Experiments, hyperelastic modeling and finite element simulation of 3D-printed thermoplastic polyurethane

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A combined experimental and numerical investigation on the mechanical behavior of 3D-printed thermoplastic polyurethane is presented. In particular, the behavior under monotonic loading until rupture is considered. For this purpose, tensile test specimens are analyzed, which were produced by conventional injection molding and by an extrusion-based additive manufacturing process. The additively manufactured test specimens have notched surfaces that influence the failure behavior due to stress and strain concentrations. For the numerical analysis, a finite element modeling approach is presented with which the experiments are simulated. It is shown that the tensile curves can be simulated using a hyperelastic material model and that first indicators can be found that enable a prediction of failure under monotonic tensile loading.

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1 Material, sample preparation and mechanical testing

The investigated material is the thermoplastic polyurethane Desmopan 487 provided by Covestro Deutschland AG. It is provided in granular form and can be processed in extrusion-based manufacturing processes. The material shows typical phenomena of rubber-like materials [3]. The manufacturing processes used are conventional injection molding, with which flat plates were produced¹, and the Screw Extrusion Additive Manufacturing process (SEAM), in which thin, prismatic structures were produced by a layer-wise printing procedure², cf. [2, 3]. For mechanical testing, tensile test specimens were die-cut from the produced structures. For the case of 3D-printed structures, different cutting angles with respect to the printing direction were regarded. This resulted in tensile test specimens with grooves that are aligned in different angles to the loading direction (see Fig. 1). The specimens were mechanically tested in uniaxial tension with different time courses and amplitudes, as described in [3]. Therein, it was found that the same basic material behavior is obtained for the investigated manufacturing and sample preparation methods. Moreover, typical phenomena of additively manufactured structures, such as anisotropy or layer adhesion issues, could not be observed.

The main impact of differently aligned notches could be seen in monotonic loading until rupture, and more specifically in the maximum strain at break \( \varepsilon \). While maximum global strains for IM-samples and 0°-samples are in the same order, significantly lower values are obtained for 45°- and 90°-samples (see subsequent data, Fig. 2 b), and [3]).

\[
\begin{align*}
\varepsilon_{IM} & = (662 \pm 2.5) \% \\
\varepsilon_0 & = (624 \pm 13) \% \\
\varepsilon_{45} & = (477 \pm 7.9) \% \\
\varepsilon_{90} & = (419 \pm 49) \%
\end{align*}
\]  

(1)

2 Hyperelastic material model

The material behavior is simulated by a hyperelastic approach based on the principal invariants, which are given by \( I_1(X) = \text{tr}(X) \), \( I_2(X) = \text{tr}[\text{cof}(X)] \), \( I_3(X) = \text{det}(X) \), with \( [X] \) being a Cartesian coefficient matrix of the second order tensor \( X \). Based on the deformation gradient \( F \), the volume ratio is defined by \( J = I_3(F) \), the right Cauchy-Green tensor calculates to \( C = F^T \cdot F \), and its isochoric part is \( \tilde{C} = J^{-2/3} C \). Using the abbreviations \( I_1 = I_1(\tilde{C}) \) and \( I_2 = I_2(\tilde{C}) \), the specific hyperelastic approach is defined by the free energy density \( \Psi \), from which stress tensors, like the first Piola-Kirchhoff stress tensor \( T \), can be directly calculated:

\[
\Psi = \sum_{i=1}^{3} \left( c_{0i}(I_1 - 3)^i + c_{0i}(I_2 - 3)^i \right) + \frac{K}{2} \left( J - 1 \right)^2, \quad T = 2 \frac{\partial \Psi}{\partial \tilde{C}} \cdot F^T.
\]  

(2)

Therein, \( K \) is the bulk modulus, which is set to \( K = 3000 \) MPa for the investigated material. Moreover, \( c_{0i}, c_{0i} (i = 1, 2, 3) \) are further material parameters, which have been identified by adapting a material point simulation of monotonic, uniaxial

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DOI: 10.1002/pamm.202100229
tension to the corresponding experimental data of injection molded samples. The identified values are: $c_{10} = 0.0 \text{ MPa}$, $c_{20} = -0.140 \text{ MPa}$, $c_{30} = 0.000514 \text{ MPa}$, $c_{01} = 3.84 \text{ MPa}$, $c_{02} = -0.272 \text{ MPa}$, and $c_{03} = 0.262 \text{ MPa}$.

