STUDY OF CRACK INITIATION AND CRACK PROPAGATION OF SHORT FIBER REINFORCED POLYAMIDE

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Abstract
This paper is about a study of the crack initiation and the crack propagation of short fibre reinforced polyamides following from cyclic loading. The crack initiation and propagation was investigated macroscopic by camera and microscopic by computer tomography.

1. Introduction

The state of art shows that in the field of polymers still static properties values like tensile strength, yield stress, strain at failure and static creeping are mostly used for the characterization of material properties and dimensioning of structural components. But many applications, e.g. in the automotive industry, are exposed to cyclic variable amplitude loading due the transmission of road asperity or motor vibration. Hence the only use of static values is not realistic for these applications and accordingly the consideration of occurred cyclic loading is necessary.
Furthermore the material values for the dimensioning often bases on the failure criteria rupture, which results from the historic used materials like metals.
But in the future of the automotive industry lightweight design is getting more and more relevant, which requires the use of new materials, more appropriate material design and the adaption of design standards.
One important issue is to allow cracks in design of the components. Therefore it is necessary to know fracture mechanical material properties where critical values are exceeded. For the component design crack initiation and crack propagation are of particular note. Therefore it is necessary to know the crack propagation velocity at the critical location of component.
Polyamides have been identified as being convenient for the cost effective mass production of complex structural components. Several types of polyamides have special advantages due to their use in a high temperature range, in aggressive fluids or in aging conditions. Heavy loaded structural components made of polymers can be reinforced with fibres to assure their functions over their whole use.
The reinforcement with fibres has a great impact on the mechanical properties of components. Fibres increase stiffness and strength and, additionally, a reduction in creep effects may be achieved.
In general components made of short fibre reinforce polymers are manufactured concerning the size by the injection moulding or the pressing process. There the melt is injected with a very high pressure into a mould. Due to this process the injection moulded or pressed component normally the fibres are aligned and from there they have anisotropic material behaviour. According to [1] for a plate the fibres aligns simplified in 3 layers. The shear flow creates a fibre orientation lengthwise in the flow direction

in the marginalised layer and the elongation flow causes a fibre orientation crosswise in the flow direction in the intermediate layer. [2,3]

Figure 1 shows the damage mechanisms that are responsible for the crack initiation and crack propagation in short fibre reinforced polymers. The crack initiation and crack propagation of reinforced polymers is mostly influenced by the interface of matrix and fibres. These are: Deformation and cracking of the matrix, fibre matrix debonding, sliding of the fibre, fibre pull out and fibre cracks.

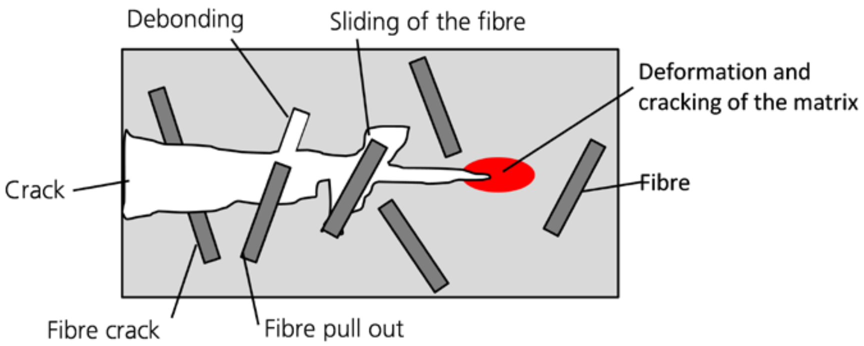

Figure 1. Damage mechanism of short fibre reinforced Polymer [4]

A possible approach of the crack initiation is the formation of crazes in the matrix. This approach is well investigated for amorphous Polymers. Compared to cracks, crazes are load-bearing. The surfaces of crazes are connected coherent to each other by fibrils. If the fibrils set off the crack initiates. In general is separated by extrinsic crazes that occur on the surface and intrinsic crazes whose occurrence is caused by local defects in the inner side of the material. [5] The dominant mechanism for the crack propagation depends on the local material properties, load scenario and design of the component[4]. The effect of crack propagation is caused by fibre matrix debonding, sliding of the fibre, fibre pull out and fibre cracks.

