INFLUENCE OF FREQUENCY AND STRESS CONCENTRATION ON FATIGUE BEHAVIOUR OF SHORT GLASS-FIBRE REINFORCED POLYAMIDES

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Abstract Materials such as short fibre reinforced polyamides are being increasingly used in structural durability applications. Hence, application related material data are required for the dimensioning of components made of these materials. However, the procedures for the performance of fatigue testing are still under discussion. In view of this current status, this paper gives attention to experimental investigations regarding the influence of test frequency on the fatigue life of short glass-fibre reinforced polyamides. Fatigue tests with constant amplitudes were carried out and simultaneously the data of hystereses and surface temperature were recorded and subsequently analysed. In addition to the value of load level, the influencing parameters stress concentration (notch factor), which reduces the highly stressed material volume, and the mean stress (stress ratio) were considered in the assessment of the influence of frequency on the fatigue life.

1 INTRODUCTION

The simplest method for fatigue testing is the Woehler-fatigue test (single level test), where a component oscillates around a constant mean stress. [1] Normally this kind of fatigue test is used to determine material parameters for the dimensioning of components, even though components are often loaded with variable amplitudes in reality.[2][3]

For example PSA Peugeot Citroën, Mark IV and Mann & Hummel need to know the fatigue life of plastic material used or usable for power train or chassis modules applications. The stakes are:

- Durability of plastic parts that are exposed to increasing stress and temperature
- Reducing the weight of cars and therefore reducing CO2 emission.

Fatigue data are used to dimension the parts but also to build robust specifications.

However, especially for components made of thermoplastics, the choice of a low test frequency during fatigue testing is very important in order to determine useful results without the effect of self-heating of the specimen.[2]-[6] Because the use of low test frequencies implies long test periods and consequently high costs, it is desirable to increase the test frequency as far as is possible without the effect of self-heating.

This paper presents three test series, which deal with the investigations of the influence of test frequency on the fatigue life of short glass fibre reinforced polyamide 6.6.

2 EXPERIMENTAL

2.1 Specimens

For these investigations, unnotched and notched flat specimens with the theoretical notch factors K_t=1.0 and K_t=2.5 were used, see Figure 1. All specimens were made of a short glass fibre reinforced polyamide 6.6 with 35 % fibre content (Zytel® 70 G35 HSLX BK357). The specimens were produced by injection moulding. The notches of the specimens with theoretical notch factor K_t=2.5 were produced by an insert in the mould during the injection moulding process. The initial state of humidity of the specimens was dry as moulded (dam).

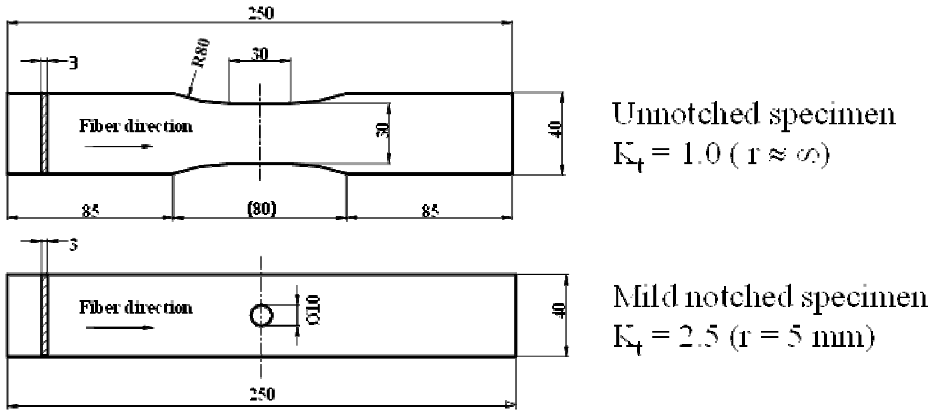

Figure 1. Unnotched and mild notched flat specimens made of short glass fibre reinforced polyamide 6.6

2.2 Test facility and test procedures

All fatigue tests were carried out with constant amplitudes (Woehler) at room temperature (RT). It is to mention, that the lab temperature and the lab humidity were not constant. The lab conditions were approximately T=20 °C and φ=40 %rh with its natural environmental fluctuation.
Figure 2 shows the general set up for fatigue tests with flat specimens. The test load was induced into the specimen by friction via hydraulic clamping. Servo hydraulic test equipment was used. The forces produced were regulated via variance comparison with a pilot valve. For all fatigue tests, which were carried out with stress ratio R=-1, a support was used to prevent buckling of the specimen. The support was fixed in such a way that it did not influence the loading and deformation of the specimen.

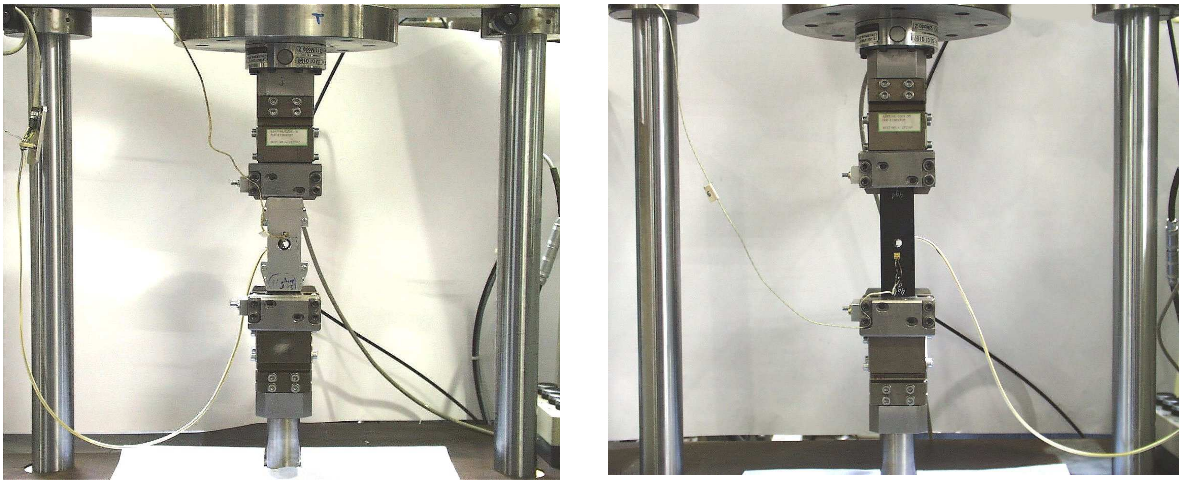

Figure 2. General test set up for fatigue tests of flat specimens with stress ratio R=-1 (using of anti-buckling support) and R=0

During fatigue testing the specimen temperature (surface) and hystereses (load and displacement) were recorded.

