Micro-CT based permeability calculations with a limited size of the model volume

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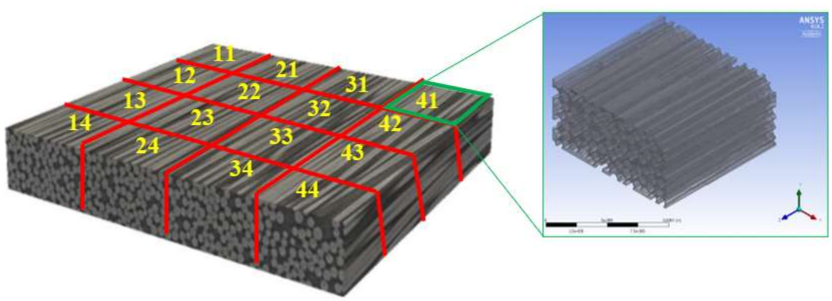
Sub-volumes for permeability calculations



$$K_{i,j,k} = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix}_{i,j,k}$$

Averaging

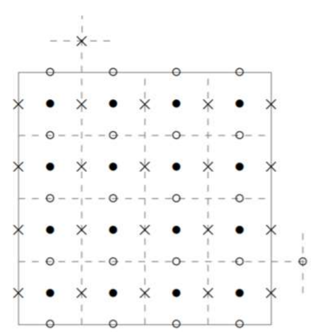
$$K_X = A_{j,k}\left(H_i(k_{X\ i,j,k}) \right)$$

$$K_Y = A_{i,k}\left(H_j(k_{Y\ i,j,k}) \right).$$

$$K_Z = A_{i,j}\left(H_k(k_{Z\ i,j,k}) \right)$$

Darcy solution

$$K_1 = \frac{\langle v_{inlet} \rangle L \mu}{dP}$$



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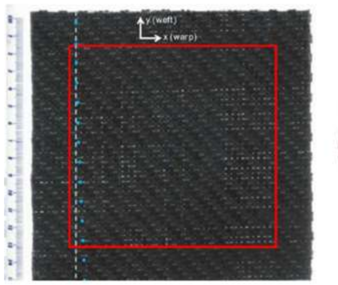
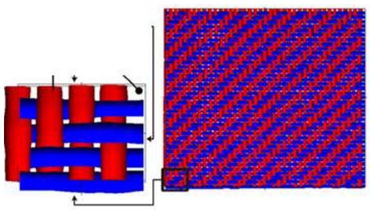
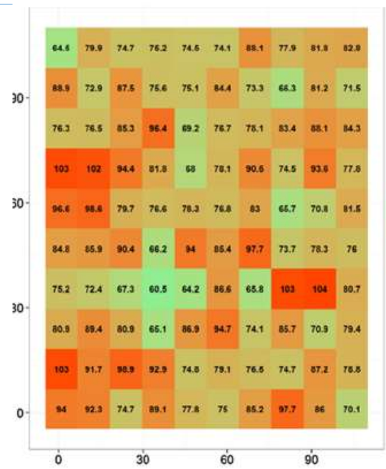
Example of similar use: variability



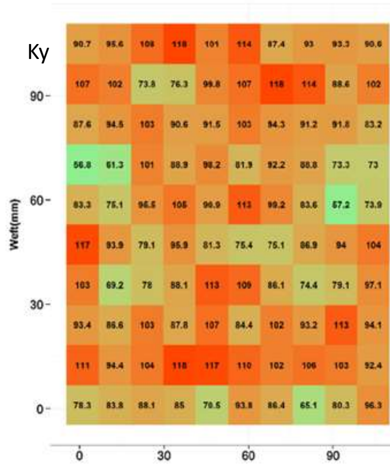


Random unit cells comprise a virtual sheet of fabric.

