INFLUENCE OF NOTCHES ON THE FATIGUE BEHAVIOUR OF SHORT FIBRE REINFORCED POLYAMIDE CONSIDERING ENVIRONMENTAL TEMPERATURE

R. Nienhaus[a*], S. Kurzbeck[a]

[a]*Corporate R&D Competence and Services, Competence Centre Structural Durability (ST/HZA-ESS), Schaeffler Technologies GmbH & Co. KG, Industriestr. 1-3, 91074 Herzogenaurach, Germany*
**ralf.nienhaus@schaeffler.com*

Keywords: fatigue, short fibre reinforced polyamide, notch effect, temperature

Abstract

In this work the combined effect of notches and temperatures on the fatigue behaviour of short glass fibre reinforced polyamide 66 (PA66-GF25) was investigated in detail to enable a characterization of the fatigue behaviour. Therefore SN-curves were determined of different notched injection moulded flat specimens ($K_{t,a}$=1,1; $K_{t,a}$=3,4; $K_{t,a}$=6,5) on servo hydraulic test benches. The tests were conducted under different temperatures (RT; 50°C; 80°C; 100°C and 130°C). The results show a significant influence of temperature on the supporting effect of the material. For the characterization of fatigue strength behaviour a concept of relative stress gradient with supporting factors was chosen. Due to the strong interaction between notches and temperature, the concept was modified for the consideration of the influence of temperature on the supporting effect.

1. Introduction

The use of short glass fibre reinforced (sgfr) polymers is becoming increasingly important in the design of automotive components. Fibre reinforced polymers have a high specific strength and are very cost efficient in high volume production by means of injection moulding. Therefore more and more automotive metal components are substituted by sgfr polymer parts, like chain tensioner arms, belt tensioner pistons and bearing cages. These components often have a complex geometry and are exposed to high cyclic loads and temperatures of up to 150°C. High mechanical and thermal loads on sgfr polymer components require a precise design and therewith an accurate knowledge about the influencing parameters and their interaction.

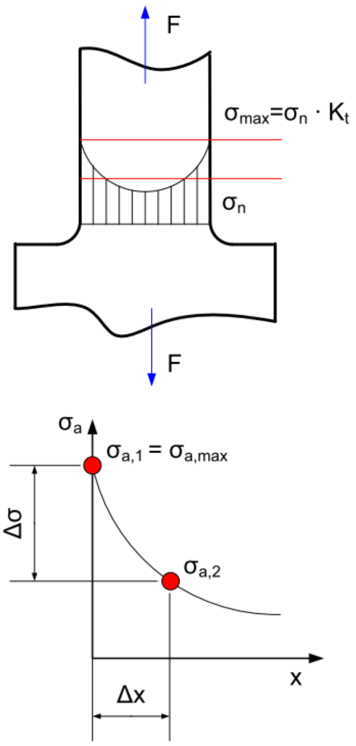
Datasheets contain only material data for monotonic loads, sometimes with the influence of temperature, but the influence of notches was never considered. Reduction ratios [1] do not consider an interaction between influence of notches and temperature and are therefore often too conservative.

The concept of local S/N-curves, which is established for fatigue assessment of metal components, was successfully applied on sgfr polymers in [2]. Parameters for notches and temperatures are essential to calculate local SN-curves. Previous studies in literature [3, 4] investigated the effect of notches and temperature on the fatigue behaviour of short fibre reinforced polymers and mentioned an influence of temperature on the notch effect.

In this work the influence of temperature on the notch effect will be characterized. Therefore the approach of Hück et al. [5] for the characterization of the support effect at notches was modified by the influence of temperature.

2. Theory

The notch effect is mainly based on three mechanisms. The first mechanism is that notches induce local stress concentrations that can be described by the notch factor K_t and is the maximum local stress σ_{max} divided by the nominal stress σ_n. This stress concentration causes a decrease of fatigue strength, which is called notch sensitivity and is defined by the notch sensitivity factor K_f in Equation 3. In most cases the decrease in nominal strength caused by the notch sensitivity K_f is less than the increase in local stress caused by the stress concentration K_t. This means that the local strength of notched specimens is higher than of an unnotched specimen. There are two reasons for this effect. First reason is the support effect, which is based on the stress gradient and the related micro-mechanical support effect. Second reason is the the statistical size effect, which considers the highly stressed volume and the related probability of defects. Both concepts have been investigated and compared in [4]. In this paper we will focus on the support effect. The support effect is described by the supporting factor n in Equation 4. The formula to evaluate the normalized stress gradient is shown in Equation 5.



