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A Fracture Mechanics Based Lifetime Assessment Approach for Polyamide used for Integrated Storage Collectors

Patrick R. Bradler[1], Joerg Fischer[1], Mathias Schlaeger[1], Gernot M. Wallner[1] and Reinhold W. Lang[1]

[1] Institute of Polymeric Materials and Testing, Johannes Kepler University of Linz, Linz (Austria)

Abstract

A novel test method simulating the superimposed mechanical, thermal and environmental service loads representative for single-loop integrated storage collectors (ICS) was developed. Engineering polyamide (PA) grades with glass fiber reinforcement, which are of high relevance for endcaps of steel-pipe ICS absorbers and all-polymeric absorbers and storage-tanks, were characterized on laboratory specimen level. An in-situ testing facility for fracture mechanics specimen was used on an electrodynamic testing machine. By in-situ characterization in hot water, a significant decrease in crack growth resistance compared to air (same temperature) was detected. For these specific loading conditions, an extrapolation to static loading was performed to better resemble the loading situation in the ICS and to calculate critical stress levels for cylindrical pipes.

Keywords: *integrated storage collector; polyamide; superimposed loading; lifetime assessment approach; fatigue crack growth kinetics*

1. Introduction

An objective in previous research projects (e.g. SCOOP – Solar Collectors made of Polymers) was to develop and implement advanced testing methods for the evaluation of the long-term behavior of polymeric materials for solar collectors under service relevant loading conditions (Wallner et al., 2004; Kahlen et al., 2010; Köhl et al., 2012; Geretschlaeger, 2015; Geretschlaeger and Wallner, 2016; Steffen et al., 2017). To fulfill the application requirements for pressurized integrated storage collectors, maximum internal pressures of 6 bar and maximum application temperatures of 90°C should be considered (Solecrafte, 2015). While in a previous paper, fatigue crack growth kinetics of PA under superimposed mechanical, thermal and environmental loads were described properly (Fischer et al., 2016), this paper deals with a lifetime assessment approach considering the previously determined most critical crack growth behavior. Special attention is given to an extrapolation procedure simulating a static loading case, as originally proposed for plastics pressure pipes (Lang et al., 2005).

2. Background

The entire discipline of fatigue crack growth (FCG) behavior in plastics is fundamentally based on the concept of linear-elastic fracture mechanics (Hertzberg and Manson, 1980; Lang, 1980; Lang et al., 1982; Hertzberg et al., 2013). The failure mechanisms are frequently described by two different regimes, the crack initiation and the subsequent crack growth regime (Lang et al., 1997; Haager et al., 2004).

Based on cyclic tests which allow an accelerated material characterization, the calculation of FCG kinetic curves is possible. In these FCG curves three different failure modes are apparent in a double logarithmic plot (see Fig. 1). Region I represents the threshold, region II the stable crack growth region typically obeying a power law (representing a linear increase in the double logarithmic scale), and finally region III which corresponds to unstable crack growth approaching ultimate failure.

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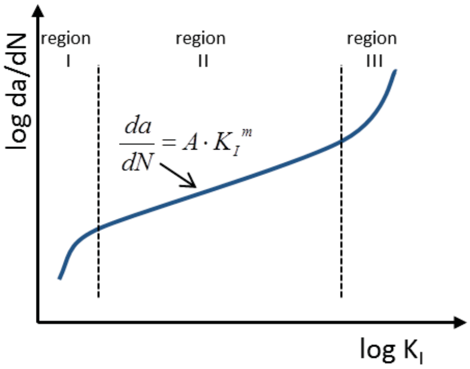

Fig. 1. Crack growth rate da/dN as a function of the stress intensity factor K_I.

However, for a lifetime prediction based on fracture mechanics, a static loading case representing creep crack growth is necessary. This requires a transformation of FCG data to static loading data with a procedure presented elsewhere (Lang et al., 2005; Frank et al., 2008; Frank et al., 2009). This procedure, in principle, also allows a prediction of lifetime of components, whereby a component and dimension dependent stress intensity factor K_I has to be simulated via finite element analysis.

3. Methodology and experimental

Materials

The test program was performed by using two semi-crystalline fiber reinforced polyamide (PA) grades. An overview of selected grade specific information as to the materials is given in Table 1. The grades are seen to vary in the glass fiber content as well as in the chemical composition. PA66-GF30 is an aliphatic PA, and PA6T/6I-GF50 is a semi-aromatic co-PA. Both material grades offer a high potential for the substitution of metals in integrated storage collectors.

