Influence of the stress gradient on the fatigue life calculation of a martensitic high strength steel

Igor Milošević, Gerhard Winter, Florian Grün
Montanuniversität Leoben, Franz-Josef-Strasse 18, 8700 Leoben, Austria
igor.milosevic@unileoben.ac.at, gerhard.winter@unileoben.ac.at, Florian.gruen@unileoben.ac.at

Martin Kober
LEC GmbH, Inffeldgasse 19/11, 8010 Graz, Austria
Martin.kober@lec.tugraz.at

ABSTRACT. Nowadays lifetime calculation in the high cycle fatigue region is commonly based on S/N curves which are modified by different influences to ensure accurate results. Especially the application of these models is important when small components with complex stress distributions are used. The influence of the stress distribution was considered by the stress gradient approach which is implemented in the lifetime tool FEMFAT. Specimens with diameters of D4mm and D7.5mm were used to examine the effect of the calculation modified by the stress gradient. On the one hand regarding different types of this approach it can be shown that the results fit very well compared to the testing results but on the other hand a big difference was observed when the gradient increases by smaller specimen sizes.

KEYWORDS. High cycle fatigue; stress gradient approach; lifetime calculation; stress based approaches; martensitic high strength steel.

INTRODUCTION

P resent technical applications regarding weight reduction and higher loads lead to increasingly complex component geometries. These complex shapes require high demands on the lifetime and therefore the lifetime calculation based on different models. Since the finite element analysis (FEA) is capable of determining different load situations and the resulting stress and strain distributions the influence of the stress distribution is implemented into commonly used simulation tools like FEMFAT known as the stress gradient approach.

In the actual case, the focus is mainly set on the lifetime calculation under the stress gradient influence. Material testing is always affected by other additional influences as size effect, temperatures, residual stresses and the stress distribution itself through different types of loads, which could cause an impact on the material properties. This has to be considered within the lifetime calculation of complex components.

The lifetime is being calculated by consideration of appearing stresses (bending loading). This was implemented into the post processing process and is going to be parameterized. In this paper it will be shown how the different size of tested specimens affect the lifetime compared to testing results.

STRESS CALCULATION

The fact that local stress concentrations decrease the expected components lifetime has been known for a long time investigated first through the work of Neuber [1]. The geometrical properties of mechanical components are designed to fulfil essential functions like transfer of forces and motion for example. Therefore, a practical way has to be found how to observe these geometrical influences and to implement the effect into lifetime calculations.

Before the effect of stress concentrations is discussed regarding the FEA results a closer look at the difference between notched and unnotched shapes will be presented. In the unavoidable event of geometrical discontinuities, the difference of the stress distribution is shown by two examples in Fig. 1. [2]
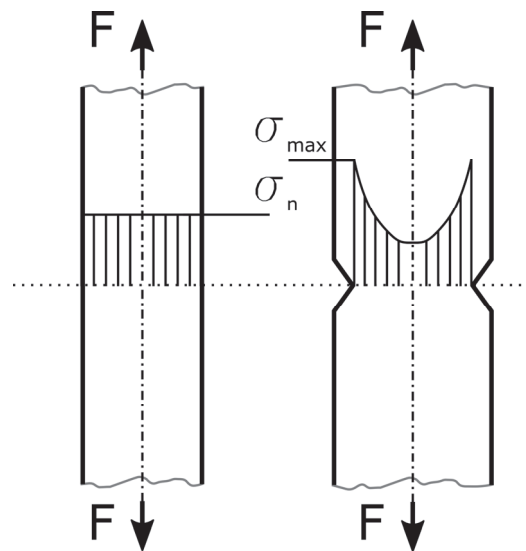

Figure 1: Difference between the nominal stress σn and the maximal stress at the notch σ_{max} [2].

On the left a smooth machined specimen is described where the nominal stress (σ_n) can be calculated through easy analytical approaches. In case of simple shapes the FEA results fits the analytical results very well. The stress will be evenly distributed (as long as no major defects within the microstructure are present) throughout the cross section. A highly uneven distributed stress curve is caused by a notched geometry, on the right, which is described by the maximum stress (σ_{max}) occurring in the notch root. As there can be observed a clear deviation from nominal stresses another sufficient description has to be applied to notched components. [1–3].

To describe the effect of notches depending on unnotched areas and their nominal stress behaviour an elastic stress intensity factor (K_t) was invented (1). The maximum stress is connected with the nominal stress through K_t. The stress intensity factor is only dependant on the geometry of the notch. K_t is determined by the local geometrical properties [2].