$$K_t = \frac{\sigma_{\max}}{\sigma_n} \tag{1}$$

$$\sigma_n = \frac{F}{A} \tag{2}$$

$$K_f = \frac{\sigma_{a,n_{unnotched}}}{\sigma_{a,n_{notched}}} \tag{3}$$

$$n = \frac{K_t}{K_f} = \frac{\sigma_a}{\sigma_{a,n_{unnotched}}} \tag{4}$$

$$\chi' = \frac{\Delta\sigma}{\Delta x} \cdot \frac{1}{\sigma_{a,\max}} \tag{5}$$

Figure 1. stress concentration at notches

3. Experimental

3.1. Material and specimen

A standard premium grade polyamide 66 with 25 wt-% short glass fibre reinforcement was used as test material. The material is heat stabilised and is in use in a wide variety of products of the Schaeffler Group.

Properties	**Polyamide PA66-GF25, DAM**	**Unit**
Glass fibre content	25	wt-%
Ultimate tensile strength Rm (RT)	172	N/mm²
Strain at break (RT)	2.7	%
Ultimate tensile strength Rm (130°C)	84	N/mm²
Strain at break (130°C)	10.8	%

Table 1. Material data of PA66-GF25

The fatigue tests were conducted on notched and unnotched flat specimens ($K_{t,a}$=1.1; $K_{t,a}$=3.4; $K_{t,a}$=6.5). The flat specimens are injection moulded according to the requirements of ISO 294-1 with regard to the moulding conditions. The dimensions are shown in Figure 1. The main fibre alignment is in load direction. The determination of normalized stress gradients and notch factors by analytical equations or isotropic FEA is not sufficient because in the case of injection moulded sgfr polymer components they depend on the geometry and fibre orientation. The anisotropic behaviour influenced by the filling process must be considered for the determination of stress gradients and notch factors. Therefore they were determined by anisotropic FEA considering the fibre orientation determined in a filling simulation.

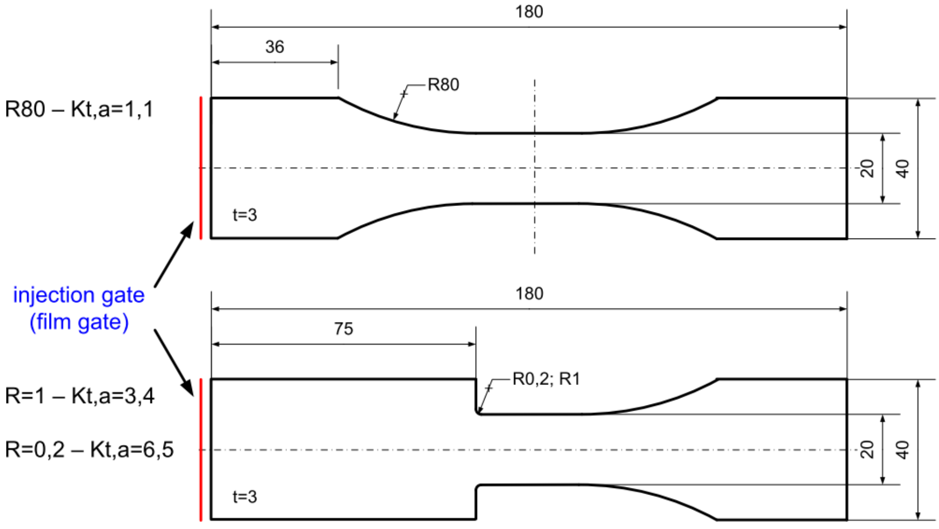


Figure 2. Flat specimens with different notch radii

3.2. Fatigue tests

The experimental setup is shown in Figure 3. The uniaxial load was applied by a servo hydraulic pulser and induced into the specimen by hydraulic clamping jaws. The fatigue tests were performed under constant amplitude at a load ratio of R=-1. A buckling support was used to prevent buckling of the specimens under compressional load.

