FATIGUE STRENGTH OF A MULTIAXIAL LOADED SHORT GLASS FIBRE REINFORCED POLYAMIDE

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Abstract

The high specific strength and excellent manufacturing process ability of short glass fibre reinforced (sgfr) polymers facilitate the application of this composite material for complexly shaped components instead of commonly used metallic designs. Based on an improved material knowledge, especially on the fatigue behaviour of these materials, highly cyclic stressed parts can be tailored for many applications. Especially in automotive applications, complex load cases can lead to multiaxial stresses within complexly shaped parts. To evaluate the lifetime of such a component in an early stage of the development process, it is indispensable to get detailed knowledge about the local fatigue influence factors. To establish a closed simulation chain, the applicability of commonly used material models has to be studied first, the models have to be adapted or even new models have to be set up for this kind of composite materials. For metals, reflecting the state of the art, the influence of multiaxiality can be described by several multiaxial fatigue criteria such as the elliptical equation proposed by Gough and Pollard. But for sgfr materials, the applicability of such a fatigue criteria has to be proven yet.

This paper will focus on the influence of multiaxial loads on the fatigue strength. Therefore, the influence of pure shear stress as well as combined normal and shear stresses on a 50 wt% sgfr partial aromatic polyamide were investigated. Fatigue tests were performed on unnotched tubular shaped specimen, which were processed by injection moulding as industrial applicable manufacturing process. Cyclic tests have been made on two different stress ratios R = -1 and R = 0.1 and four varying grades of multiaxiality $\lambda = \tau/\sigma$ ranging from infinity, to one, a half and to zero. It was found that the level of multiaxiality has a great influence on the fatigue strength of the investigated material. Due to local anisotropy, caused by the local fibre orientation, the fracture pattern show partially different critical planes compared to metals. This fact has to be considered for a multiaxial applicable fatigue criteria in a life time calculation of sgfr components.

1. Introduction

Due to decreasing product development cycles it is necessary to obtain local lifetime tendencies in an early state of development. Therefore, finite element based methods can be successfully employed to transfer local material characteristic strength values, determined on specimen, to real parts. Especially the fatigue design of highly loaded components needs an extensive knowledge about the design

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influences like mean stress, supporting effect, temperature, et cetera for this nonlinear and anisotropic sgfr material grade. Beside this design factors, both complexly shaped parts as well as complex load cases can lead to a multiaxial stress state within the component.
For metals the material behaviour under multiaxial loads is well researched in the literature [1] and for example represented by Mohr's cycle in a static case and the elliptical fatigue criteria proposed by Gough and Pollard [2, 3]. Both models are shown in Figure 1.

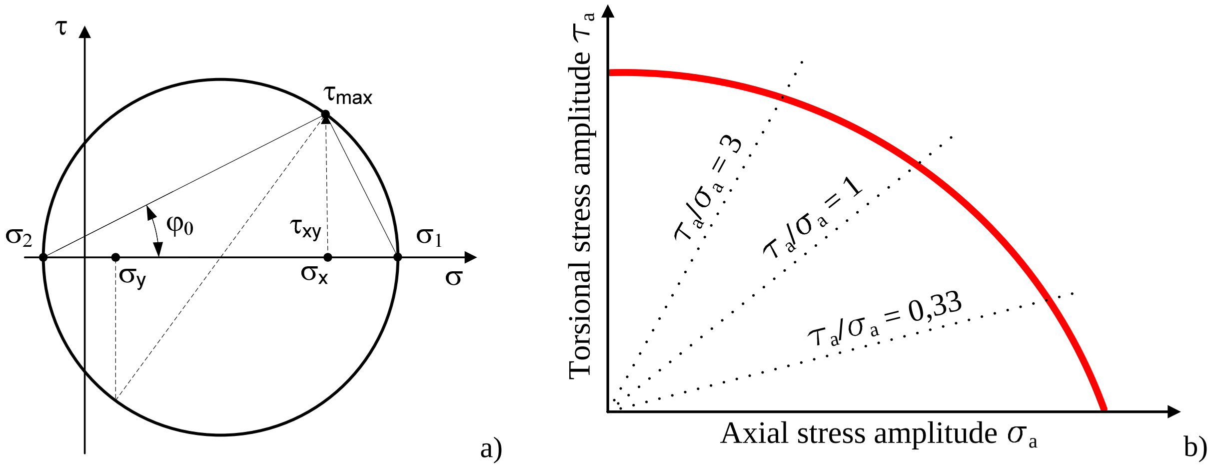

Figure 1 a) Mohr's circle, b) Elliptical fatigue criteria according Gough and Pollard