Kx



Ky



Spatial distribution of permeability of random unit cells. Homogenisation done using A- and H-averaging

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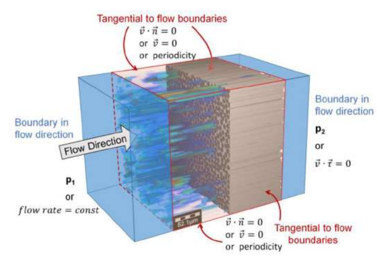
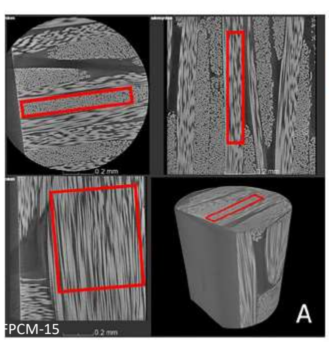
Virtual permeability benchmark

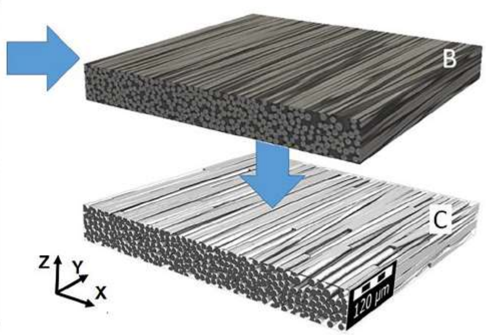
Composites: Part A 167 (2023) 107397

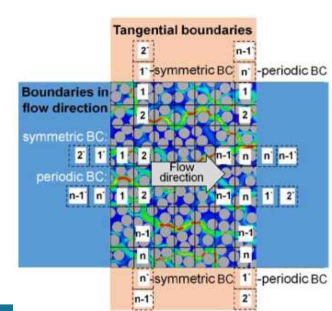
Benchmark exercise on image-based permeability determination of engineering textiles: Microscale predictions

E. Syerko [a,*], T. Schmidt [b], D. May [b], C. Binetruy [a,c], S.G. Advani [c,a], S. Lomov [d,e], L. Silva [a], S. Abaimov [e], N. Aissa [a], I. Akhatov [e], M. Ali [f], N. Asiaban [g], G. Broggi [h], J. Bruchon [i], B. Caglar [h], H. Digonnet [a], J. Dittmann [j], S. Drapier [i], A. Endruweit [l], A. Guilloux [m], R. Kandinskii [d], A. Leygue [a], B. Mahato [e], P. Martínez-Lera [n], M. Matveev [l], V. Michaud [h], P. Middendorf [j], N. Moulin [i], L. Orgéas [k], C.H. Park [o], S. Rief [p], M. Rouhi [q,r], I. Sergeichev [e], M. Shakoor [o], O. Shishkina [n], Y. Swolfs [d], M. Tahani [g], R. Umer [f], K. Vanclooster [n], R. Vorobyev [e]









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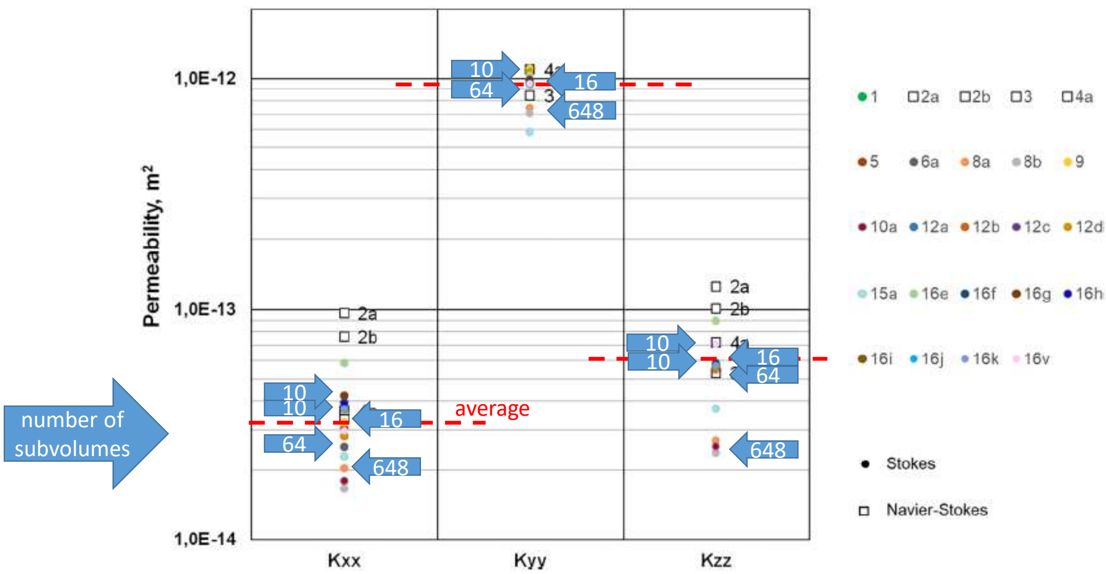
Sub-volumes solutions vs all benchmark results