2.2.1 Test series 1: Fatigue tests of unnotched specimens (K_t=1.0, R=0, RT) with recording of temperature by thermo-graphic camera and displacement by laser extensometer

For the first investigation, unnotched specimens (K_t=1.0) were used. The stress ratio was R=0 (mean stress). The fatigue tests were carried out at different stress levels with test frequencies of 5 Hz and 15 Hz. The temperature was recorded by thermo-graphic camera. The displacement of the specimen was measured by a laser extensometer. Hence the displacement was measured about the specimen length l_0,s=125 mm.

2.2.2 Test series 2: Fatigue tests of unnotched specimens (K_t=1.0, R=-1, RT) with recording of temperature by thermocouples and deformation by a laser extensometer

For the second test series, unnotched specimens (K_t=1.0) were investigated and loaded with stress ratio R=-1. The fatigue tests were carried out at two different stress levels ($\sigma_{an,1}$=80.0 MPa, $\sigma_{an,2}$=70.0 MPa) with four different test frequencies (1 Hz, 4 Hz, 8 Hz and 15 Hz). For this test series, the temperature was measured by thermocouples and the displacement of the specimen was measured by a laser extensometer, see Figure 3. The displacement was measured about the specimen length l_0,s=125 mm.

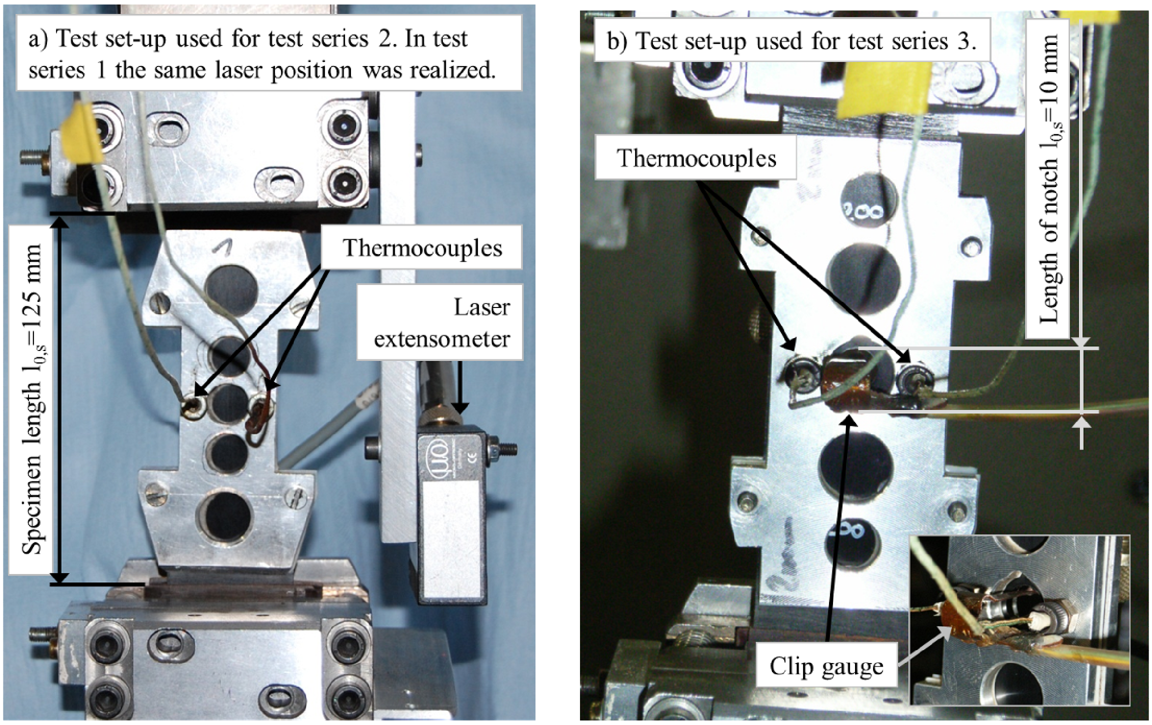

Figure 3. a) Test set up for test series 2. b) Test set-up for test series 3.

2.2.3 Test series 3: Fatigue tests of mild notched specimens (K_t=2.5, R=-1, RT) with recording of temperature by thermocouples and of local deformation in the notch of the specimen by a clip gauge

Mild notched specimens (K_t=2.5) were investigated. The stress ratio was R=-1. The fatigue tests were carried out at two different stress levels ($\sigma_{an,1}$=45.0 MPa, $\sigma_{an,2}$=35.0 MPa) with four different test frequencies (1 Hz, 4 Hz, 8 Hz and 15 Hz). For this test series, a thermocouple, which was located near the notch root, was used for the measurement of temperature. The local deformation was measured by a clip gauge (strain gauges), which was located in the notch of specimen. Hence the displacement was measured about the length of notch $l_{0,n}$=10 mm.

Table 1 shows an overview about the different test series.

Test serie	**Notch factor K_t**	**Stress ratio R**	**Temperature**	**Moisture content of specimens**	**Recording of the surface temperature T**	**Measurement of displacement s**	**Frequency f**	**Nominal stress level σ_{an}**
1	1	0	RT	dam	IR thermo-graphic camera	Laser extensometer	5 Hz 15 Hz	30 MPa < σ< 58 MPa
2	1	-1	RT	dam	Thermocouples	Laser extensometer	1 Hz 4 Hz 8 Hz 15 Hz	80 MPa 70 MPa
3	2.5	-1	RT	dam	Thermocouples	Clip gauge (local deformation in the notch)	1 Hz 4 Hz 8 Hz 15 Hz	80 MPa 70 MPa

Table 1. Overview about the different test series

3 RESULTS

3.1 Test series 1: Fatigue tests of unnotched specimens (K_t=1.0, R=0, RT) with recording of temperature by thermo-graphic camera and displacement by laser extensometer

In Figure 4, the single results of the Woehler-tests, which were carried out with frequencies of 1 Hz, 5 Hz and 15 Hz, are presented. The single tests are designated as (a) to (h).

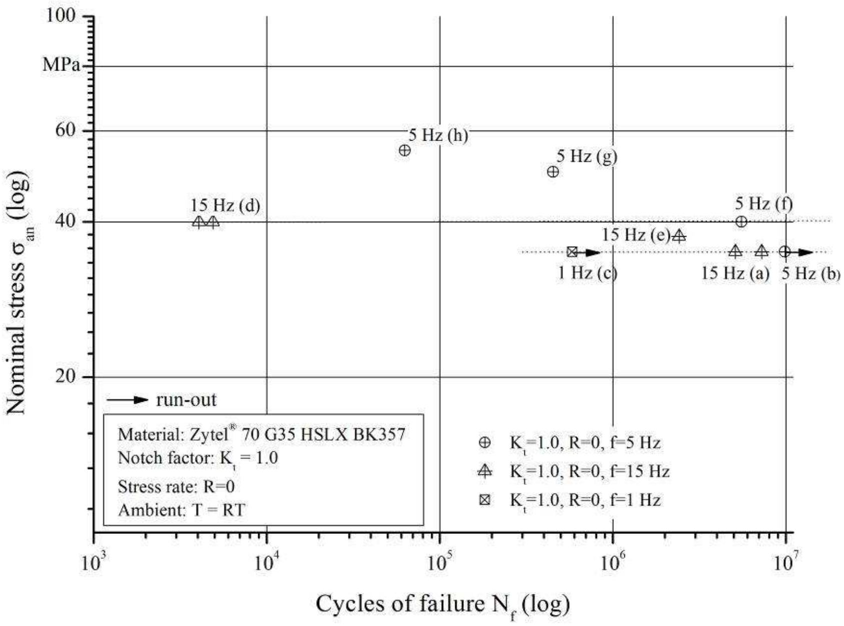

Figure 4. Influence of test frequency on the fatigue life of unnotched flat specimens made of short glass fibre reinforced polyamide at stress ratio R=0