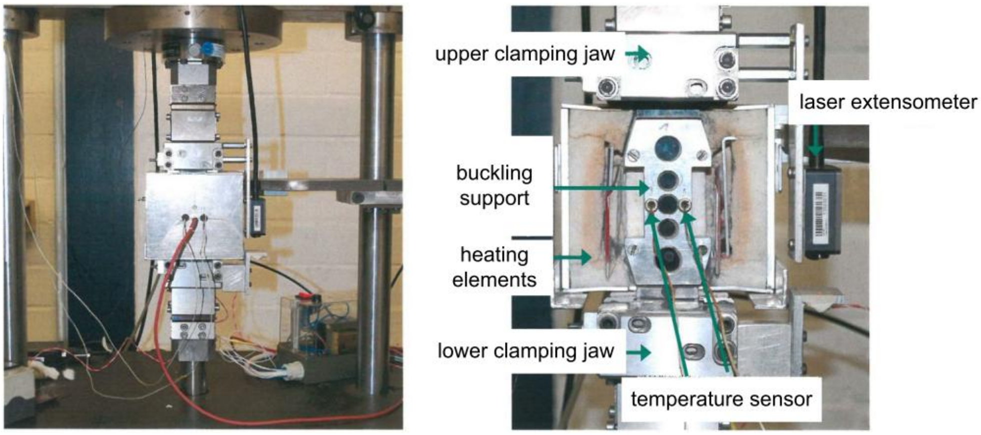


Figure 3. Experimental setup on a servo-hydraulic pulser with furnace (LBF Fraunhofer)

The failure criterion was fatigue rupture. Tests on unnotched specimens were conducted at RT, 50 °C, 80 °C, 100°C and 130°C. Whereas fatigue tests of notched specimens were performed at RT, 80°C and 130°C. The heating time for tests under elevated temperature was determined by pilot tests. For this purpose, three thermocouple elements were placed inside and two were placed outside the specimen. Times were measured until all measuring positions reached and maintained the test temperature. The frequency was adjusted between 0,5-15 Hz to prevent self-heating of the specimen. The temperature of the specimens was checked continuously by thermocouple elements. An increase of the temperature up to 35°C for tests at RT and about 5°C for tests under elevated temperature was permitted. All specimens were tested in dry state.

4. Results and discussion

Figure 4 shows an overview of fatigue strength at $N=10^6$ load cycles of the unnotched specimens under various temperatures (T_e=RT, T_e=50 °C, T_e=80 °C, T_e=100°C and T_e=130°C). The nominal stress amplitudes are normalized to the fatigue strength of the unnotched specimen at RT and 10^6 load cycles.

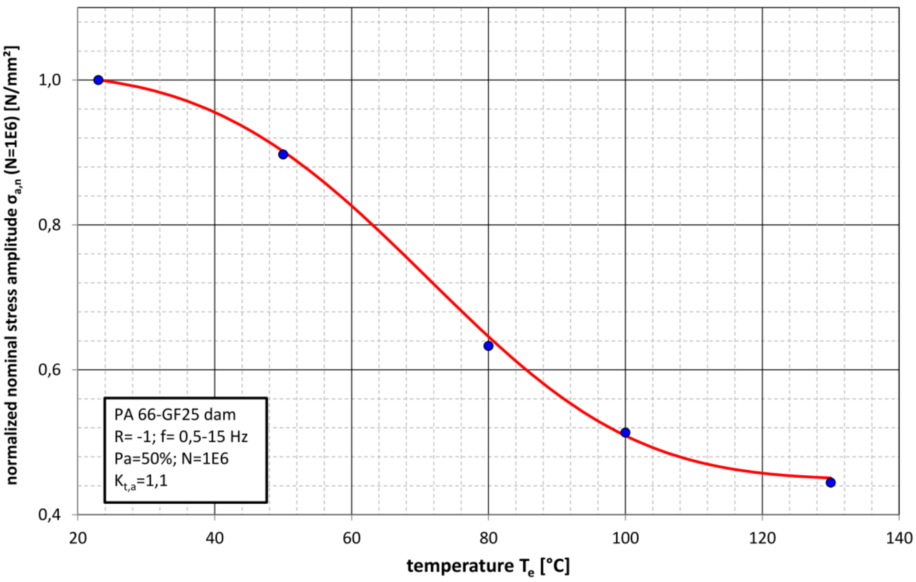


Figure 4. SN-curves at different temperatures and characterization of influence of temperature

The fatigue strength decreases with increasing temperature considerably. Equation 6 describes the influence of temperature on the fatigue strength at 10^6 load cycles, where T_e is the environmental temperature, T_t the transition temperature at the inflexion point and b is an exponent for steepness in the transition area. The transition temperature for the influence of temperature on the fatigue strength is T_t=79 °C and therefore inside the range for glass transition temperature of polyamide. The exponent b is 3.5.