Table 1. Materials with specific information

Material designation	Matrix polymer type	Glass fiber content	Commercial grade name	Manufacturer
PA66-GF30	Polyamide 66	30 w%	SCHULAMID® 66 GF 30	A. Schulmann GmbH, Germany
PA6T/6I-GF50	Polyamide 6T/6I-GF50	50 w%	Grivory HT1V-5 FWA	EMS-Chemie AG, Switzerland

Specimen and specimen preparation

The crack growth tests on the specimen level were conducted using compact-type (CT) specimens (see Fig. 2). The materials were first injection-molded to plates, which were then milled to the desired specimen geometry and subsequently notched with a razor blade for obtaining an initial crack. To cover the expected lower bound crack growth resistance of the specimens with a layered fiber orientation pattern caused by the injection molding process, the notched direction was chosen to be parallel to the main melt flow direction when injection molding the plates (Schlaeger, 2015; Fischer et al., 2016). Hence, the loading direction in these specimens is perpendicular to the main fiber orientation direction.

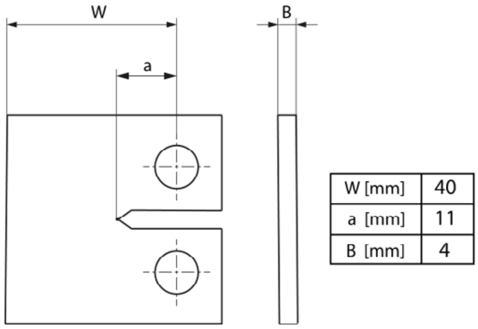

Fig. 2. Compact type (CT) specimen with test specific dimensions.

Fatigue testing and data reduction

Both PA grades were investigated in a previous research work (Fischer et al., 2016) as to their fatigue crack growth resistance under various, service relevant conditions. It has been shown that elevated temperature and liquid media are influencing and accelerating the failure kinetics of these PA-types (Hahn et al., 1982; Fischer et al., 2016). Hence, the testing conditions in this paper were chosen with a temperature of 80°C and deionized water (referred to as H_2O). In order to ensure water-saturation of grades tested in H_2O, a pre-conditioning procedure with a saturation time of 7 days in the testing-similar surrounding media was carried out (Schlaeger, 2015). To allow for extrapolation of cyclic crack growth data to static loading, the cyclic tests were performed with various R-ratios ranging from 0.1 to 0.7, with R being defined as the ratio between the minimum and maximum applied force in the sinusoidal, cyclic loading profile.

The tests were conducted in the superimposed in-situ testing media containment device originally designed and implemented by Schoeffl et al. (Schoeffl, 2014; Schoeffl et al., 2014). In contrast to tests with highly ductile materials, the camera system and the software device for crack length evaluation was especially adapted for less ductile materials. All FCG tests were conducted with an electro-dynamic testing machine of the type ElectroPlus E3000 (Instron; Nordwoos, USA) under sinusoidal loading and a frequency of 5 Hz. R-ratios were set to 0.1, 0.3, 0.5 and 0.7, respectively. To reduce overall testing times while simultaneously ensuring quasi-brittle, stable crack growth, the initial stress intensity factor levels were suitably chosen by pretesting some specimens. The calculation of the stress intensity factor K_I was done as described by Fischer et al. using eq. 1 and eq. 2 (Gross and Seelig, 2011).

$$K_I = \frac{F}{B \cdot \sqrt{W}} \cdot f\left(\frac{a}{W}\right) \qquad \text{(eq. 1)}$$

$$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)}{\left(1-\frac{a}{W}\right)^{3/2}} \cdot \left(0.886 + 4.64 \cdot \left(\frac{a}{W}\right) - 13.32 \cdot \left(\frac{a}{W}\right)^2 + 14.72 \cdot \left(\frac{a}{W}\right)^3 - 5.6 \cdot \left(\frac{a}{W}\right)^4\right) \qquad \text{(eq. 2)}$$

Lifetime assessment approach for a cylindrical ring

By using a quantitative comparison between the internal pressure loading conditions in ICS and the characterized FCG behavior, the probability of crack growth can be assessed. Therefore, calculations were carried out with eq. 3 and eq. 4 postulated by Yan (Yan and Nguyen-Dang, 1994). These equations allow a calculation of the K_I-values for a cylindrical ring under static internal pressure and small defect sizes, whereby p is the internal pressure, a the defect size and F a factor for considering different geometries relations of the cylinder. This factor contains the inner radius r of the cylinder (r=130 mm), the outer radius

R or the wall thickness. Representative values for the calculations were chosen with p=10 bar, a defect size of 0.5 mm and wall thicknesses of 2.0, 2.5 and 3.0 mm.