As described in [6] the crack propagation varies in the layers of the component, because of the diversifying resistance due to the fibre alignment. The crack propagation goes the path with the least resistance and is influenced by the local fibre orientation.

Components used in lightweight applications are often designed with notches in their design. The notches cause local stress concentrations. For a safe design of notched components, detailed material investigations of notches under cyclic loading are necessary. In the notch root the crack initiation starts and propagates to the rupture of the specimen.

2. Experimental section

In the following section the experimental test setup of two studies of the crack initiation and crack propagation of short fibre reinforced Polyamides following from cyclic loading are described. For the investigations two methods were used and compared. On the one hand crack initiation and crack propagation were investigated macroscopic by camera and on the other hand they were investigated microscopic by computer tomography.

2.1 Test Setup

For the macroscopic investigations a DSLR camera was positioned in the front of a test setup to take pictures in defined intervals, see Figure 2.

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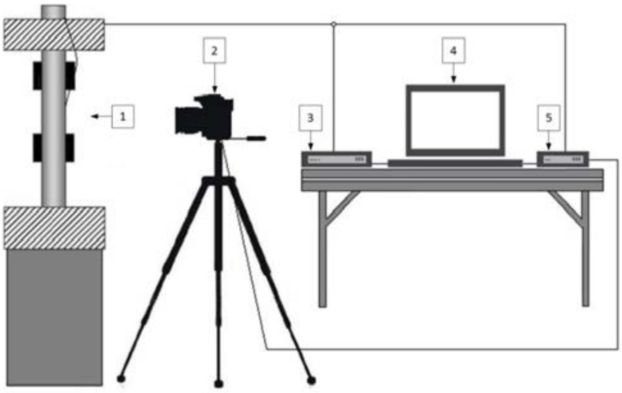

Figure 2. Set-up for macroscopic investigation by camera: 1 servo hydraulic testing machine, 2 camera, 3 modulator testing machine, 4 computer, 5 modulator) [7]

For the microscopic investigations a specified designed Computer Tomography (CT) system was used, where the radiographic examination facility was combined with the test rig of the mechanical loading, see
Figure 3 [8].

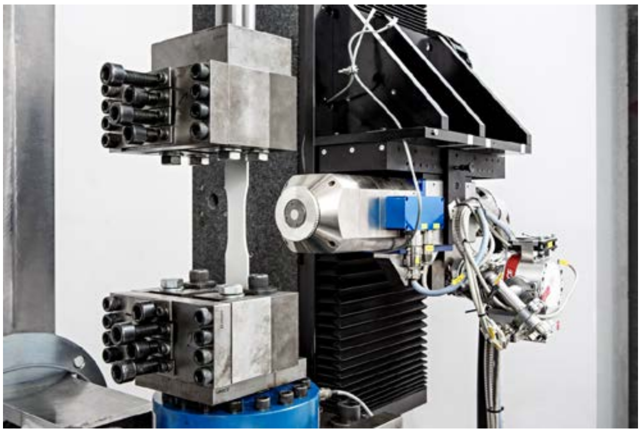

Figure 3. Computer Tomography system © Fraunhofer LBF

The CT scanner was optimized for the examination of X-ray plastic components. The tube is a so called transmission tube with 150 keV acceleration Voltage. The used transmission tube has a possible resolution of one micron. The detector which records the incoming x-rays and the x-ray tube are able to move in all directions in space which makes it is possible to get 3D CT scans. The procedure is the so called tomosynthesis [9].

2.2 Loading

The specimens were loaded cyclic by a hydraulic piston. The test frequency was in the range from 2 to 8 Hz and was chosen in dependency of the load amplitude. So the local warming caused by the mechanical loading was minimized to maximal 23°C + 5k. The stress ratio is defined as the ratio of minimum load to maximum load (Eq. 1) and was R = 0. The end of the cyclic testing was the rupture of the specimen.

$$R = \sigma_{min} / \sigma_{max} \quad (1)$$

For the microscopic and macroscopic investigation the cyclic test was stopped and the specimen was loaded with maximum load of the test condition to open a present crack. At this point a picture of the sample was taken, see
Figure 4.

