3D CHARACTERISATION OF THE MICROSTRUCTURAL EVOLUTION OF SMC DURING COMPRESSION MOULDING

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Introduction

Sheet Moulding Compounds (SMC) are pre-impregnated thermoset materials that are widely used in the automotive and aircraft industries. High performance SMC with high fibre contents or lightweight polymer matrices are currently being developed to produce parts with enhanced mechanical performance. During compression moulding, SMC are subjected to complex flow mechanisms and drastic evolution of their microstructures that are at the origin of several defects affecting their end-use properties. SMC can be subjected to in-plane tensile loading, leading to undesirable porosities and tear during the preliminary stamping phase. During the subsequent compression phase, complex mechanisms for the pore evolution as well as fibre orientation, deformation or disaggregation can also occur [1]. During this phase, plug flow is often the preferential flow mechanism of SMC [2, 3]. However, in-plane extension of SMC can also occur inside the vertical zones of the mould. In that case, SMC are subjected to in-plane extension, *i.e.*, in stress states close to tensile stress states. To improve models for the predictions of the rheology and the evolution of the microstructure of SMC during moulding, it is necessary to study the aforementioned phenomena using observation techniques such as X-ray microtomography 3D images.

Materials and methods

Two uncured industrial SMC formulations (MCR-Plastic Omnium, France) with low and high pore and fibre contents were studied. The first SMC formulation consisted of a polyester-based matrix reinforced with 29 wt% of glass fibre bundles. The second SMC formulation consisted of a vinylester-based matrix reinforced with 50 wt% of glass fibre bundles. X-ray microtomography 3D images were used to study both the evolution of the microstructure (porosity, pore size, pore anisotropy, fibre orientation) of these two SMC formulations under compression and tensile loading conditions. Details of these experiments are given in refs. [4, 5]. Simple lubricated *in situ* compression tests were performed using a specially designed rheometer mounted on a synchrotron X-ray microtomograph (ID19 beamline, ESRF, Grenoble). A tension–compression machine was used to conduct the tensile tests. A DIC setup was used to obtain 2D maps of the local Hencky strain tensor on the sample surfaces. Some samples were scanned during interrupted *ex situ* tensile tests using a laboratory tomograph (3SR Lab, Grenoble).

Results

For high fibre content SMC, the porosity was elevated (≈ 25-30%). The pores were mainly open and connected. At moderate fibre content, the porosity was moderate (≈ 5%), and the pores were mainly closed and transversely isotropic. During compression, for high fibre content SMC, the pores reduced in size and the gases (air, styrene) that they contained could flow through the network of open pores and be expelled from the samples. For moderate fibre content SMC, closed pores decreased in size and sometimes coalesced (Figure 1). The pore shrinkage was associated with the dissolution of pore gases into the SMC paste. Besides, the closed pores were expelled from the centre of samples to the sample external surfaces, following tortuous trajectories with faster displacements than the bulk of SMC. This phenomenon was attributed to the squeezing effect exerted by the complex fibre bundle network on the SMC paste and the closed pores. During tensile experiments, both SMC exhibited positive volume variation. The pore content increased (Figure 2) and the pores took slender shapes parallel to the tensile

direction. Fibre bundles also aligned along the stretching direction, following kinematics well described by the Jeffery's equation, even if SMC were compressible. For initial high pore contents, the porosity rapidly increased, yielding sample breakage: large initial pore content did not allow bundle-bundle bonds to be rejuvenated upon stretching, leading to rapid damage and breakage of SMC. Regardless of SMC formulation, flocs or aggregates of fibre bundles led to early strain localisation bands in stretched samples, thus limiting drastically their ductility.

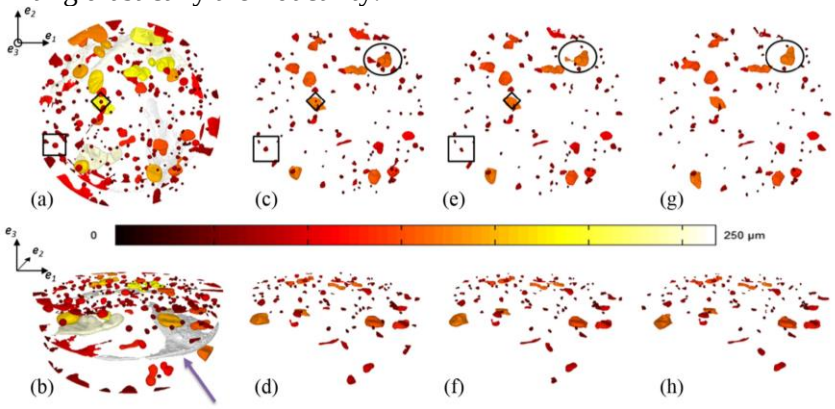

Figure 1: *3D views showing the evolution of pores at various compressive strains ε_{33}: (a-b) 0, (c-d) 0.11, (e-f) 0.14, (g-h) 0.17 for a lowfibre content SMC. The equivalent diameter of the pores is colour-coded. The arrow points to an open pore between two SMC layers. The open diamond, square and circle put in the upper views illustrate pores that either disappeared or were expelled from the sample or coalesced, respectively. Adapted from Ferré Sentis et al. [4].*

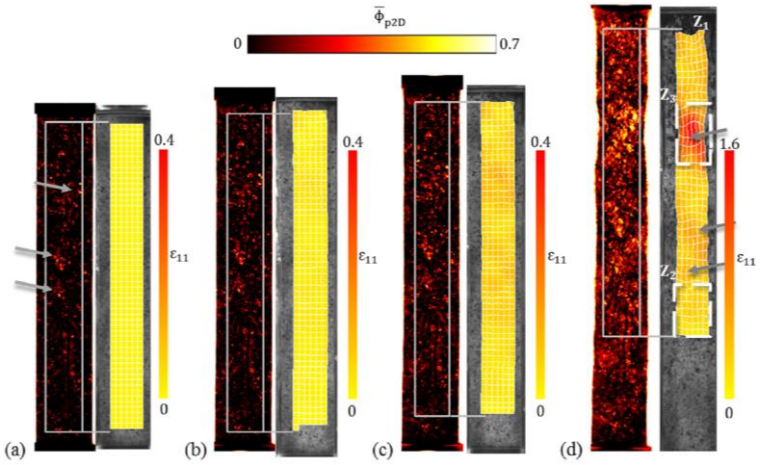

Figure 2: *2D maps obtained from the analysis of 3D X-ray ex situ microtomography images showing the porosity averaged along the thickness $\bar{\phi}_{p2D}$ of a low fibre content SMC subjected to a tensile test. Corresponding 2D strain fields ε_{11} at various average tensile strains $\bar{\varepsilon}_{11}$: (a) 0, (b) 0.006, (c) 0.09, (d) 0.28. Adapted from Ferré Sentis et al. [5].*

Conclusion

This study shows X-ray 3D images obtained from *in situ* or *ex situ* mechanical experiments can unveil at the fibre/pore scale the deformation mechanisms of SMC during compression moulding.

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