Real and Virtual Fracture Tests on Welding Lines of Injection Molded Short Fiber Reinforced Polymers

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Abstract. The failure behavior of short fiber reinforced injection molded thermoplastic polymer matrix components is of prime practical importance for many demanding engineering applications (e.g. automotive). Based on an existing injection molded specimen, which includes weld line, various fracture specimen configurations were developed and implemented in this study. The fracture behavior of these specimens was modeled by various FE methods, considering the specific behavior of an injection molded weld line in short fiber reinforced polymer composites.

Introduction and Objectives

Short and long fiber reinforced injection molded parts are frequently used in many demanding engineering applications (automotive) and are exposed to complex loading. The proper prediction of the deformation and failure behavior of these materials is of high practical importance for reliable product design. Furthermore, welding line-like structures are frequently observed in injection molded short fiber reinforced polymeric composite parts. In spite of all efforts, the presence of the welding lines in complex injection molded parts cannot completely be avoided. The welding lines are locations where the continuity of the fiber orientation flow is distorted and this high degree of local inhomogeneity may cause a significant reduction of both the global and local stiffness and the strength of such components. Hence, for supporting design efforts towards increasing safety, it is of prime practical importance the characterization of the failure behavior of weld lines.

Using modern injection molding simulation tools, however, the presence and the location of welding lines in injection molded parts can easily be predicted. Moreover, due to the different gathering degree, pressure and temperature of melt fronts, significantly different mechanical behavior of the welding line might be observed. The surrounding area around the welding line reveals a gradient like behavior. Several papers are dealing with the characterization and modeling of the mechanical behavior of weld lines [1-2]

Various fracture experiments on laboratory specimen level can be performed to characterize the fracture behavior of welding lines. Hover, comparing to conventional fracture specimens there are some special problems. In a conventional fracture specimens the crack tip and the entire ligament is in a material volume which is the same as the surrounding material (either homogenous or inhomogeneous), The fracture toughness is expected to be constant over the entire ligament in conventional homogenous fracture specimens (at least up to a certain degree a/W ratio [3]. Due to the injection molding conditions, and the resulting location dependent inhomogeneity and anisotropy, the mechanical properties of the welding line might vary over the length. Hence, a crack growing in a welding line plane is moving into material volume with increasing or decreasing toughness.

In addition to the conventional experimental fracture characterization, novel simulations method have also been developed and used for characterizing the fracture behavior of heterogeneous materials considering varying random fracture properties [4-6].

Experimental

Short glass fiber reinforced polypropylene PP(H)-GF with 30 m% glass fiber content (aspect ratio=30) was used as model material. The fracture behavior of various specimen configurations containing weld lines was investigated in this study. Injection molded specimens with 4 m thickness and sub-components were manufactured. Three types of notched specimens containing welding line were fabricated. While in one specimen type (welding line 4 mm CT loading basic (WL4CTB)) the original shape was kept and a notch in the welding line was machined and sharpened by razor blade, three holes with varying diameter were machined into the second specimen configuration WL4CTA which is also loaded similarly as a conventional CT specimen. In addition a double-torsion specimen configuration (WL4DT) was also fabricated form the original injection molding specimen. The original specimen geometry is shown in Fig. 1.

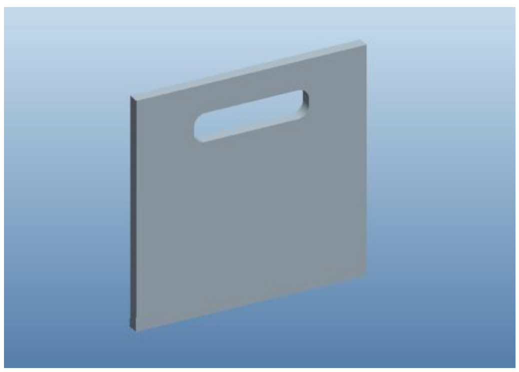

Fig. 1: CAD drawings of the WL4CTspecimen configuration

The WL4CTB and WL4CTA specimens were tested in a similar configuration as conventional compact tensile (CT) specimens. A starting notch was machined into the starting region of the welding line and was subsequently sharpened by pressing a fresh razor blade up to about 2 mm. These specimens were exposed to monotonic tensile loading and force-load-line displacement curves were recorded. In addition the strain at the crack tip and the ligament deformation was measured by the DIC method (Aramis, GOM, Braunschweig, D). Fracture toughness values in terms of K_c were directly measured and in terms of G_c were calculated applying a representative average modulus and Poisson's ratio value for the fiber reinforced composites. These values were determined in previous experiments and are described elsewhere. Furthermore, to determine cohesive zone model parameters an approach described in [7].