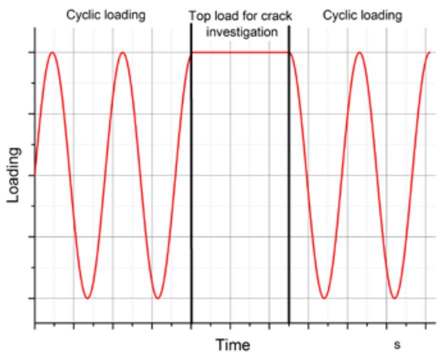

Figure 4. Load sequence for the visual documentation of damage by camera or CT

For taking the picture macroscopic by camera the needed time was about 5 seconds.
The recording time for the microscopic method by CT was about 10 Minutes.
After taken the pictures the cyclic loading was continued for without reconstruction of the specimen in the test facility. It is to mention that also for the investigations by CT the specimens remain firmly in place during the CT scan.

2.3 Specimen

The specimens were made of Polyamide 6 filled with 40 weight percent glass fibres (PA6 GF25). They were cut out of pressed plates concerning their local fibre orientation and the notches were manufactured by milling (
Figure 5). The notches have a notch factor of $K_t = 8.8$ (notch radius r=0,1mm).
For the investigation of the influence of the local fibre orientation on the crack initiation and crack propagation behaviour the specimens were cut out in 0° and 90° orientation to melt flow direction.

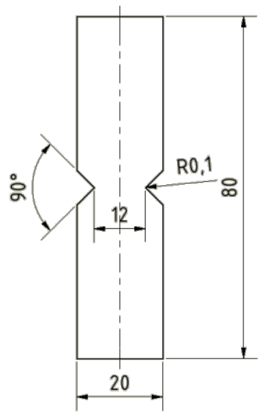

Figure 5. Geometry of the test specimen

3. Results

3.1 Macroscopic investigations

In a post process the number of load cycles at crack initiation and the length of the crack propagation were determined by the means of the photographs. For the determination of number of load cycles at crack initiation the crack length of a = 0,5 mm was used. In
Figure 6 are displayed photographs of the notched specimen at different number of load cycles. It is to mention, that the macroscopic crack was detected at the half number of load cycles of rupture. On unnotched specimens was established, that a macroscopic crack occur a short number of load cycles before rupture of the specimen.

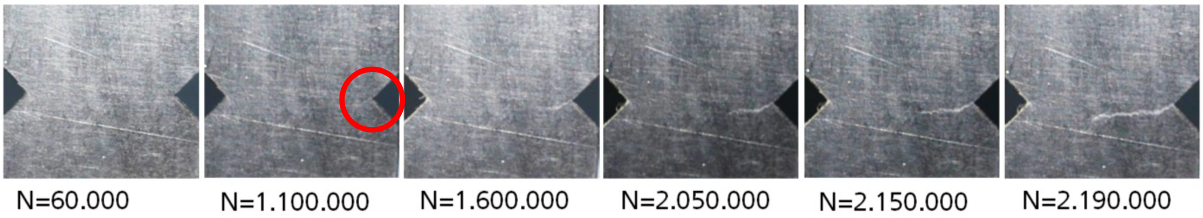

Figure 6. Determination of the macroscopic crack (N_{Crack} = 1,100,000, lengthwise fibre orientation)

In Figure 7 are displayed the S/N-curve of the investigated material for 0° and 90° fibre orientation. There is separate the number of load cycles when a macroscopic crack is detected and the number of load cycles when the specimen rupture. This is defined as N_{Crack} and N_{Break}. In general is there to mention, that lengthwise fibre orientation has a higher fatigue performance than the crosswise fibre orientation. Of particular note is that for the number of load cycles for crack initiation is nearly by half of the number of load cycles for rupture. But for lengthwise fibre orientation the number of load cycles when a macroscopic crack is detected is by one seventh to one fifth of the number of load cycles for rupture.
A possible approach of this behaviour could be that the high content of glass fibres causes brittle material properties which are more damage tolerant for notch effects. Occurring and growing cracks will be stopped at the longitudinal fibres in lengthwise direction. So the crack growth progresses is slowlier.