$$\sigma_{a,n} = \sigma_{a,n,Te=RT} - (\sigma_{a,n,Te=RT} - \sigma_{a,n,Te=130°C})e^{-(T_e/T_t)^\wedge b} \tag{6}$$

Figure 5 shows the fatigue strength at $N=10^6$ load cycles of different notched specimens ($K_{t,a}$ =1.1, $K_{t,a}$ =3.4, $K_{t,a}$ =6.5) under various temperatures (T_e=RT, T_e=80°C and T_e=130°C). This illustration, which was already published in [3, 4], shows local and nominal strengths at $N=10^6$ load cycles of notched specimens normalized on the strength of the unnotched specimens at identical load cycles and temperatures.

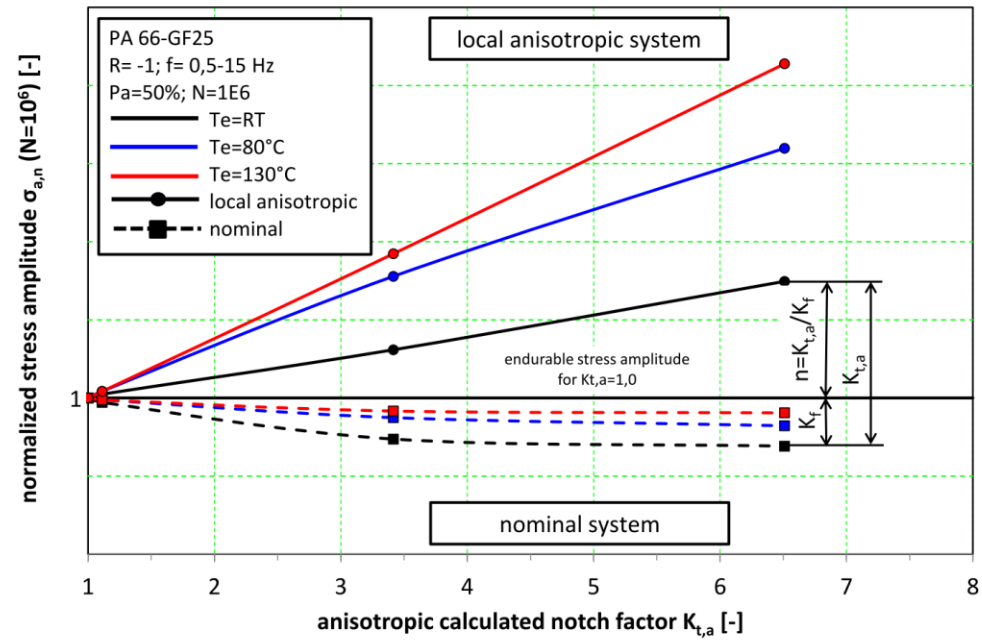


Figure 5. normalized stress amplitudes at $N=10^6$ load cycles in local and nominal system

The nominal system illustrates a decrease of notch sensitivity with increasing temperature, whereas the local system illustrates an increase of the supporting effect with increasing temperature. For the applicability of these relationships to the concept of local SN-curves, the behaviour of fatigue strength regarding the influence of notches and temperature needs to be related to relative stress gradients and mathematically characterized. In this paper the approach by Hück et al. (Equation 7), which was formerly developed for ferrous materials, was used to characterize the support effect of PA66 GF25 [5].

$$n_\chi = 1 + a \cdot \chi'^b \tag{7}$$

The anisotropic relative stress gradients were determined in a anisotropic FEA considering the fibre orientation determined by filling simulation and are listed in Table 2.

Notch radius **R** [mm]	80	1	0,2
Notch factor $\mathbf{K_{t,a}}$ [-]	1.1	3.4	6.5
Relative stress gradient χ' [mm^{-1}]	0.07	3.3	15.4

Table 2. Relative stress gradients and supporting factors for PA66-GF25 at $N=10^6$ load cycles

The relationship between the relative stress gradient χ' and the supporting factor n_χ is shown in Figure 6. The parameters for the description of the material in relation to Hück et al. were determined by optimization of the relative deviation and are shown in Table 3.