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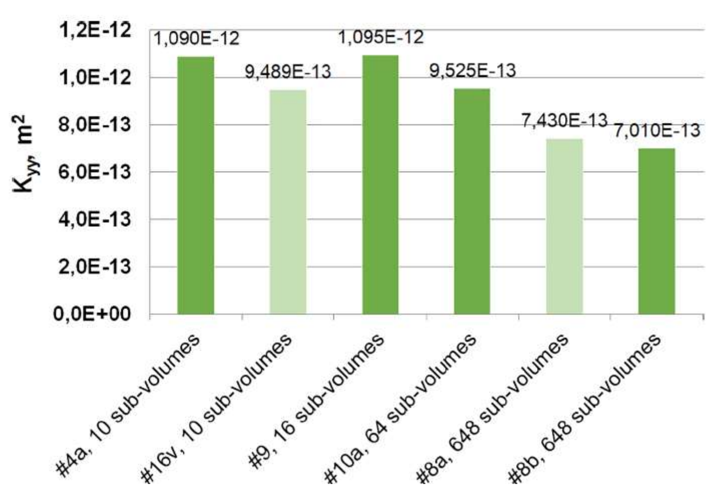
General trend (permeability along fibres)



permeability decreases with increase of number of sub-volumes

CV:
all results, including part of the full domain, outliers excluded
20%
simulation of entire domain, with or without subvolumes
16%
only simulations of the full domain
15%

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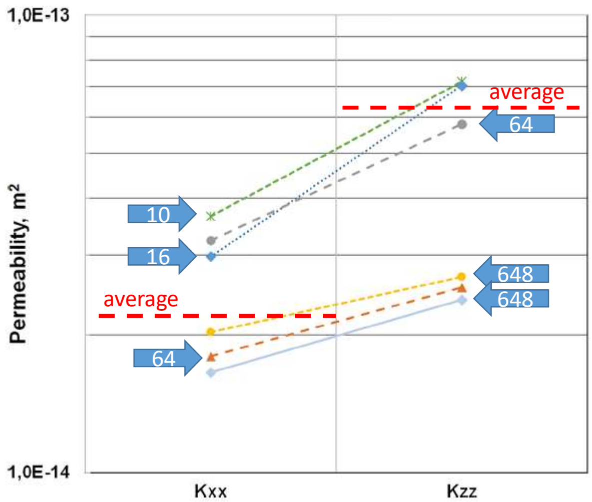
General trend (transverse permeability)

Composite materials group



A similar decreasing trend as for axial permeability is observed for the transverse permeability with increasing number of subdivisions of the domain.

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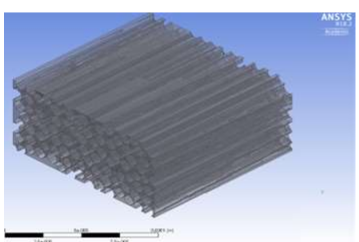
16 sub-volumes (Skoltech)