2. Experimental Work

2.1. Material and Specimen

The investigated material is a short fibre reinforced partially aromatic polyamide containing 50 wt% glass fibres (PA6T/6I – GF50). This material is successfully used for highly loaded parts in mechanical engineering, automotive as well as in electrical sector. But in most cases, the application focuses on quasistatic loads or constant amplitude fatigue design rules applying a service load factor to account for service strength. To extend the state of knowledge in regard to multiaxial fatigue of sgfr materials, tubular specimen were used for testing. The detailed geometry, originally developed in [4], is shown in Figure 2. Being produced by injection moulding through a ring gate, the main fibre orientation follows the profile of the tube.

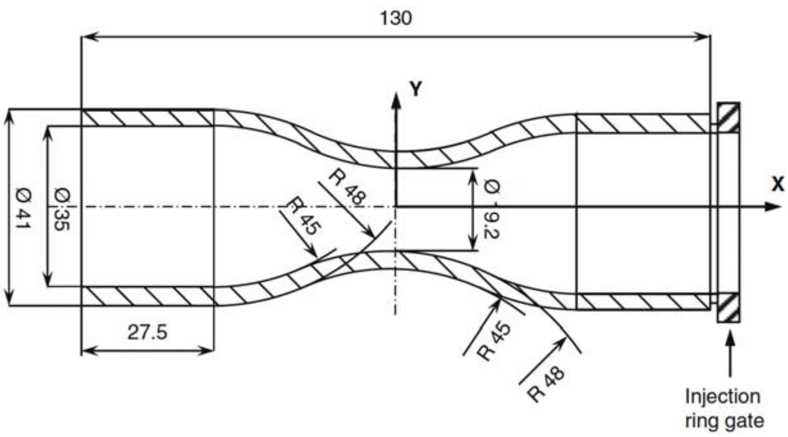

Figure 2 Tubular specimen geometry and dimensions [4]

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2.2. Fatigue Testing

All cyclic tests were performed at a servo hydraulic test machine MTS 858®. The test rig was equipped with a combined 25 kN / 250 Nm load cell. The tests were performed at an ambient temperature 23°C and 50 % relative humidity. To avoid hysteretic heating effects, quite low test frequencies between f = 0.2 Hz and f = 2 Hz are used. The temperature at the interior and outer surface of the specimen was monitored by a contact thermometer to ensure that the observed rise of temperature keeps below 5°C during the whole test period. In addition, an air cooling system was installed to blow ambient air on the external surface of the specimen. For the fatigue test a sinusoidal load function with constant amplitude was used under load control. Two stress ratios (R = -1, R = 0.1) were applied for the cyclic test series. For both stress ratios several grades of multiaxialities were defined. The ratio of multiaxlity is given by the nominal shear stress divided by the normal stress in the smallest cross section. Table 1 lists all combinations of stress ratio and multiaxiality.

Table 1 Trial design

Stress ratio R	Multiaxiality λ	Description
-1	infinity	torsion
	1	multiaxial
	0.5	multiaxial
	0	tension
0.1	infinity	torsion
	1	multiaxial
	0	tension

The nominal stress is given by the load force respectively load moment divided by the net cross-section or moment of inertia. At least three stress levels were investigated to achieve a range of fatigue cycles to burst failure from $N = 10^4$ to $N = 10^6$. The test abort criterion is the total burst fracture. In addition, the test is stopped if the maximum of fatigue cycles $N = 10^7$ is exceeded and a run-through specimen is assumed for data evaluation. At each stress level at least three specimens were tested. The evaluation of Woehler-curves in the finite life region is done according to ASTM E 739-91 [5].

2.3. Microscopy

Besides the fatigue tests, the main fibre orientation along the specimen axis is investigated by computer tomography (CT). In addition, a micro graphical investigation in the critical cross-section is done. The fibre orientation is determined by high resolution CT-scans around the parting line of the injection moulding tool as well with an offset of ninety degree. In Figure 3 the scanning path (dashed line) as well as the positions of the high resolution scans are sketched.

