INVESTIGATION OF THE CRACK DEFLECTION/PENETRATION PROBLEM IN EXTRUSION-BASED ADDITIVELY MANUFACTRED POLYMERIC MATERIALS

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Abstract

Components produced via polymeric additive manufacturing (AM), especially extrusion based methods, possess many weld lines between strands and layers. Thus, the failure of these structures is often dominated either by crack deflection between or crack penetration through individual strands. Two methods to predict the failure mode are those of Cook and Gordan, and of He and Hutchinson. In this work, the applicability of both approaches has been tested on four different polymeric materials. It was observed that the two criteria are quite limited in predicting the correct failure mode. Not only printing temperature also the formation of contact area, the diffusion between the individual strands as well as the resulting morphology of the material were found to play a key role for predicting the crack deflection/penetration problem.

1. Introduction

The use of AM components is becoming increasingly widespread in a number of areas such as e.g. medical, automotive or aerospace, where the end user has to be assured of function and durability. One of the most frequently used method for polymeric thermoplasts is fused filament fabrication (FFF), also known as material extrusion-based AM, where single filament strands are deposited in a layer-by-layer manner. Inevitably, this way of processing leads to a large number of either strong or weak weld lines, depending on the processing parameter and the used material. A crack which already impinges on an interface, can either grow into the interface (crack deflection) or penetrate through the subsequent layer (crack penetration). Two methods to tackle this problem are the approaches of Cook and Gordan (1964, strength based) [1], as well as of He and Hutchinson (1989, energy based) [2]. Cook and Gordan concluded, that the crack deflection/penetration transition occurs when the strength of the bulk material prior to the crack is five times the strength of the interface. He and Hutchinson observed that the transition between the two phenomena occurs when the toughness of the material in front of the crack is four times higher than that of the interface. To the authors' best knowledge, these rather simple approaches have not yet been investigated for AM structures.

2. Experimental

For the strength-based approach, thin plates, and subsequently tensile specimens, were cut out of a printed cube (see Figure 1). The samples were manufactured both in printing and perpendicular direction to determine the strength of the bulk material and the interface, respecitvely. For the energy-based approach single-edge-notched bending (SENB) specimens with dimensions 10 x 10 x 45 mm^3 were manufactured. The fracture toughness was determined following the DIN EN ISO 13586 standard [3]. Samples taken in printing direction were used for the

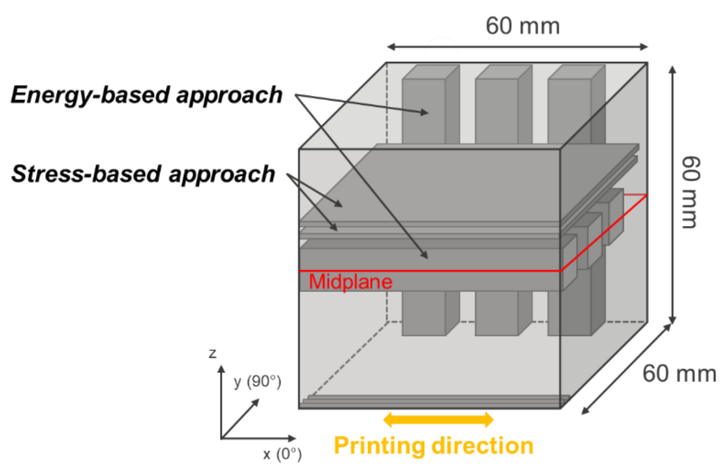

Fig.1 – Printed cube showing how the samples were prepared for the Stress- and Energy-based approach.

determination of the bulk fracture toughness as well as for the validation of both concepts. Samples taken perpendicular to the printing direction were used to determine the interface fracture toughness. A total of four different materials, a glycol modified poly(ethylene terephthalate) (PETG), a polylactide acid (PLA), a poly(methyl methacrylate) (PMMA) and a stiffer PMMA, further referred to as PMMA-s, were chosen for the investigation.

3. Results

The results show that crack deflection occurred only in PETG. Crack penetration in contrast was found for all other materials. The energy-based approach correctly predicts crack deflection in PETG, and PLA and partially for PMMA. For PMMA-s, however, no agreement can be observed. The strength-based approach, in comparison, exhibits crack penetration for all materials, which does not match the failure pattern of PETG. At this point it should be noted that the materials PLA and PMMA do not fulfill the requirements of linear-elastic fracture mechanics. Thus, two materials remain which are correctly described by one concept each. Examining the absolute values, it is noticeable that the strength and fracture toughness of the interface increases with increasing printing temperature. This is explainable by the increase of the contact area, consequently decreasing porosity and increasing time for difussion processes. Additionally, the exact morphology caused by the printing process and the presence of multiple interfaces instead of one dominat plays an key role with regard to the crack deflection/penetration problem.

4. Conclusions

Ever higher demands on additive manufactured structures in various areas may require knowledge of the fracture behavior for reliable functioning in application. The two rather simple concepts, based on strength and energy were investigated regarding their suitability to predict wether a crack deflects or penetrates through an interface in additive manufactured parts. In total four different materials were tested. It was observed, that both concepts can partially be used for the prediction, as long as the requirements of the linear-elastic fracture mechanics are fullfield. Moreover it was found that not only the ratio of strength or fracture toughness is decisive, also the way of weld line formation (contact area/porosity, degree of diffusion) and the resulting morphology after processing have a significant influence on how the crack grows.

Acknowledgements

This research was partly carried out as part of the eFAM4Ind project (877409), which is funded by the Austrian Research Promotion Agency (FFG) and the Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology (BMK).

References

[1] Cook, J., and Gordon, J.E. (1964). A mechanism for the control of crack propagation inall-brittle systems. Proc. R. Soc. London, Ser. A282, 508-520

[2] He, M. Y. and Hutchinson, J. W. (1989). Crack deflection at an interface between dissimilarelastic materials. Int. J. Solids Structures, 25, 1053-1067

[3] Plastics - Determination of fracture toughness (GIC and KIC) - Linear elastic fracture mechanics (LEFM) approach