It is obviously that the fatigue lives of the Woehler-tests with the frequencies f=5 Hz and 15 Hz differ from each other.
According to reference [7], it **c**an be stated that an increase of load velocity leads to an increase of endurable stress, if the plastic deformation is reduced without temperature increase, and, if the inserted energy can be removed from specimen to ambience, temperature equilibrium takes place.

With the differential equation according to Fourier, see equation 1, the following relationship can be described:

$$\frac{dH}{dt} = \Sigma \dot{Q}_{Fl} + \Sigma \dot{Q}_{Um} \qquad (1)$$

The change of the enthalpy H conforms to the sum of the heat flow. On the one hand, heat flow ($\dot{Q}_{Fl}$) caused by thermal conduction ($\dot{Q} = R_\lambda \cdot \Delta T$, where R_λ is the thermal resistivity, which depends on the material and the geometry) [8] and thermal convection ($\dot{Q} = R_\alpha \cdot \Delta T$, where R_α is the heat transmission resistance, which depends on the material, the geometry and the fluid flow) [8], is dependent on parameters such as the temperature difference between local specimen points and ambience, the specimen geometry, the specimen material and the ambient media. On the other hand, heat flow ($\dot{Q}_{Um}$) can be affected by generated internal heating of the system, for example by friction and inner damping. The mechanical energy dissipated per cycle is proportional to the hysteric- loop in a load-displacement-diagram.

For the stationary case, it is essential, as shown in equation 2 and accordingly in equation 3, that

$$\frac{dH}{dt} = \Sigma \dot{Q}_{Fl} + \Sigma \dot{Q}_{Um} = 0 \quad \Rightarrow \quad \Sigma \dot{Q}_{Fl} = -\Sigma \dot{Q}_{Um} \qquad (2)$$

or $\Sigma \dot{Q}_{Fl} \geq \Sigma \dot{Q}_{Um}$. (3)

This implies that the energy, which was induced into the system, can be discharged and therefore no increase of temperature can be observed, see Figure 5.

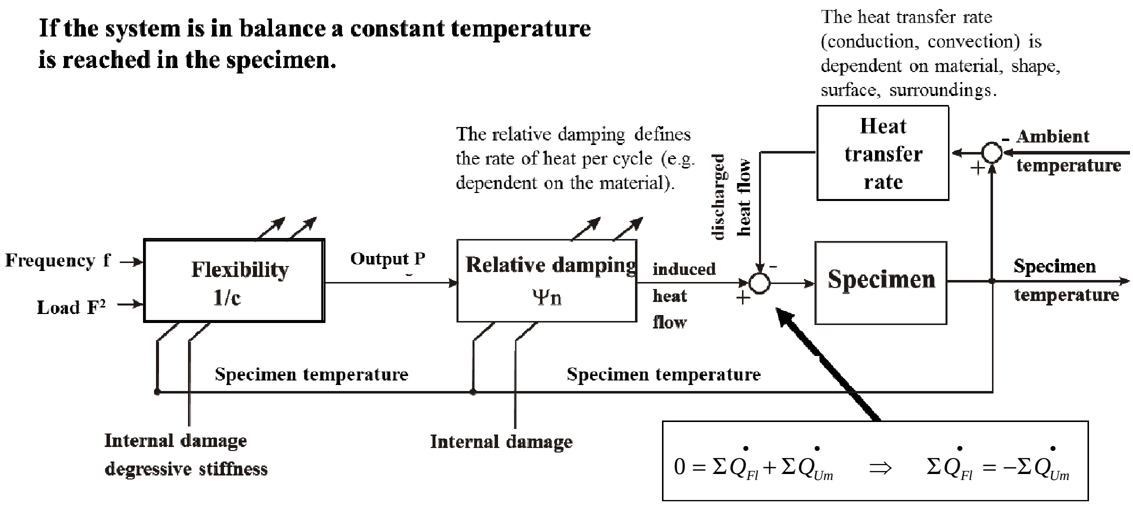

Figure 5. Thermodynamic system of a cyclically loaded specimen for the example of the stationary case

For the heating-up case, it is essential that the heat flow ($\dot{Q}_{Fl}$) is smaller than the heat flow ($\dot{Q}_{Um}$) see equation 4.

$$\frac{dH}{dt}=\Sigma\dot{Q}_{Fl}+\Sigma\dot{Q}_{Um} \quad \Rightarrow \quad \Sigma\dot{Q}_{Fl}<\Sigma\dot{Q}_{Um} \tag{4}$$

The heat quantity, which results from the induced energy into the system, is greater than the heat quantity, which can be dissipated. The specimen heats up until the stationary case is reached or the specimen fails.

This thermodynamic system can also be recovered in the hysteresis-loops of fatigue testing.
In Figure 6, the comparison of the first hysteresis-loop and last hysteresis-loop of a fatigue test is presented schematically. It gives qualitative information about the following material characteristics:

- The displacement of hysteresis in the x-direction gives information about the creep of the material.
- The change of the slope of the middle curve of the hysteresis gives details about the change of stiffness and
- The progressive widening of hystereses gives information about the increase of damping e.g. due to increase of damage of the material.