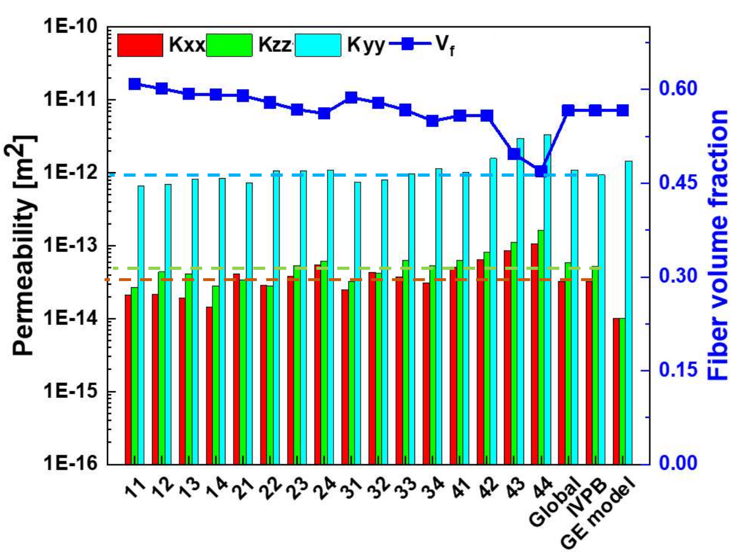
Composite materials group



ANSYS CFX
240*240*124

$$K = -\frac{\dot{m}\mu L}{\rho A \Delta P}$$

Intel® Xeon® CPU E5-2630B4 @2.20GHz
calculation time 1h / volume (16 h total)



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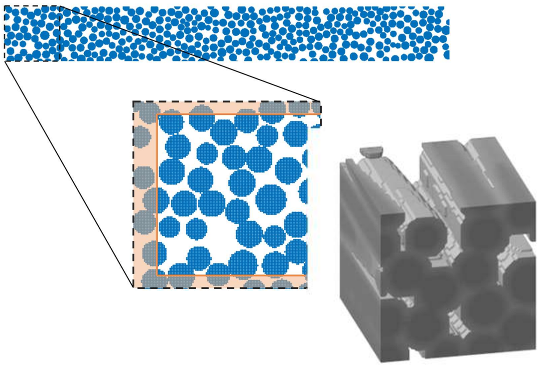
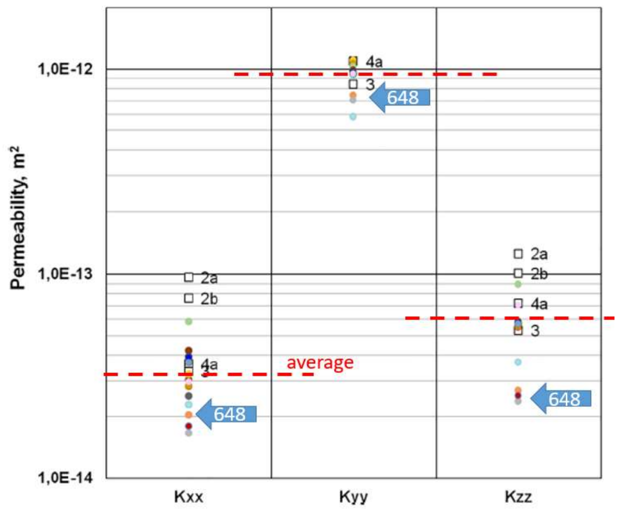
648 sub-volumes (KU Leuven)

Composite materials group



FlowTex (KU Leuven): finite difference Stokes solver
strong model size limitation (~ 800,000 voxels)
54*54*54 voxels
18*18*2 = 648 sub-volumes

Intel® Core™ i5-8350U CPU @ 1.70GHz
time for a sub-volume ~ 30 s, total per volume 5.5 h.



