Optimization and use of high-throughput micromechanical testing design for 3D-printed polymers

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Abstract

Modern materials behave differently on a micro-scale level than in bulk applications. Therefore, with ever-present miniaturization, the materials' testing on a micron-level is gaining importance. 3D printing with a sub-micron precision, such as direct laser writing by two-photon lithography, allows for relatively fast manufacturing of miniaturized specimens for micromechanical testing. In combination with precise loading by a nanoindenter tip, high-throughput micromechanical testing is enabled. Presented research shows design process of miniaturized cantilever and push-to-pull device specimens for fracture mechanics testing, aided finite element modelling, together with high-throughput testing of polymeric materials with varied printing parameters and loading conditions. Such in-situ and ex-situ experimental setup allows for systematic fracture mechanics testing on the small scale for common materials used in small-scale 3D printing.

1. Introduction

Numerous modern applications on the micron scale level use cured polymers as either structural or functional materials, gaining even more attention with increasing use of 3D printing by direct laser writing. While use of this family of materials may seem straightforward and easy-to-use with 3D printing technology, their highly varying mechanical properties (including influences of e.g. visco-elasticity, temperature, loading rates during testing, or printing parameters) pose a large obstacle in the way to fully understand their behavior and allow for reliable design of micro-devices. For a systematic evaluation of not only elastic material properties, but also yield strength and fracture criteria, a reliable high-throughput method is needed.

Direct laser writing by two-photon lithography is a suitable method for 3D printing of micro-scale testing devices. However, the method's limitations influence the micromechanical specimens' design. Standard cantilever geometry for fracture properties measurement or different push-to-pull setups include large overhanging features, which easily cause floating layers printing artifacts, resulting in unusable specimens. While construction of supporting structures during the printing would minimize such artifacts, it would lead to large increase in manufacturing times, as they must be removed afterwards in an additionall workstep, thus, rendering the method not usable for high-throughput testing. Therefore, in this work, slight changes in the geometry of the printed specimens are used to minimize the occurrence of printing artifacts while limiting the effects on the micromechanical testing itself. For this purpose, a standard notched bending cantilever beam is used as well as special notched push-to-pull devices, whereby the optimization and testing of the influence of geometrical changes was done with use of numerical finite element modelling.

Additionally, the high-throughput fracture toughness measurements results of hundreds of specimens per setup will be presented to show real usability of this method for systematic studies of modern polymeric materials.

2. Results

To prevent the floating layers artifact from happening during the printing process, the cantilever beam and push-to-pull device geometries (as shown in Fig. 1 a and b respectively) were enhanced by the addition of a small taper (see Fig. 1 c and d). The introduction of this taper shortened the overhang of initially printed layers during the bottom-up printing strategy, therefore, the susceptibility of subsequent layers to float was minimized.

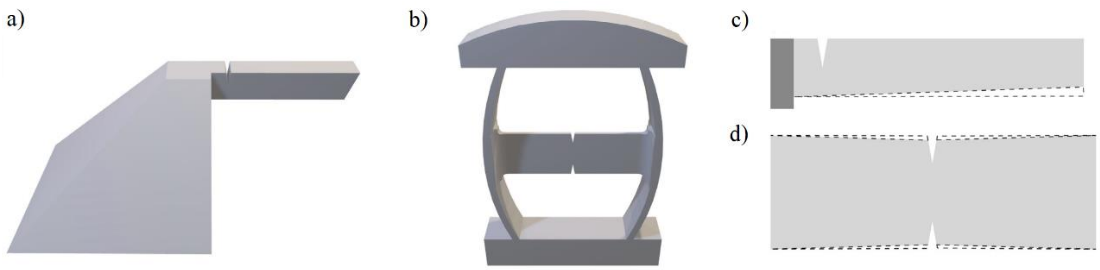

Fig. 1 – scheme of geometries of a) notched cantilever beam and b) push-to-pull device with c) one-sided taper on the cantilever beam and d) two-sided taper on the push-to-pull device to preserve symmetry

The specimens' geometries were parametrized and transferred into the finite element code (Abaqus) to obtain the quantification of taper influence on the overall stress-strain fields within the specimens.

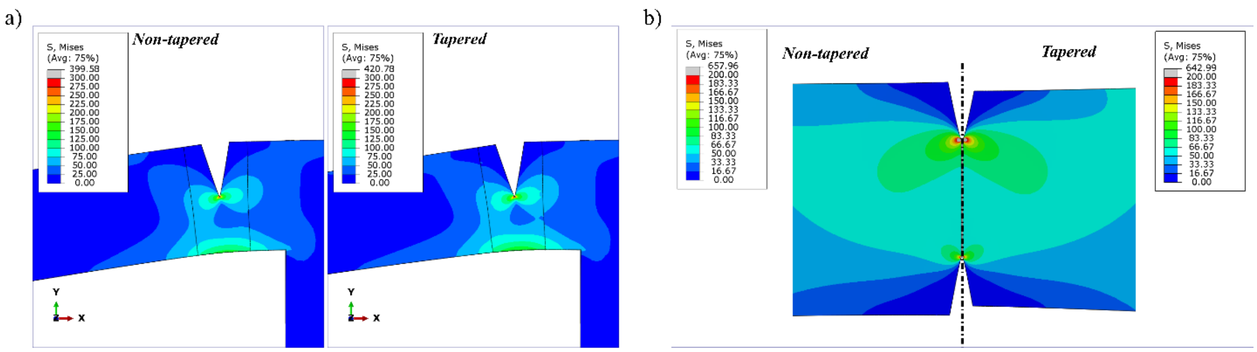

Fig. 2 – comparison of equivalent (von-Mises) stresses in non-tapered and tapered a) cantilever beam and b) push-to-pull device (detailed view on the notched area)

The introduction of 2° inclination during 3D printing, resulting in 4.4º and 3.5º tapers (after curing of the polymer) for cantilever beam and push-to-pull device, respectively, showed negligible impact on overall stress fields within the specimen. For direct comparison of equivalent (von-Mises) stresses under the same loading level, see Fig. 2. The numerical simulations show that the introduction of taper did not change the stress contours shape, it only affected the maximal stress values. Such a change does not influence the measurement, since the difference is accounted for in the overall measured stiffness of the specimens. However, simulations revealed a parasitic appearance of bending in the push-to-pull device due to the differences in the stiffnesses of top and bottom part of the whole specimen. The minimization of such bending as well as slight shifts in loading position for the present push-to-pull device will be presented together with experimental measurements.

3. Conclusions

The synnergetical use of experimental measurements and numerical simulations led to optimization of high-throughput micromechanical testing of fracture toughness specimens prepared by direct laser writing. The introduction of taper on the cantilever and push-to-pull specimens has neglectable impact on the mechanical experiment, however, the numerical simulations revealed small bending deformation of the central section of the push-to-pull device. Additionally, the whole concept of the high-throughput testing method was proved on large sets of specimens using nanoindentation for automated loading and un-loading of presented specimens, leading to reliable and fast method for determining the polymers fracture criteria.

Acknowledgements

Financial support by Montanuniversität Leoben, the EuropeanResearch Council for the ERC project TOUGHIT (project number 771146) and Austrian Science Fund FWF through ESPRIT project (project number ESP 41-N) is gratefully acknowledged.