The ratio of energy loss D to energy storage E is equal to the related damping ψ, see equation 5:

$$\psi=\frac{D}{E} \tag{5}$$

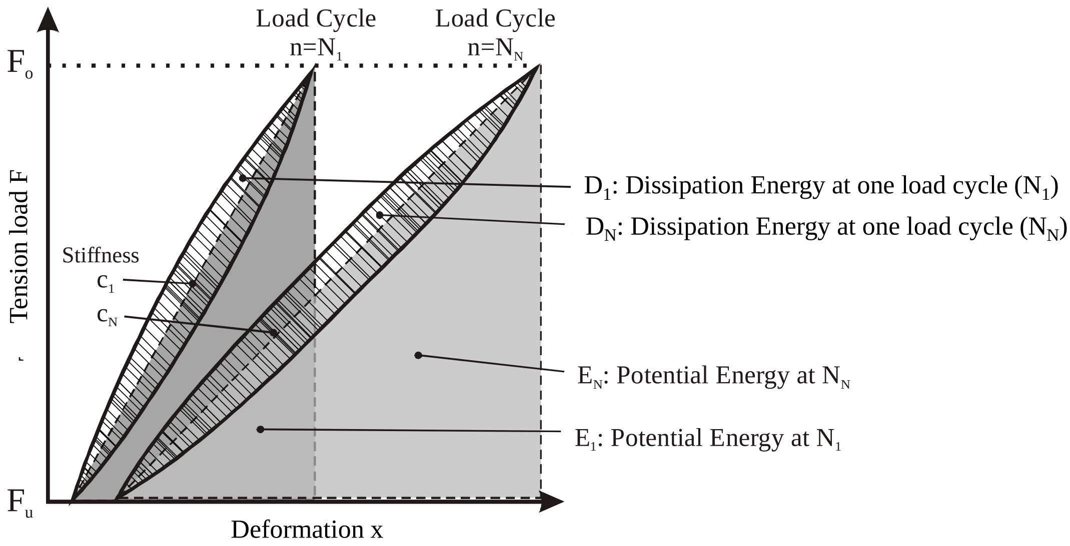

Figure 6. Hystereses (schematic)

Figure 7 compares the temperature development with increasing numbers of cycles of the fatigue tests with nominal stress amplitude σ_{an}=35 MPa (a, b, c) from Figure 6. The specimens, which were loaded with the test frequencies 1 Hz and 5 Hz, show no significant temperature change during the testing period, i.e. the stationary case takes place. In contrast to these results, the specimen, which was tested with f=15 Hz (a), also shows no change in temperature initially, which means that the stationary case also takes place. At the end of the Woehler-test, the temperature increases rapidly to about 130 °C. This temperature increase results from the inner damage of the material, which is continuatively connected to the increase of damping (heating-up c ase).

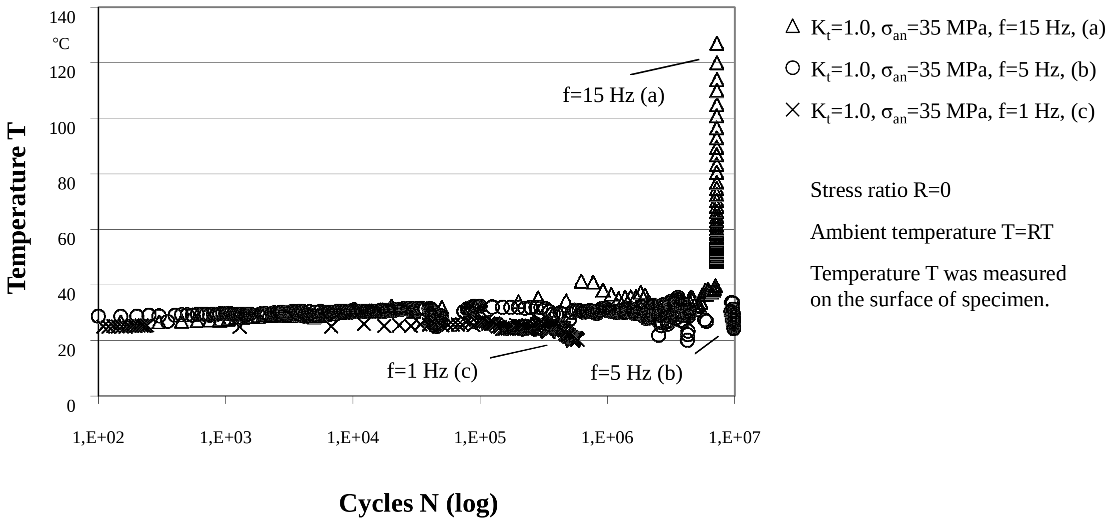

Figure 7. Temperature development of fatigue tested flat specimens. Test frequencies were 1 Hz, 5 Hz and 15 Hz.

Figure 8 shows the recorded hystereses from the fatigue tests a and c. The force F, which is presented about the displacement s, is determined by the damping characteristics (viscosity η) and the spring characteristics (Young's modulus E) of the material. The comparison of these hystereses leads to the following statement:
With increase of test frequency, the hystereses widening is increased.[9] This confirms the viscoelastic material behaviour, because of the viscous damping is proportional to the material viscosity and the load velocity and hence the frequency. The energy loss is increased due to the increasing damping force. The slopes of the hystereses middle curves of these two specimens are almost identical. At this load level, the frequency in the interval of 1 to 15 Hz has no influence on the slope of middle curve of hystereses. In terms of the tendency to creep of this material as a function of frequency and in relation to the survived number of cycles, it can be stated that the material creeps most with a test frequency f=1 Hz and creeps least with a test frequency f=15 Hz.

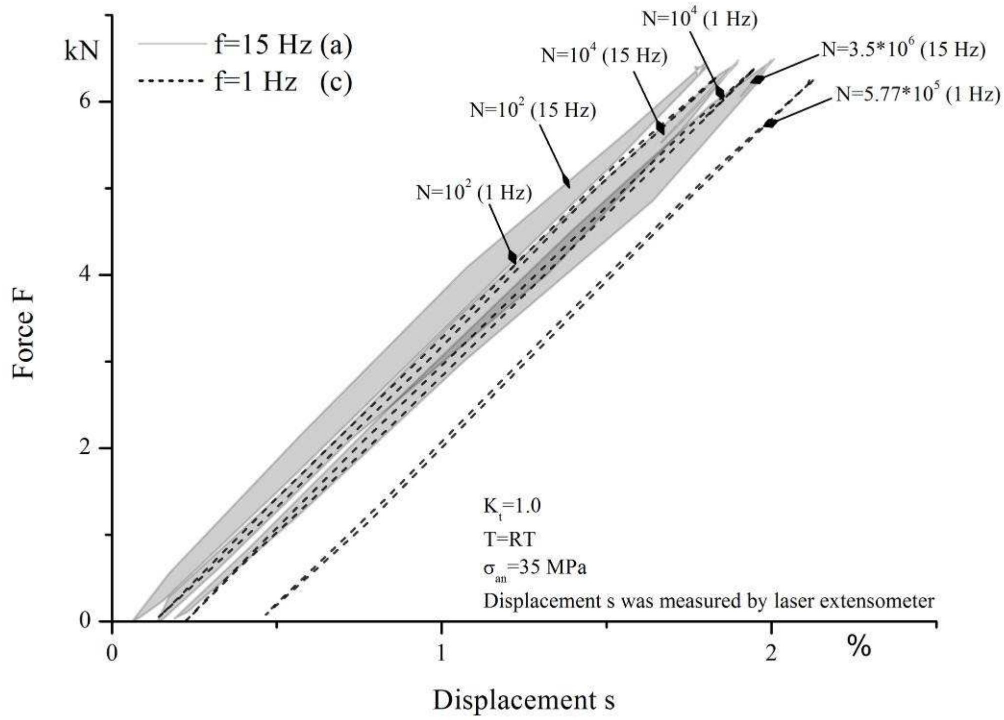

Figure 8. Comparison of Hysteresis-loops of two fatigue tests at the same load level with different test frequencies

According to [10], the mode of deformation is dependent on time. If a polymer is loaded spontaneously, the material behaves in a glass-like manner and the deformation is reversible after release. This mode is called energy elastic. If a polymer is loaded in a time dependent manner, the behaviour of the material can be thermo-elastic or thermoplastic. If the polymer behaves thermo-elastically, the deformation is entropy elastic and the deformation relaxes to its initial state after load relieving. If the polymer behaves thermo-plastically, the deformation of the polymer is plastic or viscous. After load relieving, the deformation of the polymer is irreversible. This time dependent deformation behaviour is related to the macromolecule structure of polymers.