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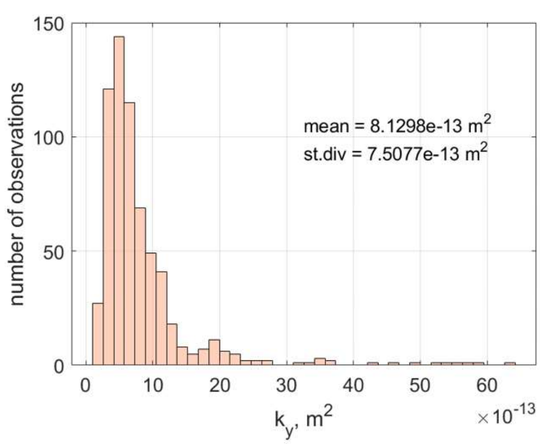
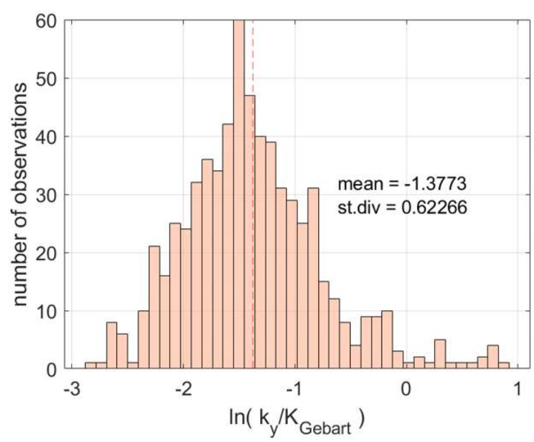
Distribution of sub-volume permeability (along fibres)

Composite materials group





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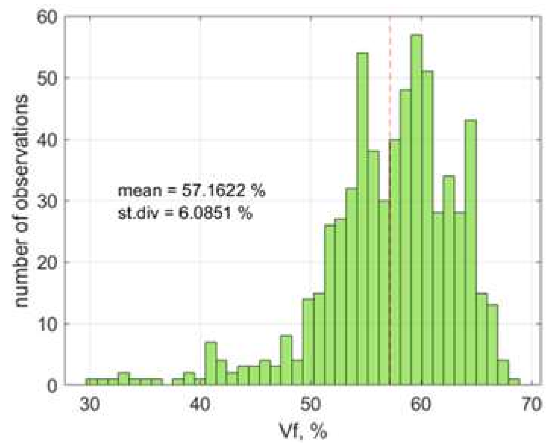
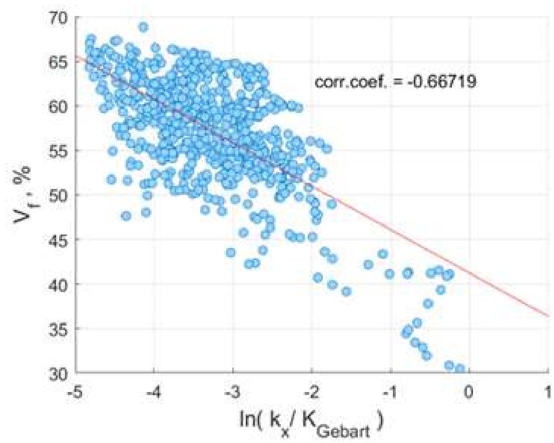
Correlation with fibre volume fraction – 1

Composite materials group





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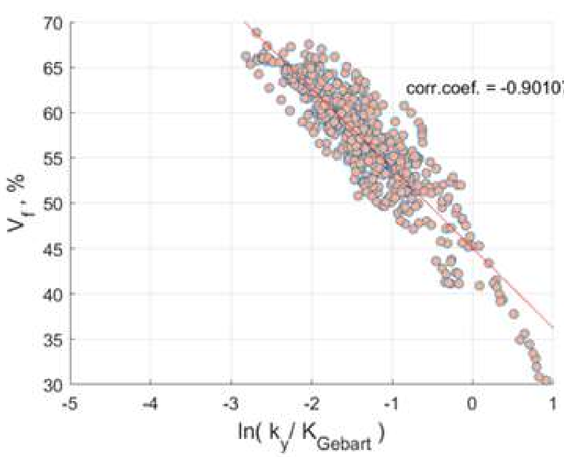
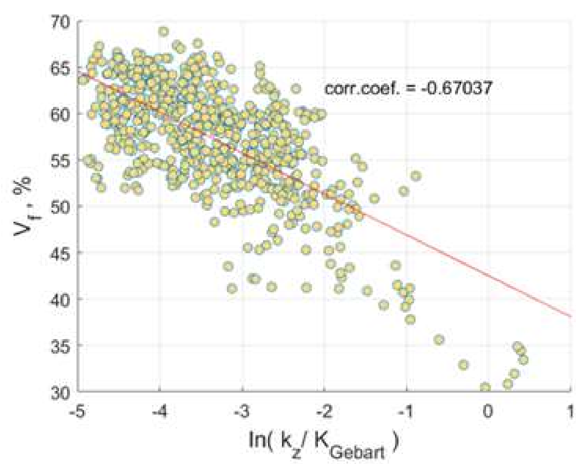
Correlation with fibre volume fraction – 2

