Fatigue characterization of potable water certified PA and PPA grades for solar-thermal applications

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Abstract

A material screening method for potable water certified plastics for solar-thermal applications based on superimposed cyclic mechanical loading was conducted. One aliphatic polyamide and three semi-aromatic polyphtalamide grades with various glass fiber contents were characterized on specimen level. Therefore, an electro-dynamic testing machine equipped with an in-situ testing device was used to obtain the crack growth kinetics at different temperatures (23°C and 80°C) in different media environments (air and H_2O) . At 80°C in H_2O, specimens revealed a significantly reduced fatigue crack growth resistance compared to tests at the reference conditions of 23°C in air. Comparing all investigated materials at 80°C in water, the polyamide grade and one polyphtalamide grade revealed the best performance. Due to different slopes in their FCG curves, PA-GF30 showed a superior crack growth resistance at low FCG rates.

Keywords: polyamide, polyphthalamide, fatigue crack growth, superimposed loading

1. Introduction

The performance of polymeric materials is strongly dependent on the mechanical and environmental loading conditions (Stern et al., 1998a; Stern et al., 1998b; Lang et al., 2005). Hence, tests are necessary under application relevant conditions. An objective in former research (Schoeffl et al., 2014; Fischer et al., 2016) was to develop and implement advanced testing methods for the evaluation of the long-term behavior of polymeric materials for solar-thermal collectors under service relevant loading conditions (e.g., for an integrated storage collector system). To fulfill the application requirements for pressurized integrated storage collectors maximum internal pressures of 4 bar and maximum application temperatures of 95°C should be considered (Solecrafte, 2017).

While in previous papers, fatigue crack growth kinetics of polyamide under superimposed mechanical loads were described properly (Fischer et al., 2016) and a lifetime prediction approach (Bradler et al., 2016) was presented, this paper deals with the investigation of potable water certified polyamide (PA) and polyphtalamide (PPA) grades with various glass fiber contents under different superimposed mechanical and environmental loads.

2. Background

Polyamides can be classified according to their composition in different polyamide types. Two of them are used in this study, namely (1) the aliphatic polyamides (PA) with an aliphatic main chain including the well known Nylon or PA 6.6 (Gilbert and Brydson, 2017), and (2) the polyphtalamides (PPA) with a semi-aromatic main chain (Wypych, 2016). In single-loop solar-thermal collector systems, potable water is acting as heat carrier fluid (Köhl et al., 2012). Hence, various system components are getting in contact with drinking water. Materials used for such applications should have an adequate drinking water certificate, which is limiting the use of stabilizers. Several studies are describing the negative impact of the lack of stabilizers on the fatigue crack growth (FCG) behavior and thus on the long-term failure (Lang et al., 1997; Pinter and Lang, 2003).

The long-term failure of polymers is usually characterized by the concept of linear elastic fracture mechanics (LEFM) (Hertzberg and Manson, 1980; Lang, 1980). For these tests, some requirements have to be fulfilled (i.e., small plastic zones and a linear-viscoelastic material behavior) (Lang, 1980; Lang et al., 1982). Based on results of fracture mechanics tests, a FCG kinetics curve can be plotted, which is a double logarithmic plot of the fatigue crack growth rate da/dN vs. the stress intensity factor range ΔK_I. The resulting plot can be subdivided into three characteristic regions, where region I describes the threshold, region II describes the stable crack growth which can be described by a power law equation (see eq. 1) (Paris and Erdogan, 1963), and finally region III describes the unstable crack

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growth at high plastic deformations. Details and the characteristic plot are described elsewhere (Fischer et al., 2016; Bradler et al., 2017).

$$\frac{da}{dN} = A \cdot \Delta K^{m} \qquad \text{(eq. 1)}$$

The stress intensity factor range ΔK_I for a cyclic loading (s. eq. 2) describes the difference between the maximum and minimum stress intensity factor ($K_{I,max}$ -$K_{I,min}$) in the loading mode I, which indicates crack opening. “$\Delta\sigma$” describes the difference between maximum and minimum global loading, “a” the crack length and “Y” a geometry and specimen dependent shape factor.

$$\Delta K_I = \Delta\sigma \cdot \sqrt{a} \cdot Y \qquad \text{(eq. 2)}$$

3. Methodology and experimental

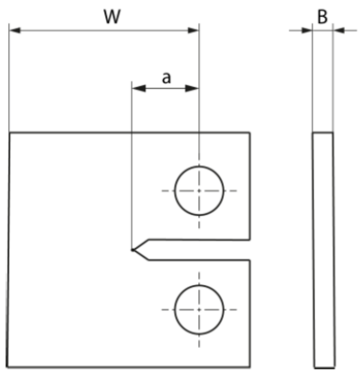
Materials and specimens

One aliphatic polyamide (PA) and three different semi-aromatic polyphtalamide (PPA) grades were investigated regarding fatigue crack growth (FCG) resistance. An overview of selected information on these grades is given in Table 1. The grades are varying in chemical composition as well as in glass fiber content.