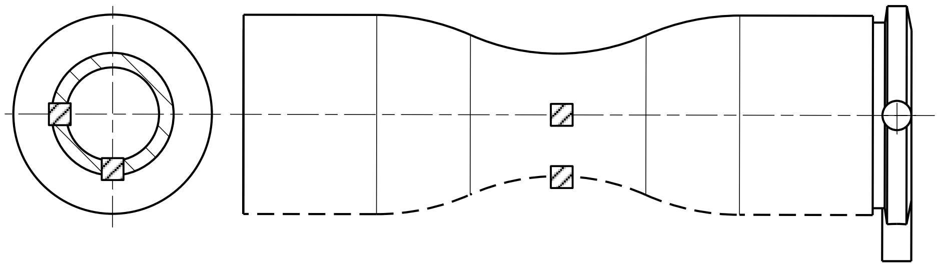

Figure 3 CT-Measurements scan–path (dashed line), positions of high resolution scans (crosshatched square)

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3. Results

3.1. Fatigue strength assessment

The global fatigue Woehler S/N-curves evaluated as normalized nominal stress over the cycles to failure are shown in Figure 4. All fatigue results are normalized to the ultimate tensile strength parallel to the main fibre orientation. The conducted tests are given in Table 1. The results show a great influence on the fatigue limit at $N = 10^6$ of the grade of multiaxiality as well as of the stress ratio, while the slope of the S/N-curves is not significantly affected. The influence of mean stress under axial loading for the investigated material is already reported in detail in [6] up to $R = 0.8$. For both stress ratios the slope of pure shear stress is slightly higher than for normal loading. This shallower slope of the S/N-curve for shear loading is in agreement to the behaviour of other materials. With an increasing amount of shear stress the fatigue limit decreases. De Monte et al. observed a similar fatigue strength behaviour for PA66-GF35 [4]. In [7] Klimkeit et al. describes the fatigue strength of PBT–PET GF30 for tubular as well as flat specimen under pure tension/compression, shear and combined loads. Both results are in agreement to the own fatigue tests conducted on PA6T/6I - GF50. Compared to former fatigue tests given in [6, 8] under pure tension and results from literature the observed normal stress fatigue limit is comparatively lower than expected. Therefore further investigations on manufacturing process, as detailed in 3.4, were carried out.

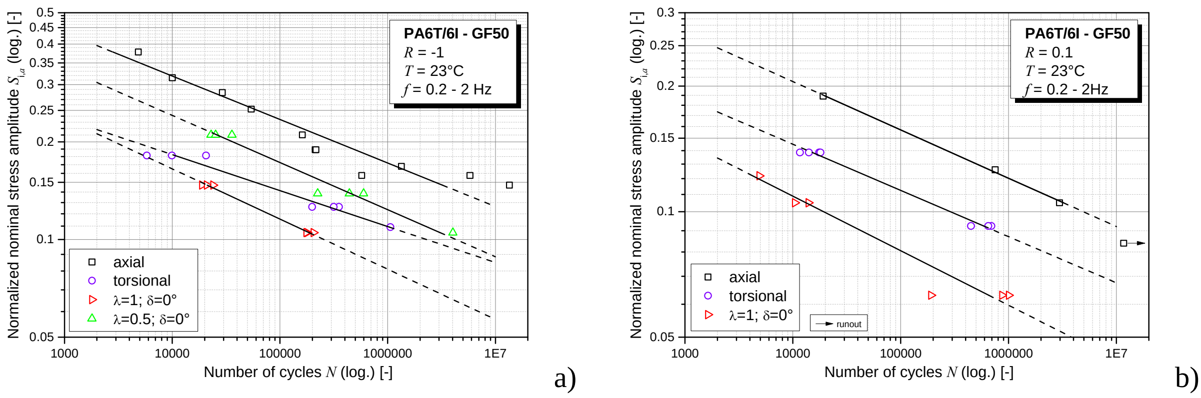

Figure 4 Global S/N-curve $S_{i,a}$ for different degrees of multiaxialities a) $R = -1$ b) $R = 0.1$

Typical observed crack paths at the specimen are shown for normal stress in Figure 5a) and shear stress in Figure 5b) where the effective crack path is represented by a red wounded line and the expected by a dashed green line. Under tension, both lines match while under shear the real crack path is significantly inclined to the expected crack growth path. Since the specimen fails under torsion along the main fibre orientation, it is likely that the material ruptures due to the greatest normal stress perpendicular to the fibre orientation.

