liquid, ρ is the density of liquid, η_D is the dynamic viscosity of liquid and θ is the contact angle between the liquid and the examined material).

3.2 I developed a multicapillary model that consists of random radius capillaries to describe the pore chains among the fibers and yarns of a yarn bundle. I used this model to estimate the average capillary radius ($\bar{r}$), and I obtained the following formula:

$$\bar{r} \approx \left[\frac{K_m}{m_\infty} \frac{2\sqrt{2\eta_D \gamma \cos\theta}}{\rho g\left(1+\frac{15}{8}V_r^2\right)} \right]^{2/3}$$

where K_m is the steepness of the liquid absorption curve as a function of $\sqrt{t}$, m_∞ is the equilibrium weight of the absorbed liquid (in case $t \to \infty$), V_r is the relative variation coefficient of the capillary radii.

I found that the average capillary radius falls into the range of 3.05 – 17.13 μm in the pore chains of the examined polyester yarn bundle in the measurements carried with device Krüss K12.

4 I proved the following statements with the help of the twist until breakage method and the diameter measurement with a CCD camera on carded and ring spun polyester yarn samples (made of the same material).

4.1 I developed a measurement method involving a CCD camera to be able to measure the diameters of the yarn sheath and yarn body in different twist states. I revealed that the examined 19 polyester spun yarns can be divided into 3, differently packed parts: the dense yarn core, the middle dense yarn body and the loose sheath. I found that as a consequence of the added twist, the yarn becomes denser and the whole yarn body behaves like the core before breakage. I determined the packing density of the whole yarn body: 33% and the initial packing density of the core is 67%. I found that in unloaded cases the average equivalent pore diameter in the yarn body is 12.81 μm, while that in the core is 6.23 μm and it is reduced (by 4%) to 5.97 μm due to the added twists.

4.2 I proved that the relation of the added twist (x) and the diameter (D_c) can be described with the following formula:

$$D_C \approx D_{C0}\, e^{-a_e x},$$

where D_{C0} is the initial yarn core diameter (132.12 μm – 301.56 μm), while a_e falls into the range of 0.0016 and 0.0063 during the measurements.

4.3 I concluded that the values of the breakage twists measured at 50 mm clamping length fluctuate around the mean values obtained in the measurements of 500 mm clamping length (relative square error is 6.7%).

5 I verified the following statements after a comparative analysis of the different measurement results and taking the data obtained from the direct measurement I carried out as reference points:

5.1 I found that the usual mercury porosimetry is the least sensitive to the difference in the shape of the fiber cross sections. Using the decomposition procedure I derived, I revealed that smaller values are obtained for the average pore diameter within the yarn than with the added twist method for the yarn body but the difference is less than 28% (i.e. 1.5 μm). At the same time these values are close to those determined with the hexagonal lattice model, as a direct method.

5.2 I proved that the measurement curve obtained from water absorption proceeds the closest to the ones obtained from direct measurements, hence the application of $V_r=1$ is also verified.

5.3 I revealed that the yarn core diameters obtained with the added twist method provide the smallest values than in any other examined case.

5.4 Fiber packing density of the unloaded yarn core came about 60% by the direct method and 67% by the added twist method, that is they provided similar values, the difference is not significant.