3 Finite element modeling and simulation

In order to evaluate the deformation behavior of 3D-printed specimens, parametric finite element (FE) models of the different test specimens have been built up using the Python scripting functionality in Abaqus. It is assumed that the stress and strain states in the measuring zone of the tensile test specimens are periodic along the loading direction. Thus, only representative sectors of the gage-sections are used, see Fig. 2 (a, top). The geometry of the models is based on microscopy images and detailed measurements of local geometric quantities (like groove height, width, etc.). Loading is applied via periodic boundary conditions on the top- and bottom surfaces of the models based on the approach described in [1]. Moreover, the hyperelastic material model of Section 2 is employed.

The FE models are evaluated for the case of uniaxial tension with monotonic increasing global strain at a constant strain rate. The maximum value of global strain is taken from the experiments and set to $\hat{\varepsilon}_{\text{sim}} = 700\%$. The stress fields of the different models is exemplified in Fig. 2 (a, bottom) for the case of a global strain value of $\varepsilon = 100\%$. Thereby, the Tresca equivalent stress is depicted. It reveals that stress concentrations occur in the notches of the $45^\circ$- and $90^\circ$-models, while stress and strain states in the $0^\circ$-model are homogeneous. Additionally, the simulated force vs. global strain curves resulting from the different models are overlaid with the corresponding experimentally obtained data in Fig. 2 (b). It reveals a very good agreement of the macroscopic behavior between simulations and experiments.

In a final step, the FE simulations are used to evaluate local stress measures and to correlate them with the deformation states, where rupture occurred in the experiments. More specifically, the simulation of the $0^\circ$-sample is used to extract the Tresca equivalent stress $\sigma_T$ at the global engineering strain level $\hat{\varepsilon}_{0}$, cf. Eq. (1). In this state, the FE simulation predicts a value $\sigma_{T,0} \approx 367 \text{ MPa}$, which is constant over the entire FE model (homogeneous deformation). Due to stress concentrations in the notches of the $45^\circ$- and $90^\circ$-samples, the Tresca equivalent stress values are already obtained at lower global strain values. More precisely, $\sigma_{T,0}$ is already obtained at $\hat{\varepsilon}_{\text{sim}45} = 477\%$ for the $45^\circ$-model and at $\hat{\varepsilon}_{\text{sim}90} = 453\%$ for the $90^\circ$-model. Compared to the experimental findings, both values are already in the same magnitude and order and, thus, support the assumption that the rupture behavior in essence can be attributed to the notch effect.

4 Conclusion

A combined experimental and numerical study on the deformation and rupture behavior of additively manufactured thermoplastic polyurethane has been presented. Based on preliminary work for the mechanical analysis of the tensile test samples (cf. [3]), an FE modeling strategy was introduced with which the measured results can be reproduced and, in addition, local stress and strain data are accessible. The simulation strategy will be used in future work for further investigations of the deformation and rupture behavior of additively manufactured materials.

Acknowledgements Open access funding enabled and organized by Projekt DEAL.

References

[1] N. Goldberg, H. Donner, and J. Ihlemann (2015), Technische Mechanik 35(2):80–99.
[2] M. Kausch (2019), Ultra-fast 3D printing using standard granules, Infosheet, www.iwu.fraunhofer.de
[3] E. Oelsch, R. Landgraf, L. Jankowsky, M. Kausch, S. Hoyer, W.-G. Drossel, and J. Ihlemann (2021), J Rubber Res 24(2):249–256.