Tab. 1: Material designation, grade, and glass fiber content.

Material designation	Grade	Glass fiber content
PA-GF30	polyamide 6.6	30 w%
PPA-GF40	polyphthalamide	40 w%
PPA-GF50-1	polyphthalamide	50 w%
PPA-GF50-2	polyphthalamide	50 w%

Fig. 1 depicts a standardized compact type (CT) specimen (E08 Committee, 2000; ISO/TC 156 - Corrosion of metals and alloys, 2011). Specimens were manufactured via milling out of injection molded plaques. According to previous results (Schlaeger, 2015; Fischer et al., 2016), for FCG tests with glass fiber reinforced polyamides and a specimen thickness of 4 mm, specimens with the initial crack in flow direction are most critical.



W [mm]	40
a [mm]	11
B [mm]	4

Fig. 1: Compact type (CT) specimen with relevant dimensions for data reduction.

Fatigue tests and data reduction

All FCG experiments were carried out on an electro-dynamic testing machine (Instron ElectroPls E3000; Nordwood, USA). For tests under different environmental conditions, an in-situ testing device was used, which was originally implemented for tests in liquid hydrocarbons by Schoeffl et al. (Schoeffl, 2014; Schoeffl et al., 2014). All tests were conducted with a frequency of 5 Hz and a sinusoidal loading with an R-ratio of 0.1. The R-ratio describes the ratio between the maximum to minimum applied stress intensity factor. The subsequent calculation of the stress intensity factor range "ΔK " was done according to eq. 3 (Gross and Seelig, 2011), where "ΔF" is the difference between maximum and minimum applied force, "B" the thickness of the specimen, "W" the width of the specimen and "f(a/W)" a geometry dependent shape factor.

$$\Delta K = \frac{\Delta F}{B \cdot \sqrt{W}} \cdot f(a/W) \qquad \text{(eq. 3)}$$

4. Results and discussion

The effect of different temperatures and different media on the fatigue crack growth resistance of the grade PPA-GF50-2 is shown in Fig. 2. In terms of temperature, in both media, the material performance was enhanced at the lower temperature of 23°C. At both temperatures, inferior FCG resistances were determined in water. These results are exhibiting hot water as the more critical environment compared to air and are in good agreement with conventional aging data obtained in another research (Geretschlaeger and Wallner, 2016). All further tests were carried out at the best and worst conditions, 23°C in air and 80°C in water, respectively.

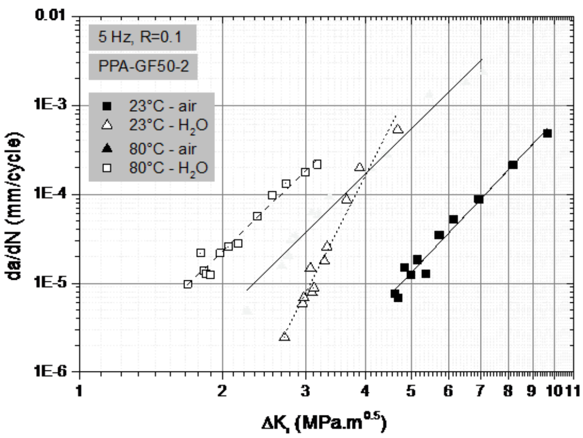


Fig. 2: Fatigue crack growth kinetics for the grade PPA-GF50-2 at various temperatures in various media.

A comparison of the FCG kinetics curves for the two polyphtalamide grades with the same glass fiber content of 50 w% (PPA-GF50-1 and PPA-GF50-2) tested at the best and worst environmental conditions is depicted in Fig. 3. Tests at 23°C in air exhibited a better FCG behavior for both materials compared with tests at 80°C in water, resulting in higher ΔK_I-values at specific fatigue crack growth rates. The material PPA-GF50-1 reveals a better FCG resistance at both conditions. At a comparable rather low crack growth rate of 2E-5 mm/cycle, the difference between the ΔK_I-values of the two materials at 23°C in air is given with a factor of about 1.2 and at 80°C in deionized water with a factor of about 1.6. The results obtained are exhibiting a higher sensitivity of the PA-GF50-2 grade against elevated temperatures and water environment.

Due to the same chemical composition of the matrix material, the grades PPA-GF40 and PPA-GF50-1 are only differing in their glass fiber content. Thus, for these two materials, the effect of glass fiber content on the FCG rates was investigated and is depicted in Fig.4. While the grade PPA-GF40 with the lower glass fiber content of 40 w% shows an inferior FCG resistance, the PPA-GF50-1 with 50 w% of glass fiber reinforcement reveal clearly a higher

FCG resistance.