While in conventional fracture specimens the crack tip and the entire ligament is in a material volume which is the same as the surrounding material (either homogenous or inhomogeneous), a significantly different situation may be found in the WL4CT specimens. The fracture toughness is expected to be constant over the entire ligament in conventional homogenous fracture specimens (at least up to a certain degree a/W ratio. The crack tip and the ligament are in the welding line plane in the WL4CT specimens, which differs significantly from the surrounding material and reveal a distinct gradient behavior. This behavior is induced by the continuous change of the microstructure (e.g. fiber orientation and density). Due to this fact, the fracture toughness is a function of the crack length in the WL4CTB specimen. To counterbalance this effect, a specimen revealing constant stress intensity factor (SIF) over a wide crack length range would be advantageous.

Hence, based on the proposal of Chudnovsky [8] the basic specimen WL4CTB was modified as it is shown in Fig. 4. The aim of this modification was to keep the stress intensity factor as constant and as long along the crack path as possible. The origins of the change and gradient of the material behavior along the welding line are described in details elsewhere [2]. Furthermore, a specimen geometry which is used in double torsion (DT) test was also fabricated. This specimen reveals also the same feature, that is, constant stress intensity factor in the ligament.

Model Preparation for Simulation

Simulation models for above specimens have been prepared. First a crack model for determining the stress intensity factor (SIF model) was developed. The model considered 2D model plane stress assumption and symmetry boundary conditions were employed along the crack propagation path. 29000 quadratic full integration elements were generated for the mesh, resulting in a characteristic element size of 0.279 mm. Degenerated second degree rectangular elements were used to model the crack tip singularity behavior (size 0.075 mm).

Furthermore, a 2D cohesive zone model developed using also plane stress assumption. In the middle section cohesive elements were used to model the damage evolution and crack propagation. Overall 18500 first degree rectangular elements were generated for the overall mesh, resulting in a characteristic element size of 0.472 mm. The cohesive elements employed have 0.3x0.3 mm. The upper half of the WL4CTB specimen is shown with the corresponding Mises stresses at the vicinity of the crack tip and in the ligament in Fig. 2.

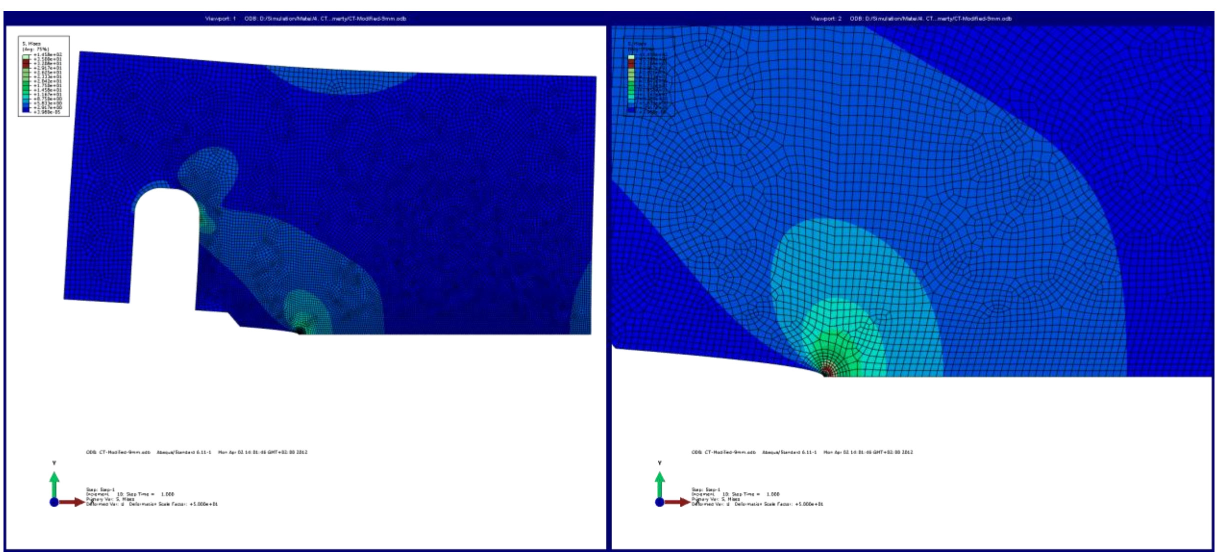

Fig. 2. FE model of the WL4CTB specimen and the Mises stress distribution.

The WL4CTB specimen including the cohesive zone model is shown in Fig. 3a and the model for double torsion configuration is shown in Fig. 3b.In both cases the Mises stress is calculated.