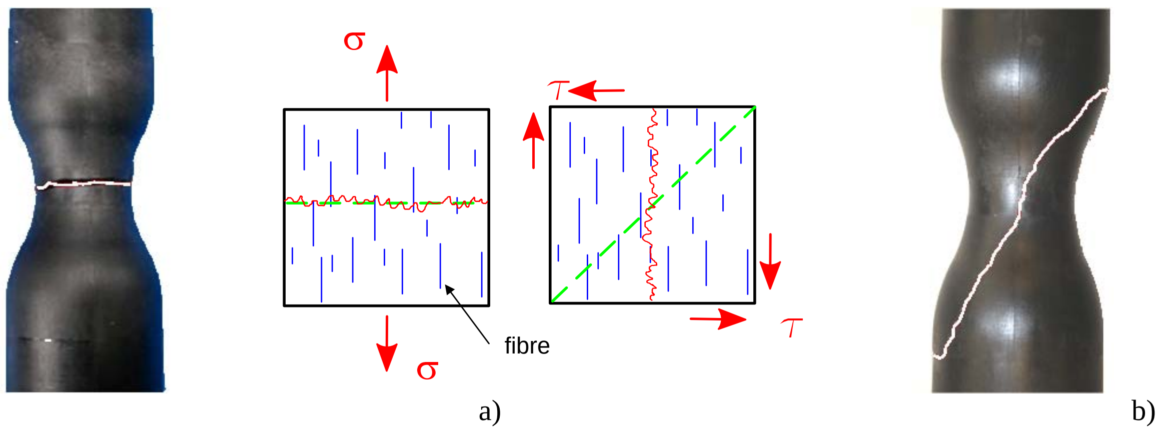

Figure 5 Crack path and corresponding stress state for a) pure tension, b) pure torsion

In literature [9–12] some basic fatigue criteria are detailed which might be applicable for sgfr materials. Figure 6 shows the failure criteria according to Gough and Pollard for the investigated material for a fatigue limit of $N = 10^6$. Therefore the normal stress amplitude σ_a is plotted over the shear stress amplitude τ_a with regard to the fatigue limits for normal- σ_{aD} and shear-stress τ_{aD} at $N = 10^6$. This multiaxial relation is given in (1) for a general case. The shape of the curve is defined by the two exponents z_σ and z_τ [2].

$$\left(\frac{\sigma_a}{\sigma_{aD}}\right)^{z_\sigma} + \left(\frac{\tau_a}{\tau_{aD}}\right)^{z_\tau} = 1 \tag{1}$$

If both exponents are equal two, the equation leads to the commonly used elliptical curve according to Gough and Pollard. Issler [13] reports the influence of the material ductility and the loading conditions (stress ratio, phase shift, etc.) on the shape of the curve. While $z_\sigma = 2$ represents a ductile material behaviour, $z_\sigma = 1$ is more applicable for a brittle material.
The results demonstrate that the sgfr material seems to be a very brittle material in terms of multiaxial fatigue strength. It should be stated, that the material behaviour and as a consequence the multiaxial exponents are influenced due to the manufacturing process as discussed in 3.4.