With reference to the results above for the Woehler-test with 1 Hz frequency and the least creep, it can be assumed that the material behaves in a more viscous manner due to the low frequency than in the Woehler test with 15 Hz test frequency. Therefore, the material creep of the test with 1 Hz is greater than the test with 15 Hz frequency loading.

The numbers of cycles reached in these three tests (a, b, c), see Figure 4, show that the test with 5 Hz (b) had the longest life time. The reason for this behaviour could be that, over the complete testing time, the thermodynamically stationary case was available and also the material crept less than in the test with 1 Hz (c) frequency.

In Figure 9, the temperature development of the specimens from the Woehler-tests with 15 Hz test frequency is plotted. The different nominal stress amplitudes were σ_{an}=35.0 MPa (a), σ_{an}=37.5 MPa (e) and σ_{an}=40.0 MPa (d). Apparently, temperature increased rapidly to T>110 °C at the end of fatigue tests for all three stress levels. The temperature of the specimen, which was loaded with the highest stress level σ_{an}=40.0 MPa (d), showed an immediate rapid increase after the start of the fatigue test. Within a short time, the heating-up case ($\Sigma \dot{Q}_{Fl} < \Sigma \dot{Q}_{Um}$) takes place. At the tests with the lower stress levels, σ_{an}=35.0 MPa and σ_{an}=37.5 MPa, it can be observed that an initial temperature plateau was established (stationary case). Close to the end of the fatigue test, the temperature increased rapidly to T>110 °C. Caused by the inner damage of the material, the earlier stable system changed to the thermodynamic heating-up case.

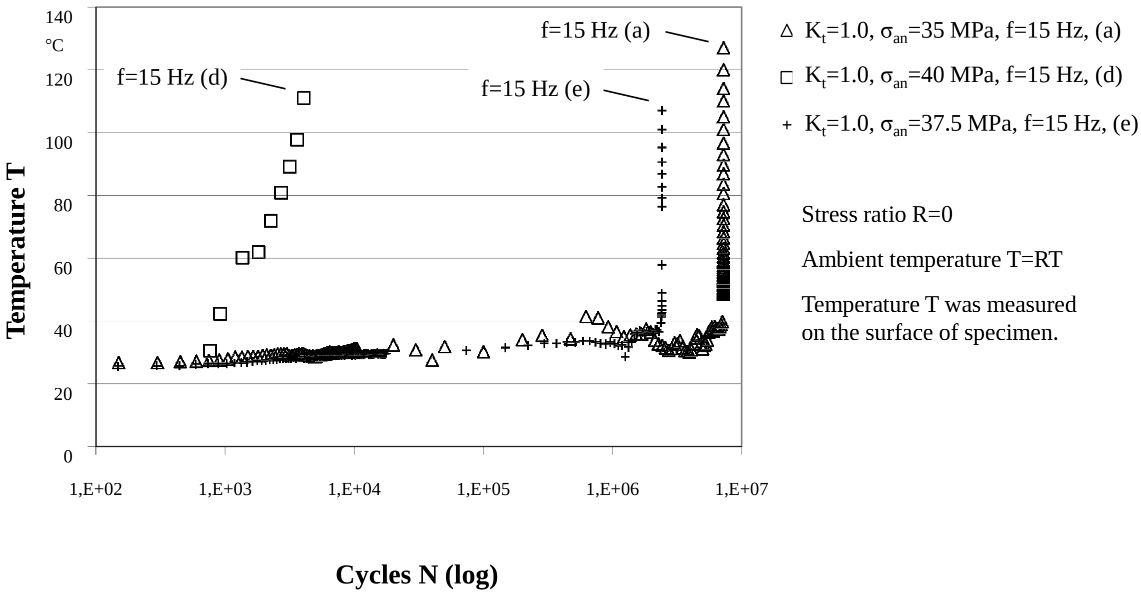

Figure 9. Temperature development of fatigue tested flat specimens. Test frequency was 15 Hz.

The comparison of the hystereses of the tests with stress amplitude σ_{an}=35.0 MPa (a) and σ_{an}=37.5 MPa (e), see Figure 10, shows that, for the test with the higher stress amplitude, a greater creep tendency relating to the number of cycles is displayed than for the test with the lower stress amplitude. Such an effect was also established in [6].

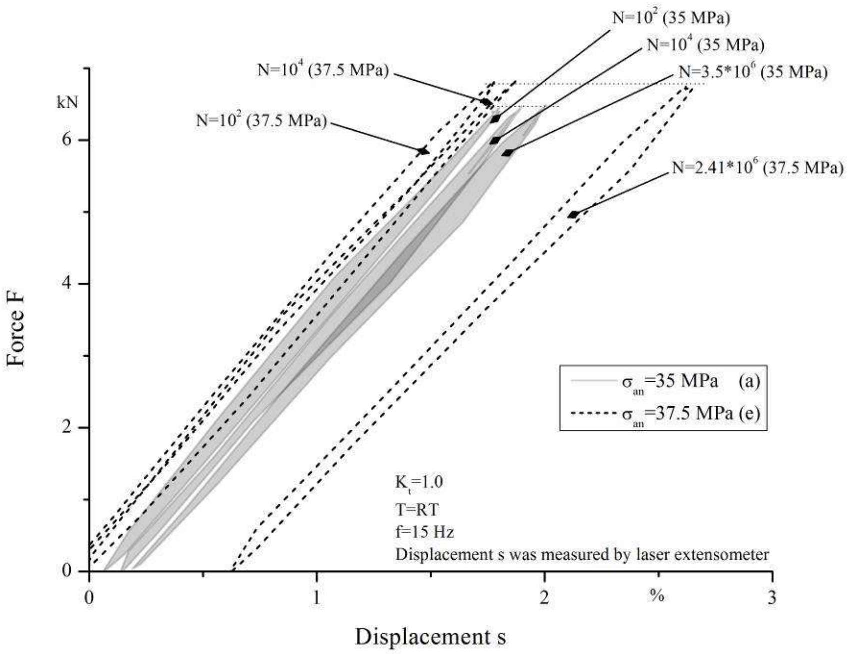

Figure 10. Hysteresis-loops of fatigue test a (σ_{an}=35.0 MPa, f=15 Hz) and fatigue test e (σ_{an}=37.5 MPa, f=15 Hz).