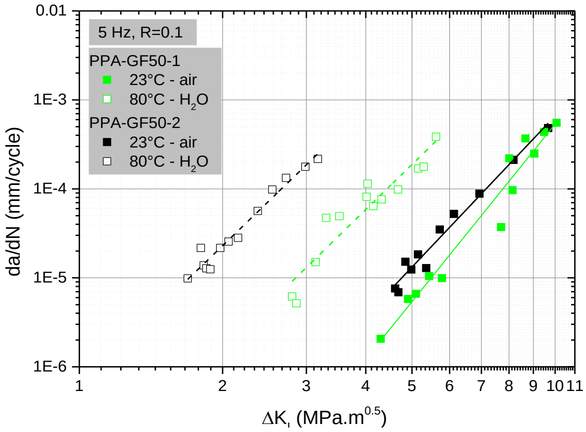


Fig. 3: Fatigue crack growth kinetics for PPA grades with 50 w% glass fiber reinforcement at 23°C in air and at 80°C in water.

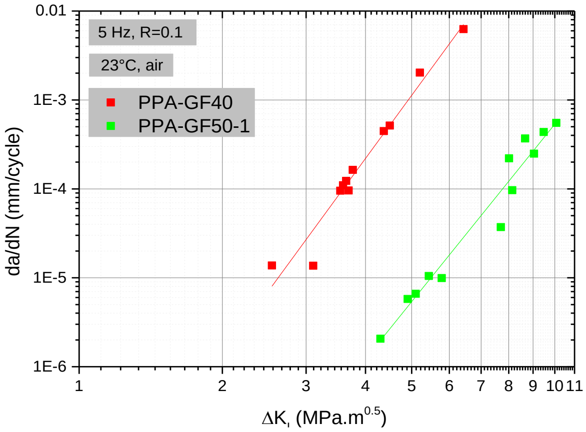


Fig. 4: Effect of glass fiber content on the fatigue crack growth kinetics for the PPA-grades at 23°C in air.

As, in this study, the most critical environmental condition for fatigue crack growth is 80°C in water, all materials were tested at this condition and resulting FCG curves are illustrated in Fig. 5. The grade PPA-GF40 shows a significantly lower FCG resistance, leading to a factor 2.6 lower ΔK_I-value at a crack growth rate of 2E-5 mm/cycle compared with PA-GF30, the best performing material at low crack growth rates. For PPA-GF50-2 and PPA-GF50-1 compared to PA-GF30, lower ΔK_I-values with a factor 1.9 and 1.2, respectively, were obtained. PA-GF30 exhibits a superior crack growth resistance at low crack growth rates. Due to a different slope in the FCG curve, at high FCG rates, PPA-GF50-1 is slightly better.

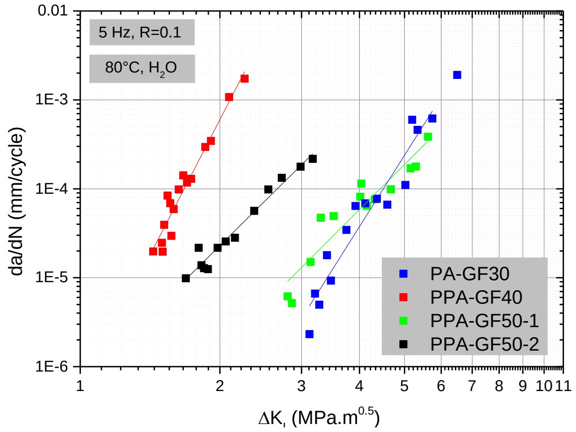


Fig. 5: Fatigue crack growth kinetics for all investigated material grades at 80°C in water.

5. Summary and outlook

The fatigue crack growth (FCG) resistance of one aliphatic polyamide and three semi-aromatic polyphthalamides varying in their glass fiber content was investigated. Due to their certification for the transport of potable water, these materials are of high relevance for solar-thermal applications. Fatigue crack growth measurements were performed at application relevant conditions in two environmental media (air and water) at two temperatures (23°C and 80°C). For the polyphtalamide PPA-GF50-2, tests at all four environmental combinations were conducted resulting in the best performance at 23°C in air and in inferior FCG resistance at 80°C in water. As to the glass fiber content of the polyphthalamides, PPA-GF50-1 showed superior FCG behavior and PPA-GF40 revealed inferior fatigue crack growth resistance. Comparing all investigated materials at 80°C in water, the aliphatic polyamide PA-GF30 and the polyphtalamide PPA-GF50-1 revealed the best performance. Due to different slopes in their FCG curves, PA-GF30 showed a superior crack growth resistance at low FCG rates. Conversely, at high FCG rates, PPA-GF50-1 is slightly better.

In this study, a very fast screening method for materials for solar-thermal applications, especially for reinforced plastics, was introduced. Based on an extension of the test program in terms of testing at different R-ratios, in a further study a lifetime prediction of these materials could be conducted.

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