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QUANTIFYING THE THERMOMECHANICAL BEHAVIOR OF HETEROGENEOUS POLYURETHANE FOAMS USING 4D MICROSTRUCTURAL ANALYSIS

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Summary: μCT with in-situ mechanical and thermal loading was combined with digital volume correlation to examine the 4D deformation fields in three distinct polyurethane foam systems. The results agreed with conventional thermo-mechanical analyses. In addition they allowed correlating spatial differences in thermal and mechanical response to particular features in their heterogeneous microstructure, providing insights for further improving foam functionality.

1. INTRODUCTION

Polyurethane (PU) chemistry is widely applied to produce a broad range of foam applications that includes seating, bedding, vibration damping, sound insulation and thermal insulation. Each of these applications requires specific mechanical and thermal properties as function of temperature that can be achieved by tuning the polymer properties and the cellular microstructure of the foam. The role of the microstructure can be analysed by tracking its evolution as function of time, load or temperature. This is of particular interest when the application includes gradients or multiple foam types to fulfil its function or when it is naturally heterogeneous due to different length scales of porosity. To demonstrate our usage of 4D μCT acquisition and analysis in the field of polymer foam, as well as to address our technical challenges, in this work three case studies are presented in which digital volume correlation (DVC) was employed to gain insight in three distinct foam systems: the thermal expansion of an insulation foam, the stiffness gradients in a soft-touch flexible foam and the mechanical heterogeneity of a thermoplastic bead foam.

2. MATERIALS AND METHODS

From three PU applications, an in-house made sample was prepared for μCT scanning with a Bruker Skyscan 1272. Sample R, a rigid polyisocyanurate (PIR) insulation foam, was scanned at a resolution of 2.6 μm at 30°C, 55°C and 80°C using Bruker's thermal heating stage. Sample S was a soft touch flexible PU foam with a 2 mm thick functional soft foam layer on top of a stiffer core foam. To avoid scanning artefacts from the clamps and to double the volume of interest, two specimens of 6x7x6 mm^3 were stacked vertically with the soft layers facing each other. This stack was compressed in Bruker's 44N in-situ materials testing stage at a speed of 0.24 mm/min in 20 steps of 0.3 mm (4%). Initially and after each compression step, a μCT scan was made at 22°C at a resolution of 5.5 μm. Sample T, a thermoplastic polyurethane (TPU) bead foam, had fine cells (30-90 μm) inside the foam beads and larger interstitial voids (0.2-0.8 mm) between foam beads. A specimen of 8x9x7 mm^3 was compressed similarly in 20 steps of 0.2 mm (2.86%) and scanned at 22°C at a resolution of 5.2 μm.

3D reconstructions and basic analyses were made using Bruker's NRecon and CTAn software. Digital volume correlations and strain-microstructure comparisons were performed using an in-house tool based on Elastix [1].

3. RESULTS

Fig. 1(a) shows for sample R the thermal volume expansion J = det(**F**) with **F** the deformation gradient resulting

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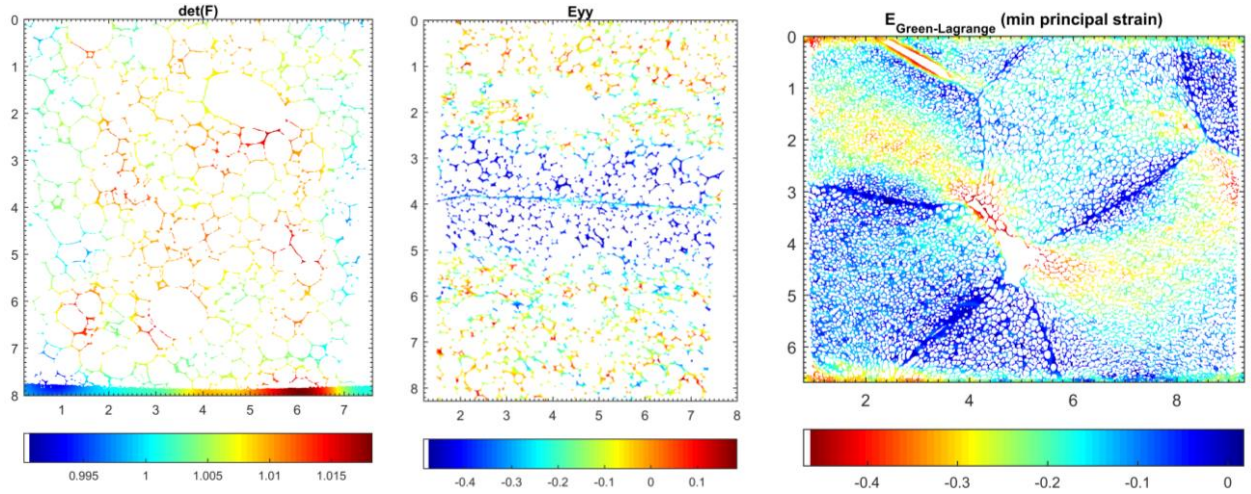
from heating up from 30°C to 80°C. Strains were lower near the edges, as these cells are open and thus lack the cell gas pressure build-up that (partially) drives thermal expansion. Strains in the core of the sample agreed with expansion coefficients measured using TMA (66-75x10^{-6} K^{-1}). The strain field was nevertheless relatively inhomogeneous, which is likely explained by the cell size polydispersity of the foam structure.

Fig. 1(b) shows for sample S the compressive strain in the vertical direction at 40% technical compressive strain. The soft layer deformed on average by 42% and the core foam by 9.5%. The apparent stiffness ratio of 4.4 could not be explained by the microstructure alone, as e.g. density differences were less than 15%. The discrepancy was mainly due to a lower polymer stiffness of the soft layer. Remarkable were also the large deformations around large cells at the soft-core interface and the stiff behaviour of the skin membrane.

Fig. 1(c) shows for sample T the minimal principal strain field at 20% technical compressive strain. In this material, strain correlated strongly with the local density of the foam within the beads and to some extent with local anisotropy. High strains were also seen near voids between foam beads and near weld-line defects, as these may lead to stress concentrations [2].



(a) (b) (c)

Figure 1: Panels (a), (b) and (c) show central, vertical cross-sections through the strain fields for respectively sample R, S and T. Strain fields are overlaid with the foam microstructure and shown in the (undeformed) reference axis system with units in mm. The applied loads were (a) heat-up from 30°C to 80°C, (b) 40% compressive strain and (c) 20% compressive strain.

4. DISCUSSION AND CONCLUSION

In conclusion, for three distinct foam systems the combination of in-situ scanning with DVC enabled analysing the deformations due to thermal and mechanical loads. Comparison between the strain responses and underlying microstructural features facilitated identifying the governing structural features and enabled correlating structural parameters (e.g. density) to material properties. This is useful for the development of micro-mechanical models.

A (here for space reasons omitted) discussion of sample representativity, scan and load cell limitations, and DVC parameters versus strain field resolution addresses further challenges and proposes improvements to in-situ test equipment and digital volume correlation software with the aim on achieving industrial strength research tools.

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