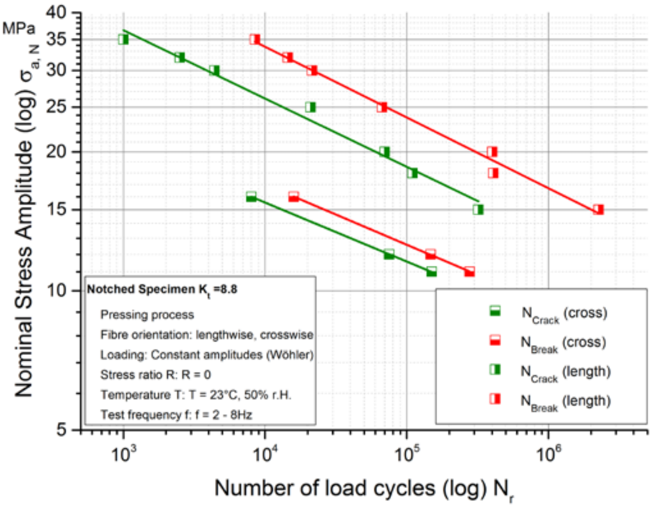

Figure 7. S/N-curve by the means of crack and rupture of the specimen for lengthwise and crosswise fibre orientation of the injection moulding process

Additionally the rupture surfaces of the investigation of PA66 GF25 injection moulded and PA6 GF40 pressed are compared, see Figure 8. There is to mention that for the PA66 GF25 the mainly aligned fibres across the loading direction the crack in the middle layer was leading. For PA6 GF40 this effect was not clearly detected.
For the specimens with the mainly aligned fibres in the loading direction it could not find clearly for all specimens that the cracks were leading in the surface layers.

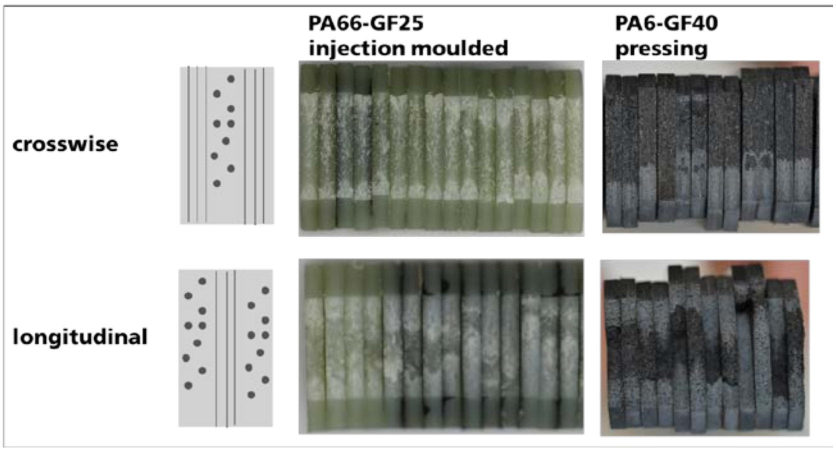

Figure 8. Rupture surfaces of the tested specimens with crosswise and longitudinal fibre orientation to the load direction

3.2 Microscopic investigations

In Figure 9 the microscopic investigations with CT are displayed. It shows the crack initiation and crack propagation in the layer near the specimen surface (layer 62) and in the middle layer of the specimen (layer 215).