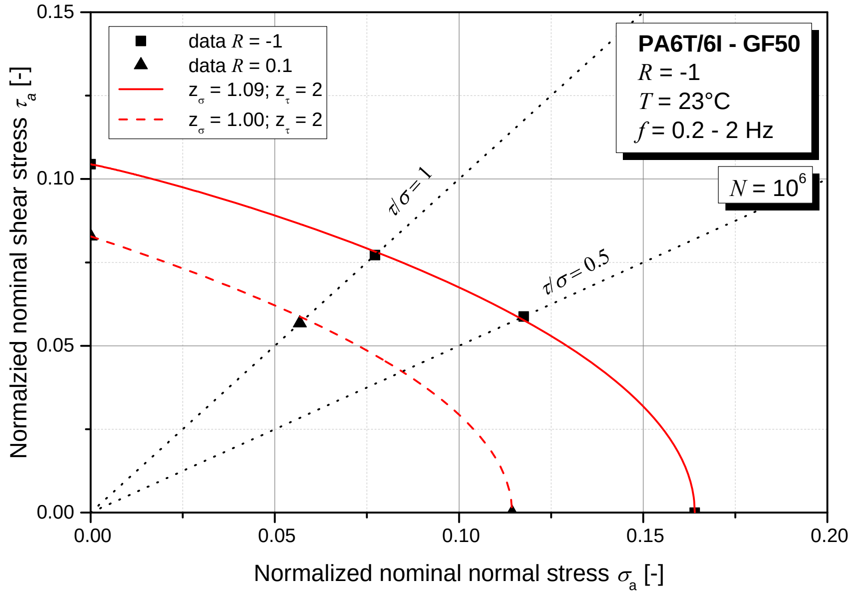

Figure 6 Multiaxial failure criteria for PA6T/6I – GF50 according to Gough and Pollard

3.2. Manufacturing influence

Fatigue tests under pure tension show a significantly reduced fatigue limit than expected due to the orientation model initially formulated by Gaier [14]. Figure 7 shows the influence of the fibre orientation on the fatigue limit. Based on the test results, the estimated main fibre orientation is around $a_{xx} = 0.5$. But filling simulation exhibit an improved fibre orientation value of $a_{xx} = 0.8$.

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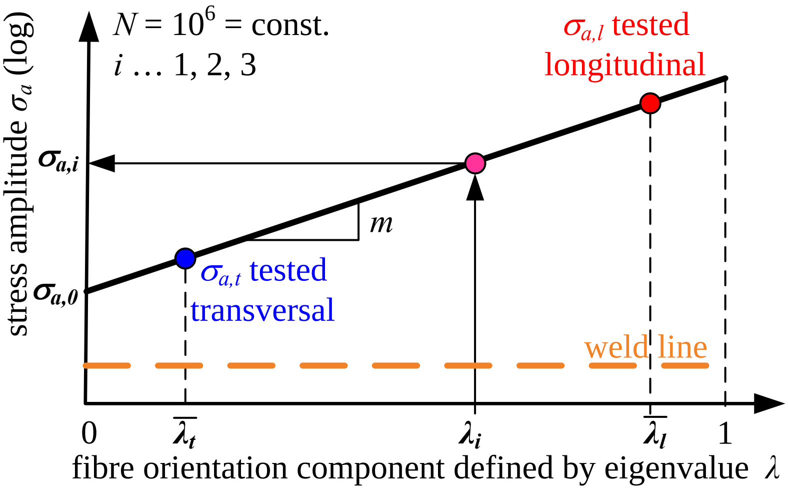

Figure 7 Fatigue strength depending on the fibre orientation for PA6T/6I –GF50 [15]

Due to this deviation between simulation and test results, the actually existing fibre orientation is additionally checked by CT-scans. The fibre orientation is measured at two points as documented before. For both positions the averaged fibre orientation is around a_{xx} = 80% over the thickness as expected in the filling simulation. The result of the CT-measurement is shown in Figure 8.

