THREE-DIMENSIONAL MESO-SCALE MAPPING OF THE FLUID CONTENT IN PARTIALLY IMPREGNATED REINFORCEMENT TEXTILES USING HIGH-RESOLUTION MAGNETIC RESONANCE IMAGING

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ABSTRACT: In this study, high-resolution MRI techniques are employed for 3D mapping of the distribution of engine oil as a test fluid in fully or partially impregnated reinforcement fabrics (glass or carbon fibre, different architectures, fibre volume fractions up to 48 %). This allows identification of dry spots and distinction of fabric zones with full or partial saturation and complements macro-scale observations acquired by more conventional means. Changes in impregnation can be tracked by repeated scanning at different times in intermittent injection. Effects related to the difference in magnetic properties of fibre material and test fluid and the fibre volume fraction may reduce the image quality and need to be considered in interpretation of the results.

KEYWORDS: Fabrics/textiles, Liquid Composite Moulding (LCM), Porosity/voids, Magnetic Resonance Imaging (MRI)

INTRODUCTION

The fabric impregnation behaviour in Liquid Composite Moulding (LCM) processes is critical for the quality of the finished composite component and for optimisation of the manufacturing process. Since visualisation of fabric impregnation at the meso- and micro-scale is generally not possible using conventional means, identification of the resin distribution is in practice based on micrographic analysis of moulded and cured specimens. For non-invasive mapping of the fluid distribution in fabric specimens and identification of dry spot formation, Magnetic Resonance Imaging (MRI) is potentially suitable. In short, MRI is based on measurement of the signal emitted from an energetically excited ensemble of atomic nuclei (in most cases protons in a fluid), magnetised in an external magnetic field. This allows spatial images of the concentration of nuclei (or fluid concentration) to be generated. MRI techniques have proved particularly useful in diagnostic medical imaging, but have also been employed successfully to study flow in industrial processing technologies [1]. Regarding

investigation of the static or dynamic fluid distribution in fully or partially wetted textile fabrics, several applications are documented in the literature, e.g. by Leisen and Beckham [2].

Here, high-resolution MRI is used for 3D mapping of the fluid content in fully or partially impregnated reinforcement fabrics (glass or carbon fibre, different architectures, realistic fibre volume fractions). This allows the typical impregnation behaviour of specific fabrics to be characterised and complements macro-scale observations acquired by more conventional means.

MATERIALS AND METHODS

Imaging experiments were carried out in a clinical whole-body scanner with a magnetic field strength of 3 T (Philips Achieva). A head coil designed for brain imaging was used as receiver for the signal emitted from the test fluid. An impregnation tool with a cavity large enough to accommodate fabric specimens with multiple unit cells along the weft and warp direction (140 mm×90 mm×5 mm) was made from Perspex with Nylon fittings. For mapping of the fluid distribution in different examples of glass fibre and carbon fibre reinforcements impregnated with engine oil as a test fluid, FLASH-based (fast low-angle shot [3]) imaging sequences were employed with some success. At an isotropic resolution of 0.5 mm, scan times for acquisition of 3D image data were in the order of several minutes (dependent on the specific protocol). While this resolution does not allow distinction of filaments and inter-filament voids (~μm), it is sufficient for visualisation of the impregnation of textile structures at the unit cell level (meso-scale) and estimation of the fluid content in fibre bundles (micro-scale). Limitations to this method are caused by dispersion of the test fluid in microscopic inter-filament voids, where it may be bound to the filament surfaces, and differences in magnetic properties between test fluid and fibres. Both affect the emitted signal and, in some cases, may make its detection difficult.

RESULTS

For illustration of the potential and limitations of the employed method, a few examples for results obtained so far are presented here:

Figure 1 shows a transverse slice (view along vertical axis) through the impregnation tool containing a random discontinuous carbon fibre preform (high strength fibres STS40, filament count c_f = 24K, chop length 58 mm, average superficial density $S_0 \approx$ 1.4 kg/m^2, 3 layers, fibre volume fraction $V_f \approx$ 48 %) and a 0°/90° stitch-bonded non-crimp E-glass fibre fabric (linear fibre bundle density 1200 tex in warp direction, 600 tex in weft direction, $S_0 \approx$ 800 g/m^2, 6 layers, $V_f \approx$ 37 %) with the weft direction oriented along the tool axis, both impregnated with the test fluid. The greyscales indicate the local fluid concentration (bright: high; dark: low). Completely dark voxels suggest occurrence of dry spots. Comparison of the slices with a corresponding photograph of the specimen indicates plausibility of the acquired image data. Features of the fibrous structures visualised in the photograph can be clearly identified. In the glass fibre fabric, fibre bundles and inter-bundle voids can be distinguished, and the (almost) regular structure can be identified. In the carbon fibre preform, the random distribution of the fibre bundles results in irregular variations in the fluid concentration.