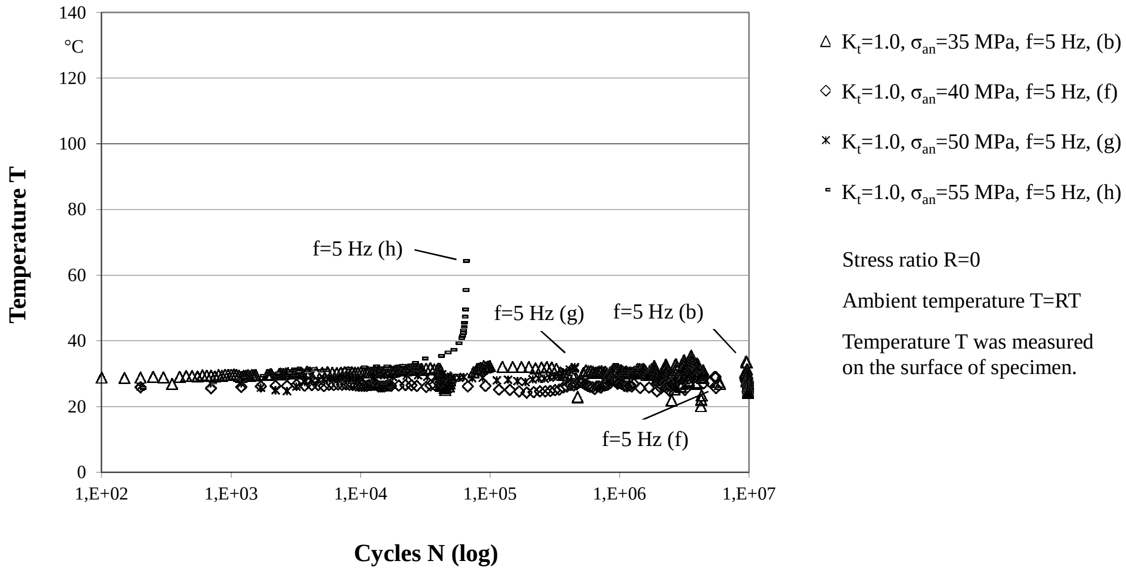

Figure 11. Temperature development of fatigue tested flat specimens. Test frequency was 5 Hz.

Figure 11 shows the temperature of the specimen developing during the fatigue tests, which were carried out with 5 Hz test frequency. The different stress levels were σ_{an}=35.0 MPa (b), σ_{an}=40.0 MPa (f), σ_{an}=50.0 MPa (g) and σ_{an}=55.0 MPa (h). Altogether, the temperature-curves show no significant change of temperature as a function of the number of cycles except for the curve from the fatigue test with stress level σ_{an}=55.0 MPa. This test, with the highest stress level of σ_{an}=55.0 MPa, shows a stable temperature similar to the other specimens, which were tested at lower stress levels. At the end of fatigue test, the temperature increases rapidly to about T=70 °C.

3.2 Test series 2: Fatigue tests of unnotched specimens (K_t=1.0, R=-1, RT) with recording of temperature by thermocouples and of deformation by a laser extensometer

In Figure 12, the numbers of cycles reached in the single Woehler-tests with different test frequencies (1 Hz, 4 Hz, 8 Hz and 15 Hz) were plotted. The graph shows that, with increase of frequency, the number of cycles decreases. This same result was obtained for both stress levels studied, $\sigma_{an,\,1}$=80.0 MPa and $\sigma_{an,\,2}$=70.0 MPa, apart from the test with a frequency of 4 Hz at the low stress level $\sigma_{an,\,2}$=70.0 MPa, which reached almost the same number of cycles as the test with 1 Hz test frequency.

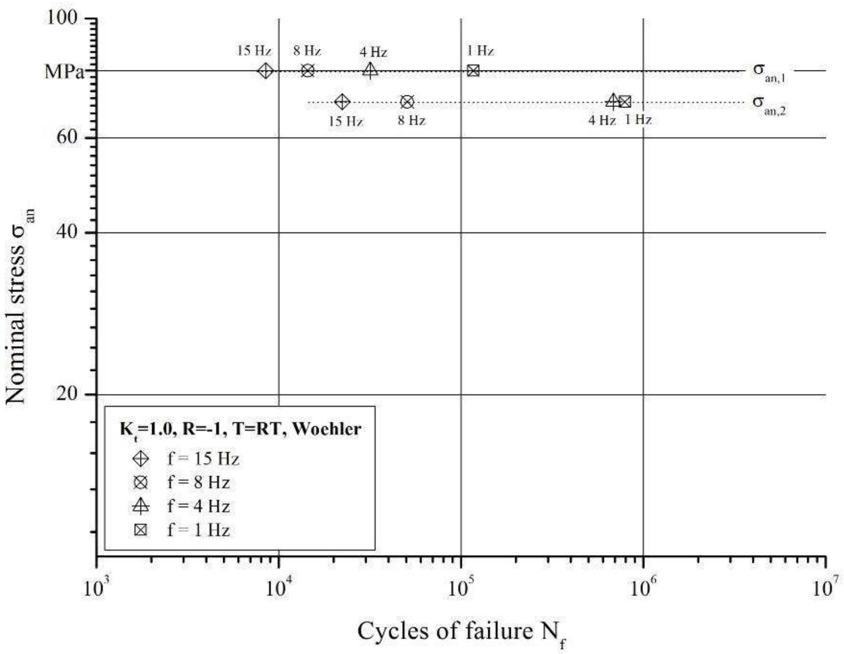

Figure 12. Influence of test frequency on the fatigue life of unnotched flat specimens made of short glass fibre reinforced polyamide at stress ratio R=-1

Figure 13 shows the temperature curves of all eight Woehler-tests. For the Woehler test with 1 Hz test frequency and the test '$\sigma_{an,\,2}$, 4 Hz', no change of temperature as a function of the number of cycles was determined (stationary case). For all the other fatigue tests, a temperature increase was observed. This graph shows that the temperature development is dependent on both the test frequency and the stress level.