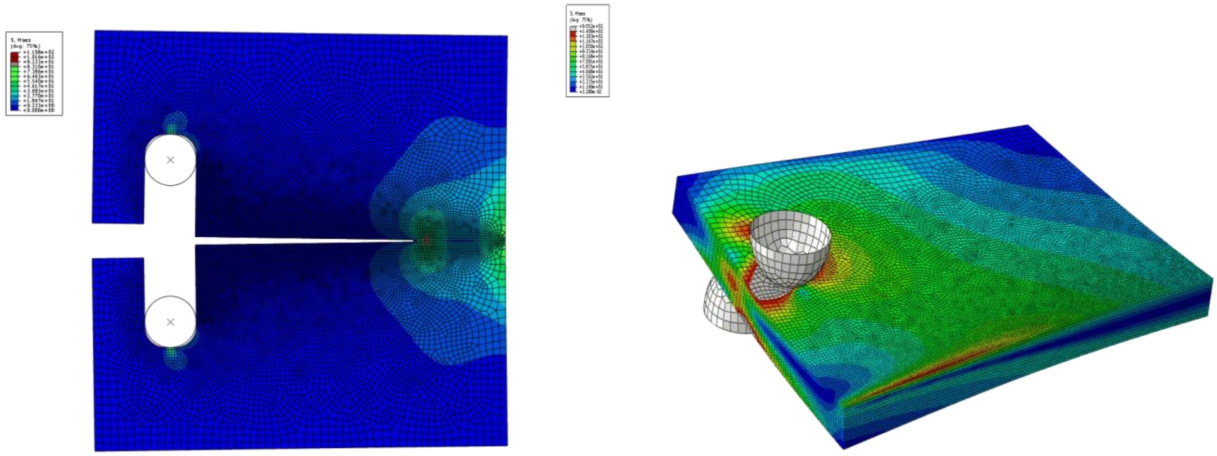

Fig. 3. (a) Cohesive elements in the model of the WL4CTB specimen and (b) the double torsion configuration with the Mises stress distribution.

The following material behavior was assumed in the welding line. Due to the injection molding conditions, over the ligament length the microstructure is varied (various fiber orientation and degree of welding). Hence, the properties depend also on the distance. Near to the crack tip; low stiffness, strength and toughness, far field; higher stiffness, strength and toughness. That is, the cohesive zone parameters are also varying over the distance. The crack is starting from the worst case and moving to a better material. A linear change was assumed and realized by an apparent temperature dependence of the parameters in the model. Similar models with other assumptions are described by other authors [4-5].

Results

Simulations

The stress distribution in terms of the Mises stress in the WL4CTA specimens is shown in Fig. 4 and can be compared with Fig. 2. Both simulations have been performed using fracture elements. These simulations provided the variation of the stress intensity factor values over the crack length. The variation of the SIF over the crack length for both specimens is shown in Fig. 5. While the stress intensity factor, K values increased with decreasing ligament length for the conventional specimen (WL4CTB), a nearly constant K was found for the modified specimens. To achieve even lower variation, further simulations will be performed in further studies.

The fracture behaviour of the WL4CTB specimen was also simulated by using cohesive type elements and cohesive parameters. The force-displacement response of this simulation reveals in agreement with the model parameters a linear response. Further studies will also be performed with a systematic variation of the cohesive zone parameters.

The damage evolution (crack propagation) is shown in Fig. 6 for the double torsion tests. The blue area represents the damage where the crack has already grown.