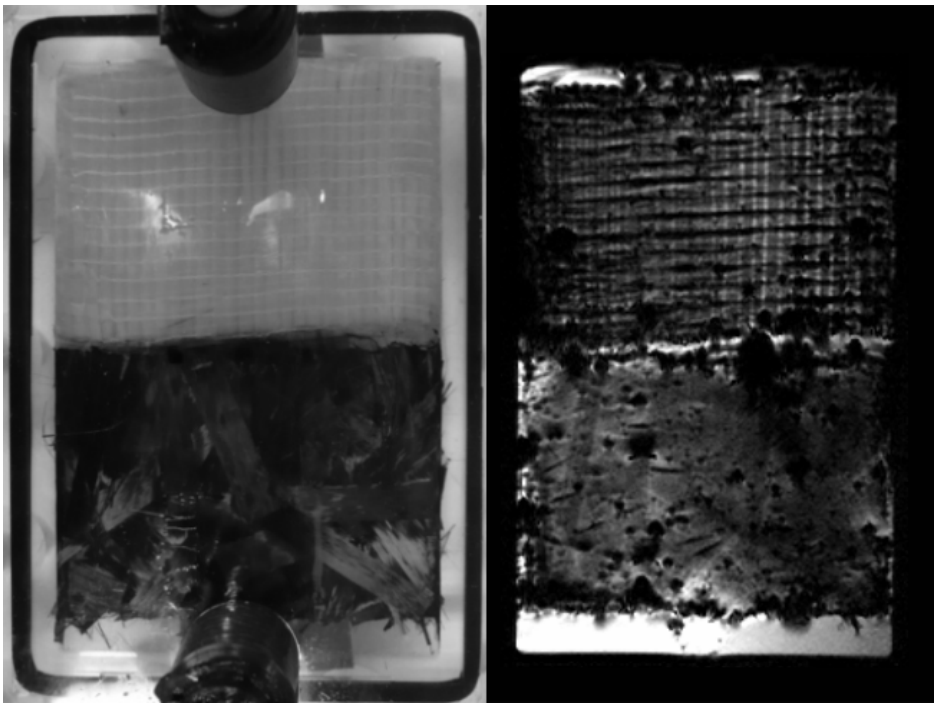

Fig. 1 Injection tool with fully impregnated random discontinuous carbon fibre preform and 0°/90° stitch-bonded E-glass fibre fabric; left: photograph; right: transverse slice

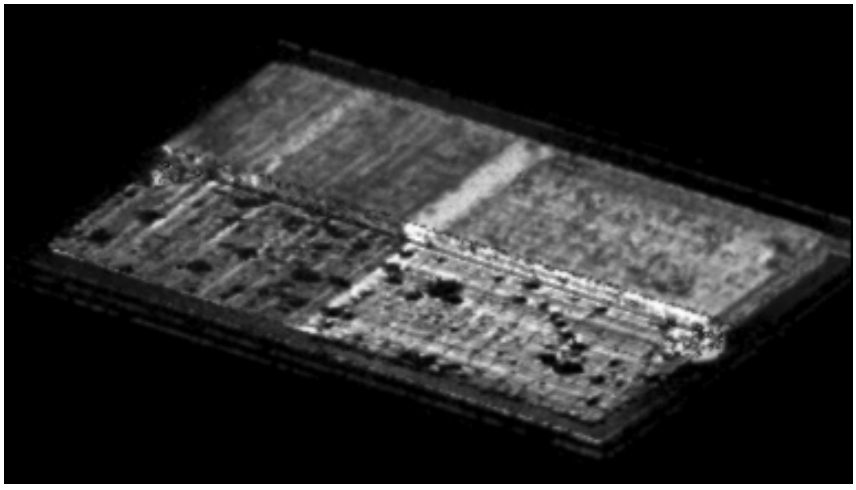

Fig. 2 Injection tool with fully impregnated uni-directional carbon fibre fabric, oriented parallel (right) and perpendicular (left) to tool axis

Figure 2 shows a 3D rendering (with a cut-out along the tool axis) of volumetric image data of an impregnated uni-directional carbon fibre fabric (high strength fibres STS40, c_f = 24K, S_0 = 450 g/m^2, 9 layers, $V_f \approx$ 46 %), oriented parallel and perpendicular to the tool axis. Fibre bundles and inter-bundle voids can be distinguished, and the fibre orientations can be identified. The impregnation of the fabric in this specific specimen is particularly poor. Multiple micro- and meso-scale dry spots, which were not visible to the naked eye (viewing though the transparent Perspex tool), are clearly visible in the

image data. This demonstrates the potential of MRI to help identify defect formation in a laminate. The reason for occurrence of the defects is that no gap (as in Fig. 1, bottom) was left in the cavity. Thus, impregnating flow is affected by the through-thickness permeability of fibre bundles, which is typically significantly smaller than the in-plane permeability. Achieving a good degree of impregnation is more difficult than for pure in-plane flow. In the figure, the influence of anisotropic magnetic properties of the carbon fibres on the imaging process is reflected in the lower signal-to-noise ratio, where the fibres are oriented perpendicular to the tool axis (and the magnetic field direction).