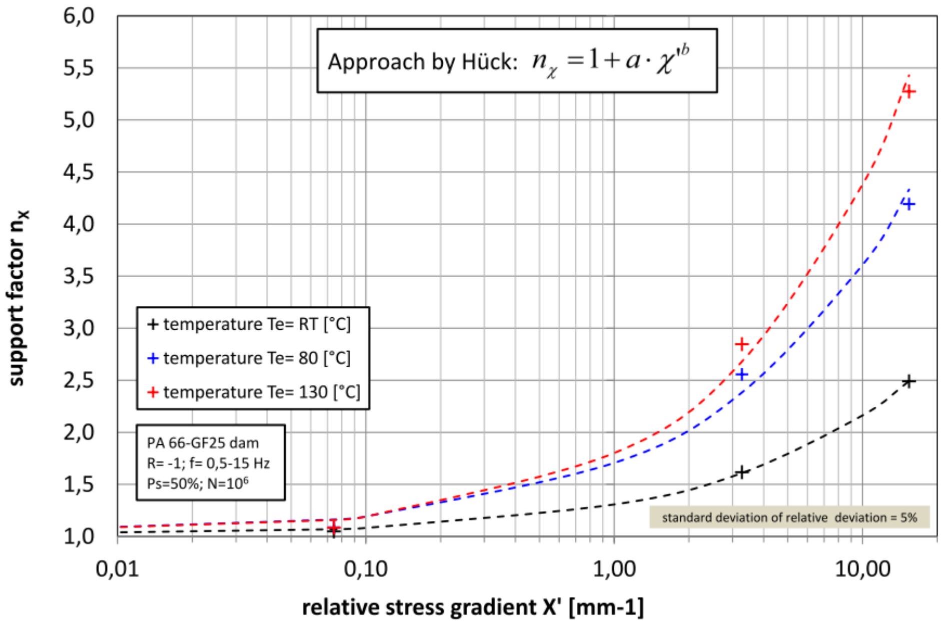
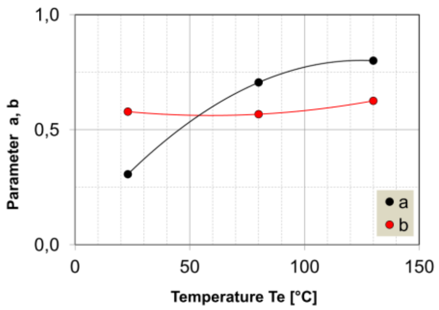


Figure 6. Concept of relative stress gradient regarding to Hück et al.

Temperature $\mathbf{T_e}$ [°C]	RT	80	130
a	0.307	0.706	0.800
b	0.579	18.5	0.626

Table 3. Parameter determined by the optimization of Hück et al.

The influence of temperature on the parameter a and b is described by the quadratic Equations 8 and 9 and are shown in Figure 7.



$$a = -4.78 \cdot 10^{-5} \cdot T_e^{\,2} + 1.19 \cdot 10^{-2} \cdot T_e + 5.76 \cdot 10^{-2} \qquad (8)$$

$$b = 1.27 \cdot 10^{-5} \cdot T_e^{\,2} - 1.51 \cdot 10^{-3} \cdot T_e + 6.07 \cdot 10^{-1} \qquad (9)$$

Figure 7. Concept of relative stress gradient regarding to Hück et al.

Figure 8 shows the characterization based on Hück et al. and modified by the integration of temperatures. The increasing supporting effect of PA66-GF25 with increasing temperature is clearly visible. The supporting effect at 130°C is approximately double compared to RT.