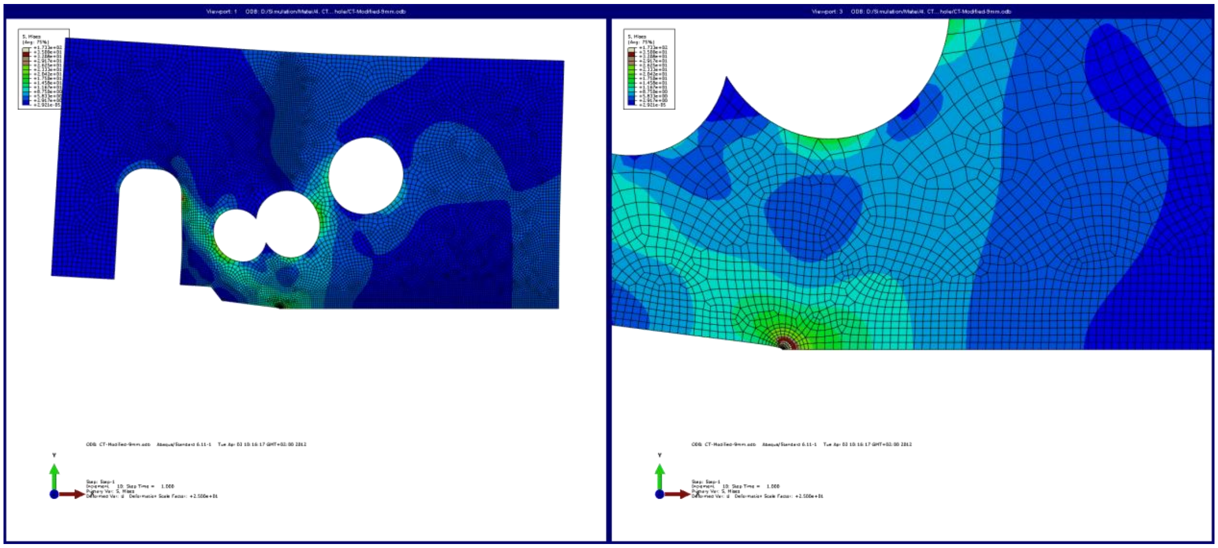

Fig. 4. Fracture simulation of the modified WL4CTA specimen.

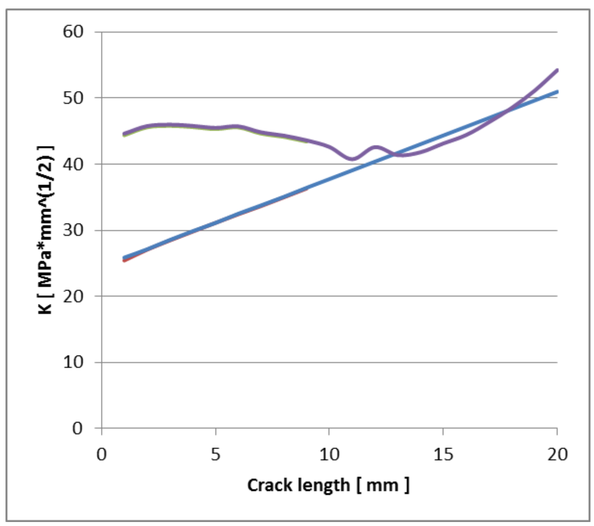

Fig. 5. The variation of the SIF, K over the crack length for both WL4CTA and B specimens.

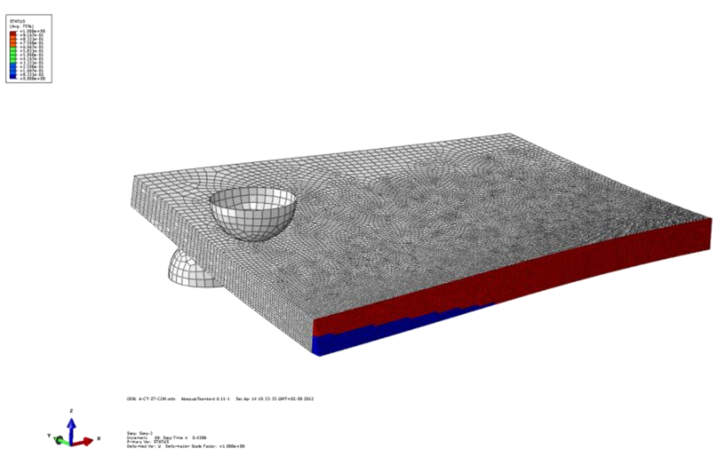

Fig. 6. Damage evolution in the specimen during the double torsion test.

Based on the combination of the simulation models and the experiments a fracture map for accounting processing parameters and material structure dependence of the strength and fracture toughness of welding lines will be developed.

Summary

Various processing induced inhomogeneity's play an essential role in the strength and toughness of short and long fibre reinforced injection molded polymer composites. The welding line is one of the most important type of these inhomogenities and the presence of welding line may significantly reduce the strength and toughness of injection molded products. This is of high importance for components which are exposed to complex combinations of loads under sever loading conditions (e.g. automotive components at low temperatures under crash conditions). Welding lines reveal, however, a complicated microstructure and represent different degree of inhomogeneity. The definition of proper model along with adequate material parameters is not an easy task

Three different fracture specimen configurations based on an injection molded welding line specimen were developed and investigated in this study. Fracture tests were performed on the various specimen configurations and both the global force-displacement response as well as the local strain distribution at the vicinity of the crack tip and in the ligament was determined by digital image correlation (DIC) technique. The same specimens have been modeled in finite element situations. While for the basic WL4CTB configuration both fracture elements and cohesive elements were applied, for the WL4CTB and WL4DT specimens only fracture elements were used.

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