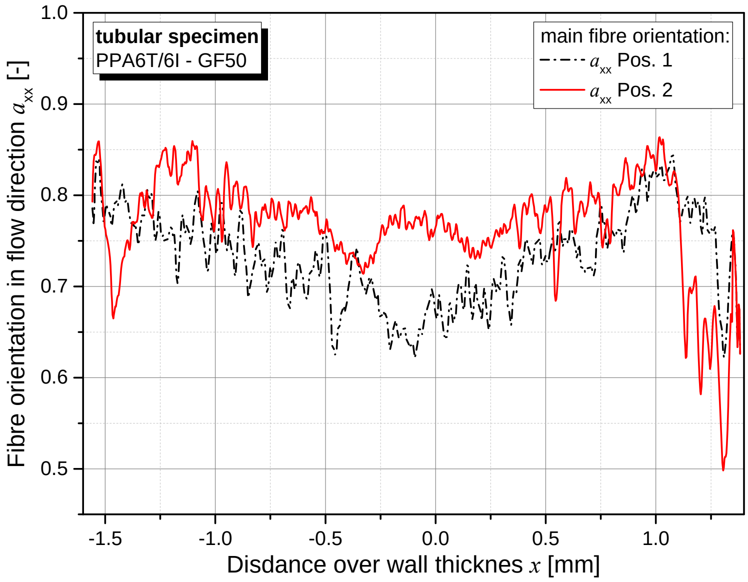

Figure 8 Fibre orientation over specimen wall thickness

Since the real fibre orientation a_{xx} = 0.8 is much higher as the expected value based on component fatigue testing, the in testing observed reduced fatigue limit could not sufficiently explained by the orientation model only and therefore other manufacturing effects must be responsible.
An additional CT-scan over the whole specimen indicates the formation of voids around the parting line of the tool through the whole specimen. The pore diameter is around three to four times of the fibre diameter. A micrograpical investigation in midsection of the specimen reveals a region with significant deviation in fibre texture and occurrence of pores in this critical volume. Therefore, the presence of pores can be confirmed and attributes as additional manufacturing effect on design strength of sgfr components. Figure 9 shows the results of the CT-scans and the micro section of the specimen.

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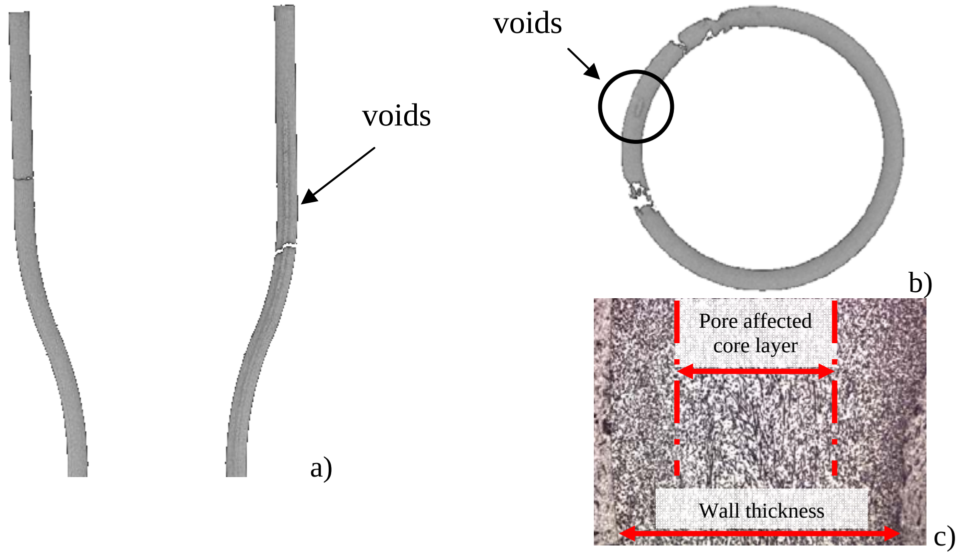

Figure 9 Void detection a) Pore path, b) CT-scan, c) Micro section

It is obvious that the detected void frequency cause the reduction in fatigue strength. Especially for normal stresses the weakened cross-section leads to a decrease in material strength. But as shear loading concentrates on the outer layer, the influence may be not so significant for this load case. Further investigations are scheduled to study the effect of injection moulding based formation of voids and their influences on fatigue strength for sgfr materials.

4. Conclusions and Outlook

Both uni- and multi-axial fatigue tests under varying stress ratios were performed on tubular shaped specimen. The grades of multiaxiality as well as the mean stress condition have a significant influence on the fatigue strength of sgfr polymer components. It was observed that with an increasing amount of shear stress the fatigue limit decreases. The test results show quite brittle fracture behaviour based on this specimen testing series. The elliptical failure criterion according to Gough and Pollard is basically applicable for these tests. But fatigue tests under pure tension revealed a reduced fatigue limit compared to former tests. Hence additional CT-scans were conducted to study manufacturing influences. Microscopic examinations showed the formation of voids along the parting line of the injection moulding tool in the tested tubular specimen. Due to this voids the fatigue strength is significantly reduced and further tests and analysis steps are scheduled as follows.
At first, it must be clarified what causes the formation of the voids in the injection moulding manufacturing process. At second, further fatigue tests with new void-free specimen will be conducted. Finally, other multiaxial criteria like the Tsai-Hill criteria are scheduled for comparative evaluation.

Acknowledgment

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