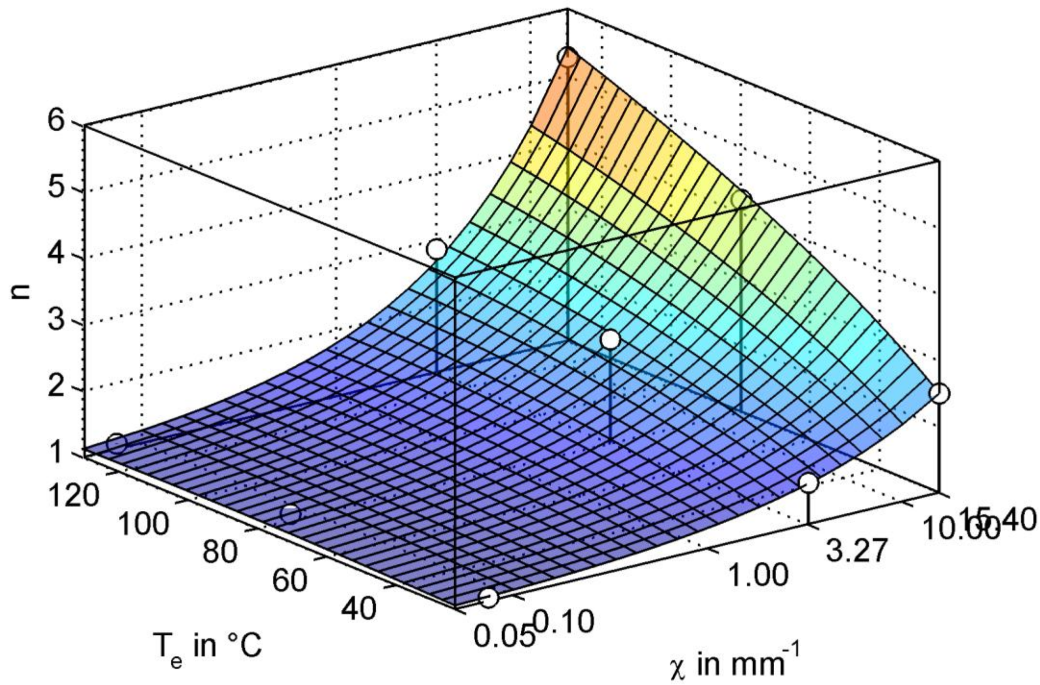


Figure 8. Concept of relative stress gradient regarding to Hück et al. considering influence of temperature

The relative deviation of the support effect optimized by Hück et al. is listed in Table 4. The maximum deviation is 7%. Highest deviations are given for small relative stress gradients at elevated temperatures. The best fit is given for room temperature. The standard deviation of the relative deviation is 5%.

Relative stress gradient χ' [mm^{-1}]	0.07	3.2	15.4
Deviation at $\mathbf{T_e}$ = RT [%]	+2	0	0
Deviation at $\mathbf{T_e}$ = 80°C [%]	+7	-7	+3
Deviation at $\mathbf{T_e}$ = 130°C [%]	+7	-6	+3

Table 4. Deviation of material model compared to material data

5. Summary

The influence of stress concentration on the fatigue behaviour of PA66-GF25 considering environmental temperature was investigated. For this purpose, flat specimens with different notches were produced by means of injection moulding. Notch factor and relative stress gradient were determined by an anisotropic FEA considering fibre orientation determined in a filling simulation. SN-curves at temperatures between RT and above glass transition temperature were conducted. Temperature and notches have a strong influence on the fatigue strength. Fatigue strength decreases with an increase of temperature. The influence of temperature has a inflexion point which is inside the range of the glass transition temperature of polyamide. Stress concentration reduces the nominal strength, whereas the local strength increases. This support effect is characterized by an approach by Hück et al.. Furthermore the effect of temperature on the supporting effect was investigated. The supporting effect at high temperatures is approximately double compared to RT. On the basis of this behaviour the characterization of the supporting effect by Hück et al. was modified by the integration of temperature.

6. Acknowledgement

We would like to thank the Fraunhofer Institute for Structural Durability and System Reliability LBF in Darmstadt, Germany, for conducting the fatigue tests at elevated temperatures.

References

[1] G.W. Ehrenstein. In *Mit Kunststoff konstruieren*. Carl Hanser Verlag, München Wien, 2007.
[2] A. Mösenbacher, P.F. Pichler, J. Brunbauer, Ch. Guster and G. Pinter. Lebensdauerberechnung an Strukturbauteilen aus kurzfaserverstärkten Thermoplasten. *40. Tagung des DVM-Arbeitskreises Betriebsfestigkeit*, Herzogenaurach, Germany, DVM-Bericht 140, pages 301-316, 2013.
[3] J. Hartmann, A. Büter. Relationship between mechanical loading, environment and geometry and its influence on the fatigue behaviour of short fibre reinforced thermoplastics. In *14th European conference on composite materials*, Budapest, Hungary, Paper ID: 271-ECCM14, year.
[4] A. Mösenbacher, Ch. Guster. Fatigue bahviour of a short glass fibre reinforced polyamide: Effect of notches and temperature. In *3rd Fatigue Symposium Leoben Leightweight Design*, Leoben, Austria, 2012
[5] D. Radaj. 4.6 Spannungsgradientenansatz, In *Ermüdungsfestigkeit*. Springer Verlag, Berlin Heidelberg New York, page 154, 2003.