$$K_{I,critical} = p \cdot \sqrt{\pi \cdot a} \cdot F\left(\frac{a}{r}, \beta\right) \qquad \text{(eq. 3)}$$

$$F = 1.12 \cdot \frac{\beta^2 + 1}{\beta^2 - 1} \quad with \quad \frac{a}{r} \approx 0 \quad and \quad \beta = \frac{R}{r} \qquad \text{(eq. 4)}$$

As mentioned before, to obtain creep crack growth curves for static loading (R=1) from FCG curves, a procedure proposed by Lang et al. was followed (Lang et al., 2005; Frank et al., 2008; Frank et al., 2009). It allows for an extrapolation of FCG tests at different R-ratios to creep crack growth (CCG) curves under static load. If the K_I-values of these extrapolated CCG curves are higher than the calculated stress intensity factor K_I, FCG curves may be extrapolated back to those calculated component typical, calculated K_I-values, assuming no threshold regime occurs in the extrapolated range. In any case, this calculation remains on the safe side should such a threshold regime occur in the extrapolated range.

4. Results and discussion

The effect of R-ratio on the FCG resistance of PA66-GF30 is shown in Fig. 3 in terms of the da/dN vs. $K_{I,max}$. This illustration (rather than a ΔK diagram) was chosen as it is more prone to extrapolate the data directly to the static case. Clearly, the crack growth lines for constant R-ratios shift towards higher $K_{I,max}$-values as the R-ratio is increased.

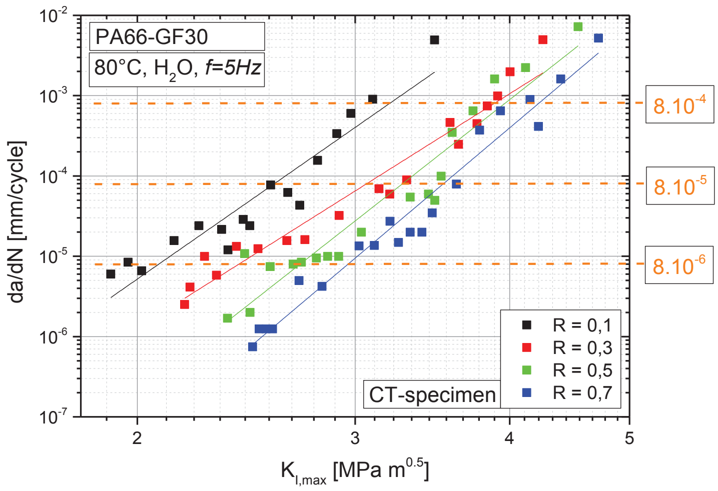

Fig. 3. Measured FCG kinetics for PA66-GF30S under various R-ratios.

In Fig. 4, the corresponding $K_{I,max}$ values at constant crack growth rates are plotted as a function of the R-ratio. Based on an exponential curve fitting and extrapolation using the existing data sets, values for the static loading conditions are achieved. The coefficient of determination R^2 was consistently above 0.9. By using the extrapolated data sets a CCG curve under static load was derived. Hence, a quantitative "synthetic" kinetic law for static loading (R=1) is obtained, which is shown in Fig. 5 together with the experimental kinetic laws at lower R-ratios. The results are in good agreement with expectations and results from previous studies with other materials (Lang et al., 2005; Pinter et al., 2007; Frank et al., 2009).

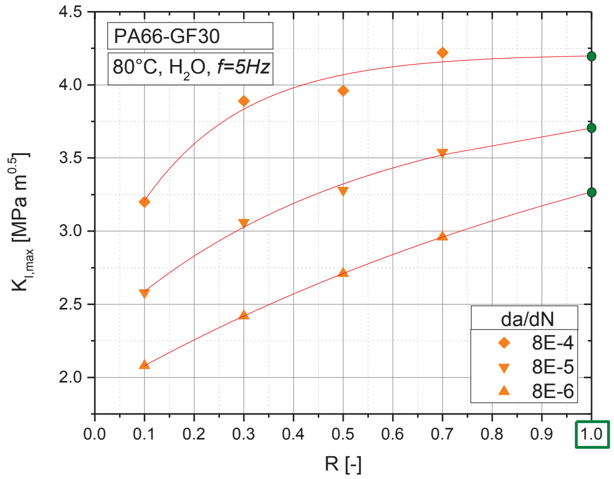

Fig. 4. Extrapolation of $K_{I,max}$-values at different R-ratios to R=1.

