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Finite element study of mode I crack opening effects in compression-loaded cracked cylinders

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ABSTRACT

Mode I crack opening effects in compression-loaded cracked cylinders were examined using finite element analysis. The situation ahead of the crack tip was characterized using linear elastic fracture mechanics in the form of the stress intensity factor (K) concept. Different cylinder dimensions in combination with different loads and crack radii (circular crack shapes were used) were investigated. By using the line load as normalization parameter for the K values, load independent K-curves (K as a function of the normalized crack length a/W) were obtained. The K-curves were compared for different cylinder dimensions to examine the scaling behavior.

1. Introduction

The working principle of cylindrical bearing elements has been used since the ancient times. While in the past it was mainly used to transport heavy loads over wide distances its application has nowadays extended to roller bearings, guide rail systems, carrier rollers, deflector rolls, etc. With changing application field also the materials used for bearing cylinders adapted. The initially used wood and stone materials are nowadays replaced by metals, ceramics and polymers.

Compared to metals and ceramics, polymers have the following advantages in this field: They allow mass production of small-sized parts and because of higher damping (compared to ceramics and metals) the noise production is strongly reduced. However, modern bearing applications often require high load levels and high cycle numbers in service. These requirements can be quite challenging for polymeric bearing elements. Limiting factors in these terms are global [1,2] and local [3] deformations during stop times (static loading phases) as a result of the viscoelastic behavior of polymers, wear and surface fatigue [4–7] and/or global fatigue of the bearing elements.

Polymers usually used in this context are different Polyamide types, Polyoxymethylene and Polyetheretherketone. They were all found to work quite well for gear wheels [8,9] which have a similar mechanical loading situation (periodical line load, surface contact with friction). Although bearing elements are not exclusively made of these three polymer types many of them are. All three materials have one thing in common: they are semi-crystalline thermoplastics showing crystallization (significant shrinkage) when cooled down from the melt. In injection molding this shrinkage is compensated by the so-called holding pressure applied after filling the cavity. However, for different reasons (disadvantageous geometry for injection molding: high thickness/length – ratio, premature freezing of gate in combination with technically limited gate dimension,

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Nomenclature

a	crack length/crack radius
a/W	normalized crack length/normalized crack radius
CT specimen	Compact Tension specimen
D	cylinder diameter
K	stress intensity factor
K_I	stress intensity factor in mode I crack opening
$K_{I,norm}$	normalized stress intensity factor in mode I
L	cylinder length
W	specimen width/in-plane ligament length in the component

demand of economic cycle times and processes) the shrinkage cannot be totally compensated for in industrial processes and voids remain in the core of the bearing elements. Depending on the loading situation these holes can act as initial defects for crack growth initiation followed by crack growth and failure of the component.

Inspired by polymeric bearing elements which showed this failure mechanism, the goal of the present study is the numerical analysis of the loading situation in cylinders having such centric cracks inside. For this the linear elastic fracture mechanics approach is used and the loading situation is expressed using the concept of stress intensity factors (K). Although polymers used for bearing elements, such as Polyoxymethylene, typically show nonlinear viscoelastic behavior [10], which is additionally dependent on the hydrostatic stress state [11], the applicability of linear elastic fracture mechanics for such semi-crystalline polymers was shown by several studies [12–14]. One big advantage of using the K concept is that, in combination with experimental data for crack growth initiation and crack growth kinetics, the results obtained can rather easily be used for life time estimations on component level. As it was demonstrated in the literature, this works also quite well for polymeric components [15,16]. Methods for the determination of the corresponding experimental data are documented in the literature for different specimen types [15–18]. Alternatively, the K levels calculated in the component can also be used for the ranking of pre-selected material types and grades on specimen level [18,19].

2. Materials and methods

The present study examines numerically the stress conditions inside of cylinders with cracks by applying the fracture mechanics approach in terms of the stress intensity factor, K. The cylinders are loaded in compression via a Hertzian contact situation. The numerical analysis was done using the finite element software tool ‘‘ABAQUS” (ABAQUS 6.13; Simulia, Dassault Systèmes, Vélizy-Villacoublay, France). For the determination of the K values at the crack tips the ‘‘contour integral analysis” method according to [20] in combination with a significant mesh refinement in the crack tip vicinity was used. All simulations were conducted using linear elastic materials with Young's moduli and Poisson's ratios adequate for polymers.

The study can be subdivided into the following main parts:

1. Verification of the simulation parameters and settings using a Compact Tension (CT) specimen
2. Study of cylinders with cracks oriented in loading direction (mode I crack opening)
3. Analysis of the scaling properties of the cracked cylinders in dependence on the length to diameter ratio (aspect ratio)

The dependence of K_I on the crack length (a) was determined in parts 1 and 2 by the stepwise extension of the crack length, subsequent simulation of the (apart from the crack length extension) unchanged model and the calculation of the corresponding K values. While in part 1 this was done only for one specific CT specimen geometry, in part 2 several different cylinder geometries (diameters and lengths) were analyzed in this way.

2.1. Verification of the simulation settings

For verification and reference purposes the parameters and settings used for the ‘‘contour integral analysis” method were first tested on a simple geometry with a known solution. For this the ‘‘K-curve” (K as a function of the crack length a) of a CT specimen was determined and the results were compared to the K-curve calculated on the basis of the formula found in the literature.

The CT specimen geometry used in the ABAQUS simulation model (Fig. 1) was based on the dimensions given in [21] (W = 40 mm) except for the thickness which was chosen with 1 mm. The specimen was built as a 2-dimensional half model with shell elements (plane stress). For illustration purposes both halves are shown in Fig. 1. For the specimen an ideal-elastic material with material parameters typical for Polyethylene (Young's modulus 1100 MPa, Poisson's ratio 0.45) was used. In