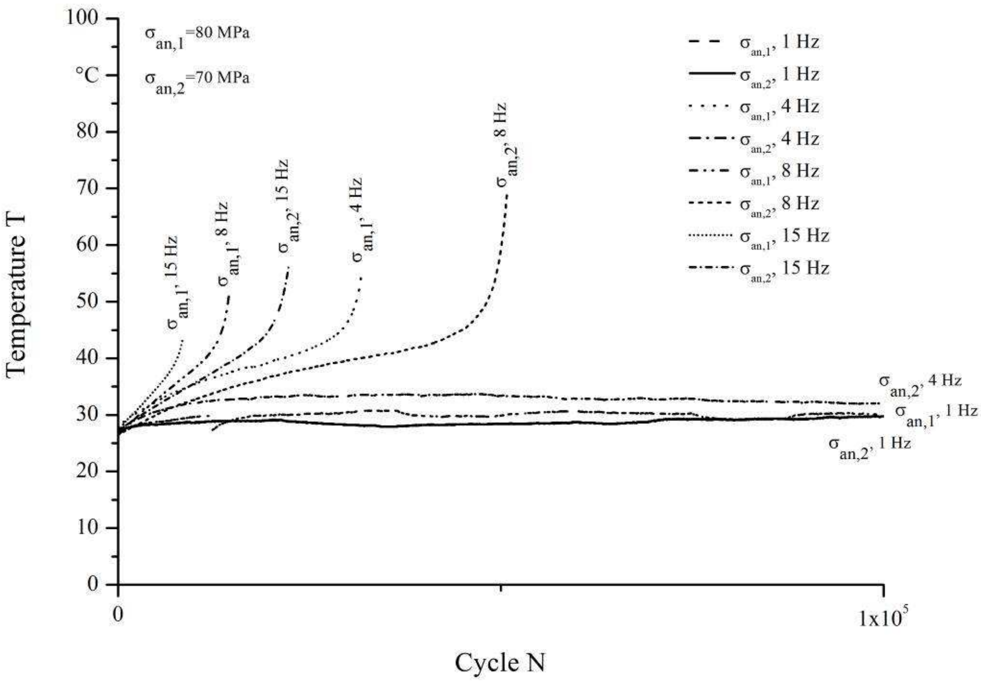

Figure 13 : Temperature development during fatigue testing of mild notched specimens

In Figure 14, the hysteresis-loops of the first 2000 cycles from the two specimens, which were loaded at stress level $\sigma_{an,\,2}$=70.0 MPa with 1 Hz and 15 Hz, are plotted. Obviously, the hystereses of the tests with these different test frequencies are superimposed in the first 2000 cycles. This graph shows again that the hysteresis-loops from the test with 15 Hz are wider than those from the tests with 1 Hz. This means that, with an increase of the frequency, the enclosed hystereses area increases and consequently the energy loss (dissipations energy D) increases.

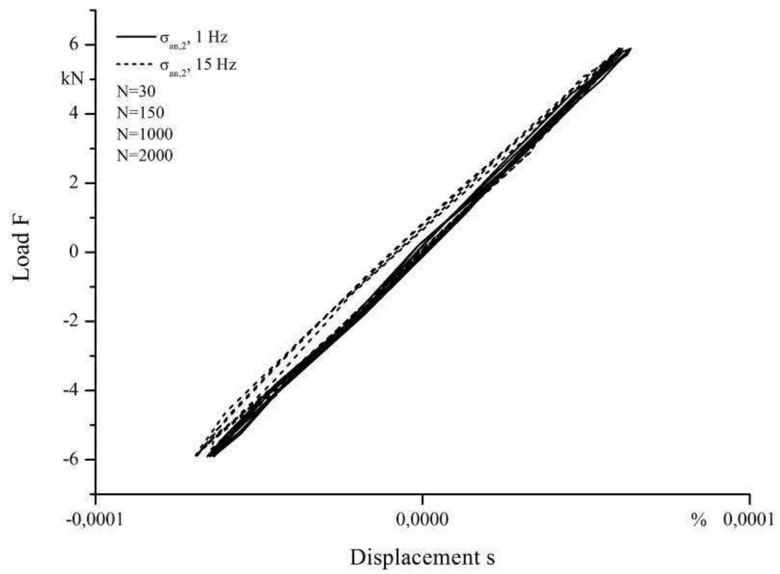

Figure 14. Comparison of hysteresis-loops of two fatigue tests at the same load level with different frequencies

3.3 Test series 3: Fatigue tests of mild notched specimens (K_t=2.5, R=-1, RT) with recording of temperature by thermocouples and local deformation in the notch of specimen by a clip gauge

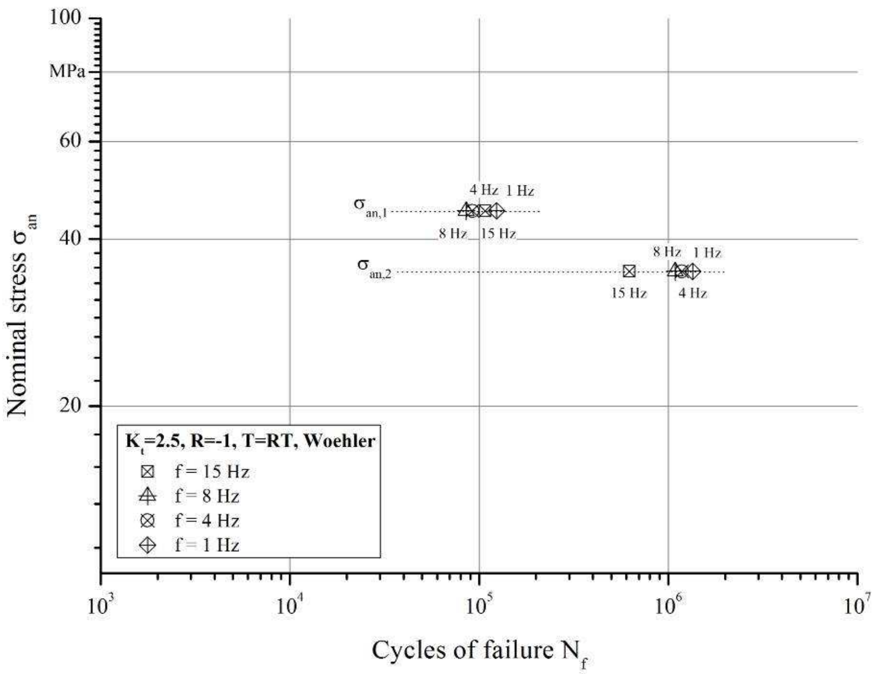

Figure 15. Influence of test frequency on the fatigue life of mild notched flat specimens made of short glass fibre reinforced polyamide at stress ratio R=-1

Figure 15 shows the number of cycles reached in the tests at the two stress levels $\sigma_{an,1}$=45.0 MPa and $\sigma_{an,2}$=35.0 MPa with the different test frequencies 1 Hz, 4 Hz, 8 Hz and 15 Hz. Conspicuously, the points of the Woehler-tests from the frequency investigation are very close to each other. In contrast to the investigations in test series 2 with unnotched specimens, it seems that the test frequency in the interval from 1 to 15 Hz has no significant influence on the fatigue strength.