Composite materials group





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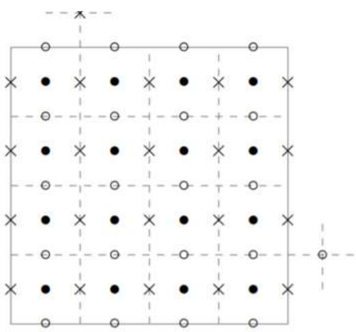
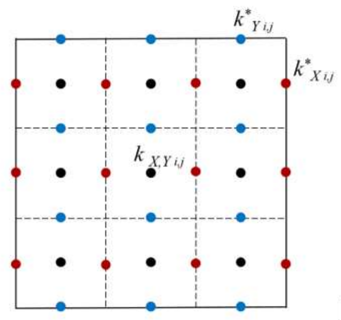
Darcy averaging – 1





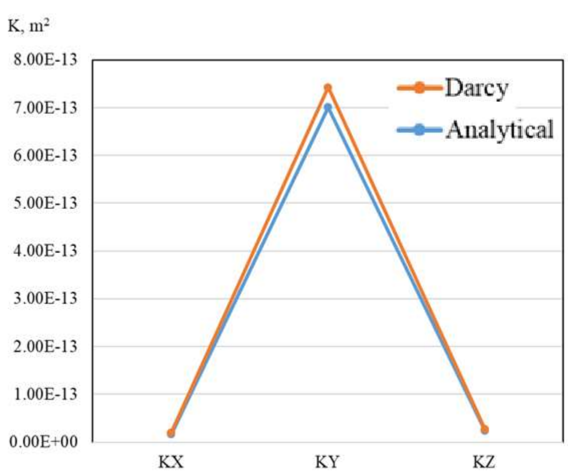
$k_{X,Y\ i,j}$ – where the permeability values are located,
$k^*_{X\ i,j}$, $k^*_{Y\ i,j}$ – where we need them to be located

Staggered grid location of unknowns for the MAC scheme. The discrete pressure p is defined at cell centers (•). The discrete velocity u and v are defined at vertical edges centers (×) and horizontal edges centers (○), respectively.

[Wang, Chen *J Sci Comp* 2013]

interpolation to get *k*'s in the staggered nodes

Darcy averaging – 2



	Analytical	Darcy	average benchmark
KX	1.7×10^{-14}	2.0×10^{-14}	3.2×10^{-14}
KY	7.0×10^{-13}	7.4×10^{-13}	9.4×10^{-13}
KZ	2.4×10^{-14}	2.7×10^{-14}	5.2×10^{-14}

	Analytical	Darcy	average benchmark
KY/KX	42	36	29
KY/KZ	29	28	18

Conclusions

BENCHMARK PAPER

- **The higher the number of cropped sub-volumes**, i.e. the higher the number of artificial boundaries introduced into the domain, **the lower the predicted permeability is**.
- Calculating the permeability of the entire sample by **this renormalization approach can be a good solution if the number of sub-volumes is not too high** and in cases where the computational resources are limited in terms of memory or time.
- The minimal number of sub-volumes (10) used in the benchmark study resulted in **only 15% deviation** from the cluster average value.

DARCY HOMOGENISATION

- Darcy homogenisation of subdomains is **very close** to the analytical "arithmetic – harmonic mean"
- Analytical averaging cannot represent the skew terms of **K** tensor; **Darcy can**.

Acknowledgements

In KU Leuven the work leading to this publication has been funded by the SBO project "MOR4MDesign", which fits in the MacroModelMat (M3) research program, coordinated by Siemens (Siemens Digital Industries Software, Belgium) and funded by SIM (Strategic Initiative Materials in Flanders) and VLAIO (Flemish government agency Flanders Innovation & Entrepreneurship).

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