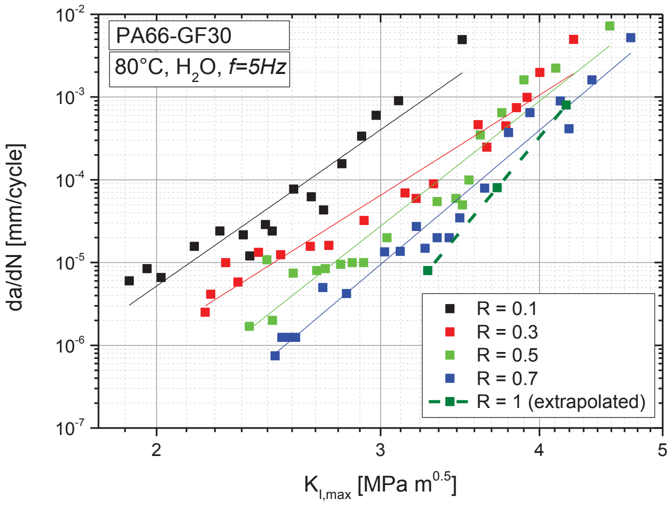

Fig. 5. Measured and calculated fatigue crack growth kinetics for PA66-GF30 under various R-ratios .

Using the assumptions for a pressurized ring component under service conditions described above (pressure p=10 bar; inner cylinder radius r of 130 mm; defect size a=0.5 mm; wall thicknesses of 2.0, 2.5 and 3.0 mm), "initial" K_I-values for the component level were calculated and are listed in Table 3.

Table 3. Calculated "initial" stress intensity factors under internal pressure for a cylindrical ring

Wall thickness (mm)	K_I-values (MPa.m$^{0.5}$)
2.0	1.47
2.5	1.17
3.0	0.97

These "initial" K_I-values are depicted in Fig. 6 together with the extrapolated "synthetic" CCG curves for both materials investigated. It appears that the CCG curves, when linearly extrapolated to lower stress intensity factors, would intersect the lines for initial stress intensity factor values at crack growth rates substantially below 10^{-8} mm/cycle. Considering that in a crack growth threshold may actually exist as one moves towards such low crack growth rates, it is feasible to assume that the material inherent crack growth resistance may be sufficient for such an application. This conclusion, at least at this stage, does not necessarily apply to weld-bonded areas, an aspect which needs to be looked at in detail separately.

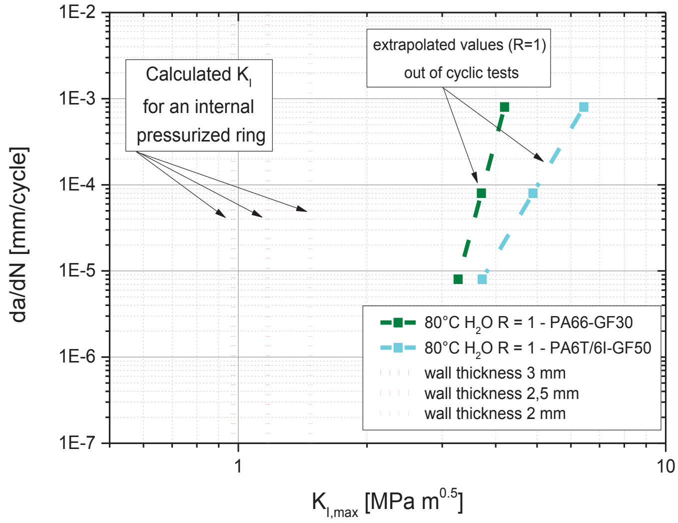

Fig. 6. Comparison of K_I-values of an internal pressurized cylinder with generated crack kinetics curves (R=1) for PA66-GF30 and PA6T/6I-GF50 at 80°C in water.

5. Summary and outlook

In this paper, based on a lifetime assessment approach for two polyamide grades with different glass fiber contents, the probability of crack growth under application conditions was investigated. Fatigue crack growth (FCG) experiments at different R-ratios (ratio of minimum to maximum force) were conducted at a temperature of 80°C in deionized water. The loading was applied to the injection molded compact-type (CT) specimens perpendicular to the main fiber orientation direction, i.e. the most critical case. Experimental data show that the FCG curves are strongly affected by the R-ratio, showing higher $K_{I,max}$-values with increasing R-ratio at a given crack growth rate. The experimental results were used to extrapolate towards a "synthetic" creep crack growth curve for both materials, which in turn were utilized to assess the long term performance capability of pressurized ring components in service such as in a single-loop integrated storage collector. While both PA material grades investigated seem to exhibit sufficient material-inherent crack growth resistance under service conditions, the crack growth resistance of weld-bonded sections remains a topic of further studies.

6. Acknowledgements

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