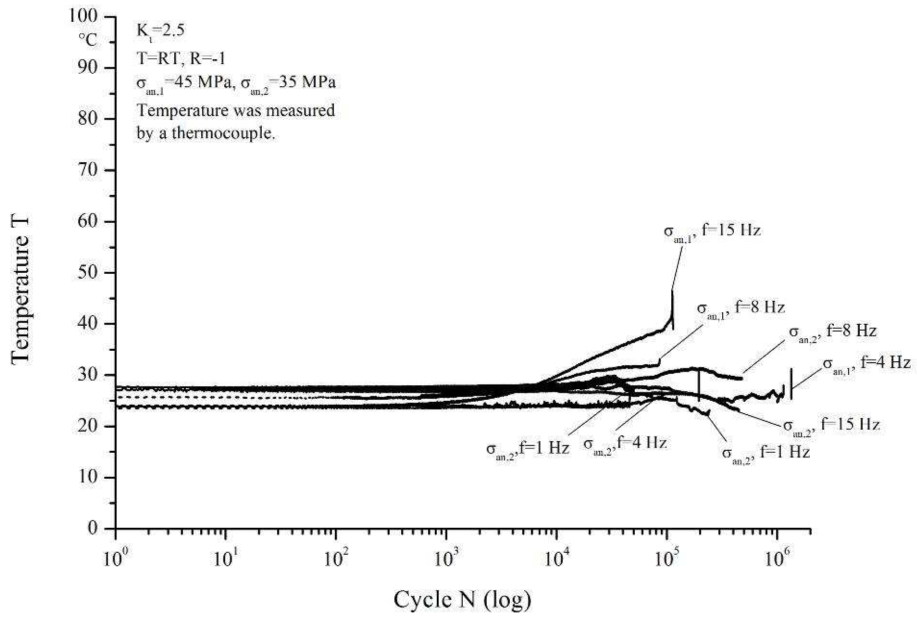

Figure 16. Presentation of the temperature development of notched specimens during fatigue testing with different frequencies

In Figure 16, the recorded temperatures are plotted as a function of the number of cycles. This graph shows, for the stress level $\sigma_{an,\,2}$=35.0 MPa, a constant temperature progression until the end of the fatigue tests for the frequencies 1 Hz, 4 Hz, 8 Hz and 15 Hz. The temperature progression in the tests at stress level $\sigma_{an,\,1}$=45.0 MPa also shows, for the tests with f =1 Hz and f=4 Hz, no significant change of temperature with the number of cycles. Only the fatigue tests at the same stress level with frequencies of 8 Hz and of 15 Hz show an increase of temperature at the end of testing. Thereby, the increase of temperature in the test with a frequency of 15 Hz is higher than that in the test with a frequency of 8 Hz. According to [2], notched specimens can be loaded with a higher frequency than unnotched specimens. The highly stressed volume of notched specimens is smaller and, hence, the generated heat can be passed to the neighbouring spheres, which are more lowly stressed.

The plotted hystereses of all tests show that only marginal creep took place, which is caused by the mean stress σ_{mean}=0 for the stress ratio R=-1 and the specimen geometry. Additionally it can be determined that, with an increase of test frequency, the hystereses are expanded (viscous damping), see Figure 14, as was also established in test series 1 and test series 2.

The plotted hystereses of the fatigue test with f=1 Hz show a break in the hystereses. This break indicates the tension-pressure-loading and shows damage (crazes) of the specimen. During the tension loading, the damaged specimen is performing a greater displacement than it would do in an undamaged state. This phenomenon was also determined for other tests (R=-1).

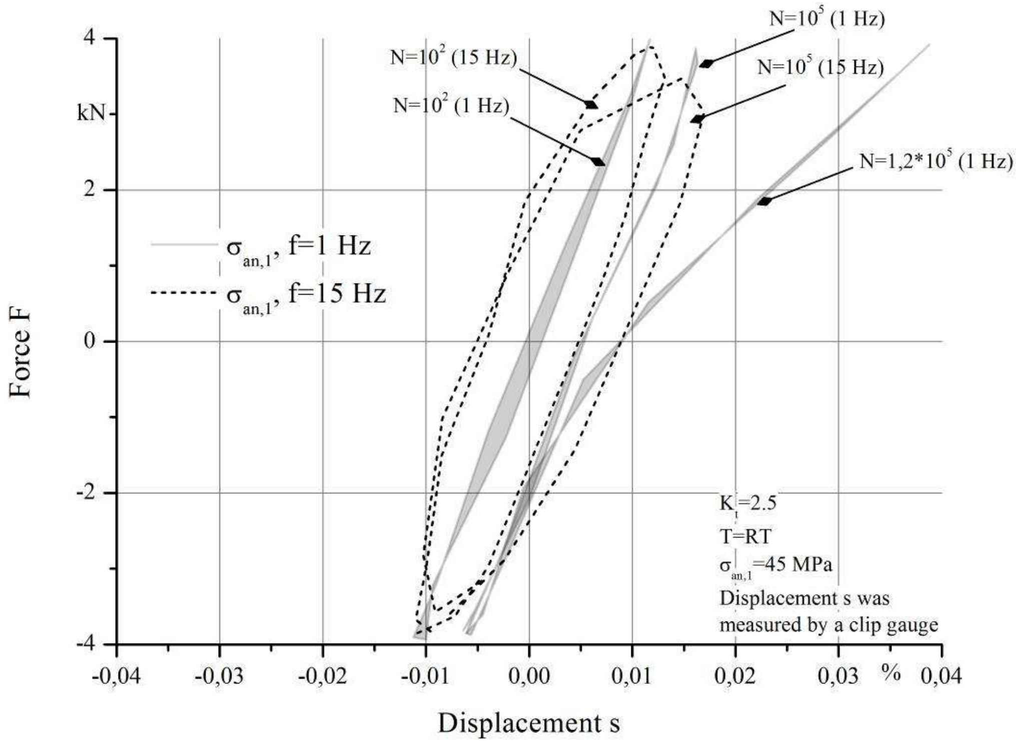

Figure 17. Presentation of hysteresis-loops of the two fatigue tests at load level $\sigma_{an,1}$=35.0 MPa with f=1 Hz and f=15 Hz.

4 CONCLUSION

Investigations of the influence of frequency on the fatigue life were carried out. Thereby, three test series were performed, which were with unnotched specimens and stress ratio R=0 (K_t=1.0, R=0), with unnotched specimens but with stress ratio R=-1 (K_t=1.0, R=-1) and with mild notched specimens and stress ratio R=-1 (K_t=2.5, R=-1). The main results were:

In test series 1, it was determined that the number of cycles reached was dependent on the thermodynamic condition of the material system and the creep of the material. The cyclic creeping was dependent on the test frequency. With a decrease of test frequency, the creeping was increased. Furthermore, it was found that the creep is dependent on the load level. The creep was increased with an increase of load.

In test series 2, it was determined that the frequency in the range of 1 Hz to 15 Hz has a significant influence on the specimen temperature and consequently on the number of cycles reached.

In test series 3, it was established that notched specimens can be loaded with a higher frequency than unnotched specimens. Due to the smaller highly stressed material volume of the notched specimens, the heat can be passed to the lower stressed neighbouring spheres. Significant creep was no longer determined.

For all test series, it was determined that an increase of frequency produces a widening of the hysteresis-loops.

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