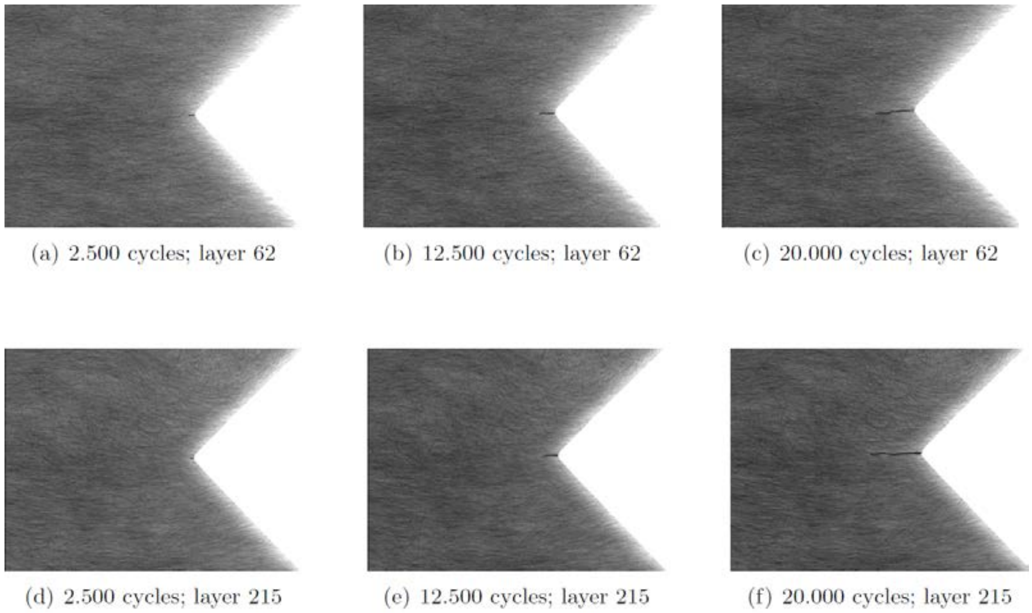

Figure 9. CT images, which show the crack progression near the surface and in the middle layer of the specimen

The results of the radiologic examination show, that cracks inside the material start later than visible on the outside surface, but prolong faster.

4. Discussion

This study was carried out to get more information about the damage mechanisms of short fibre reinforced polymers and to compare the macroscopic and microscopic methods.

For the macroscopic method by DSLR camera the identification of crack initiation and propagation is visible only from outside of the tested sample. The crack initiation and the crack propagation of the tested short fibre reinforced polyamide could be recorded very well. The benefit of this method is that the recording time during the test is quiet short and the set-up is simple.

If the crack initiation starts inside the material for example induced by inhomogeneities in the material or unsteadiness in the geometry like notches, the only possibility to detect and to monitor the crack initiation and propagation is to watch inside by using radiological methods (CT).
In this investigation the glass fibre reinforced polyamide started to fail within the connection of the fibres to the polymer matrix.
In this study the differentiation between the polyamide matrix system and the embedded glass fibres is clearly visible and presentable. The embedded glass fibres were only down to 15 micrometre small in diameter, the resolution of the chosen testing method needs to be able to visualize these microscopic points. This can only be achieved by using x-ray, especially a computer tomography which can analyse the whole component in 3D. By creating a 3D volume of the material specimen gave the opportunity to scroll through the layers of the material in very small steps. These steps through the layers are usually a few microns of thickness, so no damage was overseen.
For this investigation was decided to have a lower resolution but to have the opportunity to overlook all critical parts of the specimen because of the crack initiation could occur on both notches of specimen. Because of this, the resolution was lower than physically possible. For the visibility of the embedded glass fibres, a resolution half of the fibre diameter would be required. Hereby the resolution was lower so that the surface of the fibres and their interaction was not presentable. The main focus was to detect the place and depth, and on which side the first cracks were initiated.

When the concrete location of failure is known, one can zoom in directly to this spot and have a high resolution. This was not carried out in this study.
First cracks start on the tip of the notch close by to the surface but grow slower due to the fibre orientation crosswise to the crack direction. A larger and faster crack because of the parallel fibre orientation was found inside the material.

5. Conclusion

The failure criteria rupture, which is common in metal based material constructions do not highlight the benefits of fibre reinforced polymers. The benefit from plastic materials is to allow cracks in the dimensioning of plastic components to reduce weight and to design components in the term of lightweight design.
The need to investigate upon the crack initiation and crack propagation is essential to learn about the behaviour of reinforced polyamides. The monitoring of the start of failure and the following of the crack propagation give essential information about the fatigue behaviour of the material.
The macroscopic investigation of the crack initiation and propagation help to understand the failure behaviour on the specimen and component level. The macroscopic test set-up can easily adopt to usual fatigue investigations.
With the microscopic investigation by CT it was possible to detect cracks inside the material and to visualize the initiation of cracks on the surface and on the inside during a fatigue test with cyclic loads. This method is more complex than the macroscopic but gives us the opportunity to get information of the material behaviour inside a specimen or component.
With these methods, whether the macroscopic or the microscopic, it can be created an additionally information, which can be used for the design of structural parts.

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