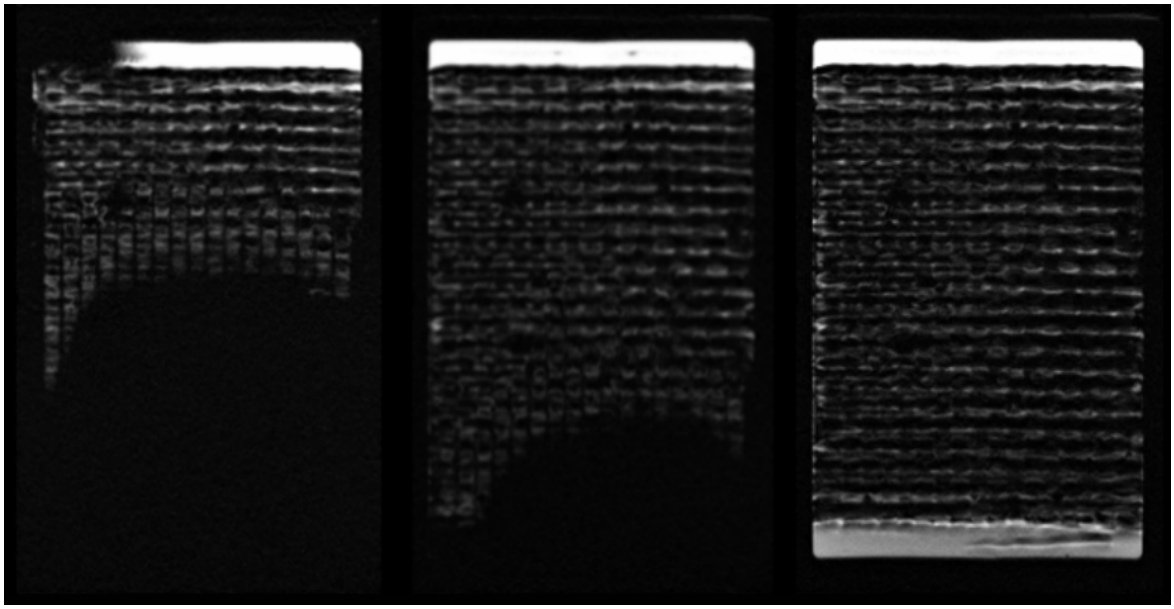

Fig. 3 Transverse slices from plain weave E-glass fibre fabric, taken at different injection times

For a plain weave E-glass fibre fabric (linear yarn density 2400 tex in both fabric directions, $S_0 \approx 912$ g/m^2, 6 layers, $V_f \approx 42$ %) with the warp direction oriented along the tool axis, Fig. 3 shows the same slice from scans taken at different times during vacuum-driven impregnation. Since the time for complete impregnation of the fabric (2 min to 3 min) is shorter than the scan time (approx. 7 min), tracking of the flow front propagation during continuous injection was not possible, and a strategy of intermittent injection was adopted. A drawback is that capillary flow during the scan time (when the pressure gradient is switched off) may affect the fluid distribution and thus result in misleading data. However, based on visual observation in additional experiments for validation of the procedure, this effect was found to be negligible for most fabrics and fibre volume fractions studied here. Qualitative evaluation of the image data indicates that the macro-scale flow front position is identical in all slices of the scans, i.e. there is no significant through-thickness variation in flow front propagation. There is some effect of racetracking along the left edge (in the figure) of the specimen. On close inspection, zones of full and partial (near flow front) saturation can be identified in the fabric. This is a finding of potentially high impact and will be analysed in more detail to allow correct interpretation. A general observation is that the scans of this specimen are affected by signal loss in the weft yarns, which needs to be considered to avoid false positives in detection of dry spots.

CONCLUSIONS

For examples of carbon and glass fibre fabrics at fibre volume fractions of up to 48 %, fully or partially impregnated with engine oil as a test fluid, mapping of the fluid content employing MRI techniques allowed identification of dry spots and distinction of fabric zones with full or partial saturation. While the scan time for acquisition of high-resolution 3D image data is too long for dynamic imaging of impregnation processes, images at different injection times can be acquired in intermittent injection to allow tracking of changes in impregnation state. Effects related to the difference in magnetic properties of fibre material and test fluid and the fibre volume fraction may reduce the image quality and thus, in some cases, mitigate the usefulness of the results. Alternative imaging protocols, which are influenced to a lesser extent by these effects, are currently tested.

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REFERENCES

1. M.D. Mantle and A.J. Sederman, “Dynamic MRI in chemical process and reaction engineering”, *Progress in Nuclear Magnetic Resonance Spectroscopy*, Vol. 43, No. 1-2, pp. 3-60 (2003).

2. J. Leisen and H.W. Beckham, “Quantitative Magnetic Resonance Imaging of Fluid Distribution and Movement in Textiles”, *Textile Research Journal*, Vol. 71, No. 12, pp. 1033-1045 (2001).

3. A. Haase, J. Frahm, D. Mathaei, W. Haenicke and K.D. Merboldt, “FLASH imaging. Rapid imaging using low flip-angle pulses”, *Journal of Magnetic Resonance*, Vol. 67, No. 2, pp. 256–266 (1986).