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

Not only the intensity factor has an influence on the notch effect, the course of the stress at the notch root is being a matter of importance. The amount of stress increase is given by the differential quotient dσ/dx. To define a stress gradient at the notch root just under the surface the quotient is divided by the maximum stress in order to provide an evaluation criterion. The mathematical and graphical description of the relative stress gradient χ', is given by (2) and Fig. 2 [2–6].

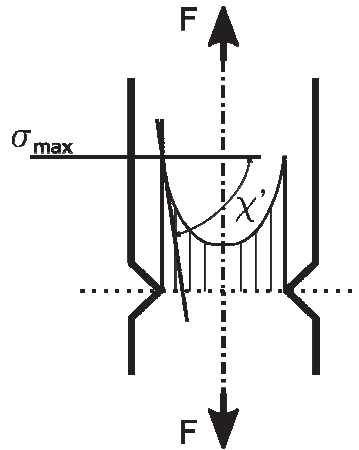$$\chi' = \frac{1}{\sigma_{max}} \left(\frac{d\sigma}{dx} \right) \tag{2}$$

Figure 2: Description oft the relative stress gradient χ' [2].

The relative gradient is dependent on the application of different types of stress to a certain geometry (bending loading in Fig. 3). This natural stress gradient, shown in Fig. 3, is pointing out that for example smaller specimen sizes lead to different stress gradients. In this case the gradient is represented by the function of the specimen thickness $\chi' = 2/b$. [2]
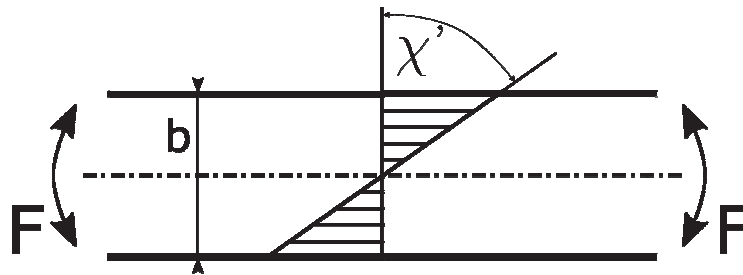

Figure 3: Influence of the loading type to the stress gradient occurrence [2].

Different approaches have been invented regarding the assessment of a stress gradient, which are used to determine local component strengths. The approach of interest was introduced by Eichlseder [6] being applied as an exponential function to describe the nonlinear behavior of the fatigue limit increase caused by the stress gradient. The fatigue limits of compression/ tension loaded specimens $\sigma_{f,t}$ ($\chi' = 0$) and bending loaded specimens $\sigma_{f,b}$ ($\chi' = 2/b$), both unnotched behave according to this approach. Taking $\sigma_{f,t}$ as the initial condition the local fatigue limit $\sigma_{f,l}$ according to the local χ' is calculated by the multiplication with the notch sensitivity factor n_χ which are pointed out below in (3) and (4). Since this nonlinear behavior is material specific the material parameter K_D has to be determined. [3–6]

$$\sigma_{f,l} = \sigma_{f,t} * n_\chi \tag{3}$$

$$n_\chi = \left(1 + \left(\frac{\sigma_{f,b}}{\sigma_{f,t}} - 1 \right) * \left(\frac{\chi}{\left(\frac{2}{b} \right)} \right)^{K_D} \right) \tag{4}$$

For a sufficient lifetime calculation the adjustment of the local strength is not enough as common high cycle fatigue damage models are defined by S/N curves which are given by the fatigue limit, the slope k and the cycles at the fatigue limit N_D [2].

$$k = k_{min} + \frac{k_{max} - k_{min}}{n_{\chi}^{K_k}}$$

(5)

$$log\left(N_D\right) = log\left(N_{D\,min}\right) + \frac{log(N_{D\,max}) - log(N_{D\,min})}{n_{\chi}^{K_n}}$$

(6)

Eqs. (5) and (6) explain the mathematical background behind the adjustment of the local S/N curve modification. S/N parameters are modified by another set of key ratios K_k and K_n which are dependent on the group of materials used in the calculation. The min and max values of k and N_D are given by the limits of fatigue testing. All these influences were implemented into the calculation tool establishing a contribution to the calculation process of complex components. [2]

EXPERIMENTAL

The material used in the actual investigations was a high strength martensitic steel commonly known as 1.4542, X5CrNiCuNb16-4 according to EN standards and A480 (630) according to ASTM standards. An extract of the chemical composition is given in the Tab. 1 below. Depending on the type of application different heat treatments can be carried out to achieve the final condition.

C	Si	Cr	Ni	Cu
0.04	0.25	15.30	4.50	3.25

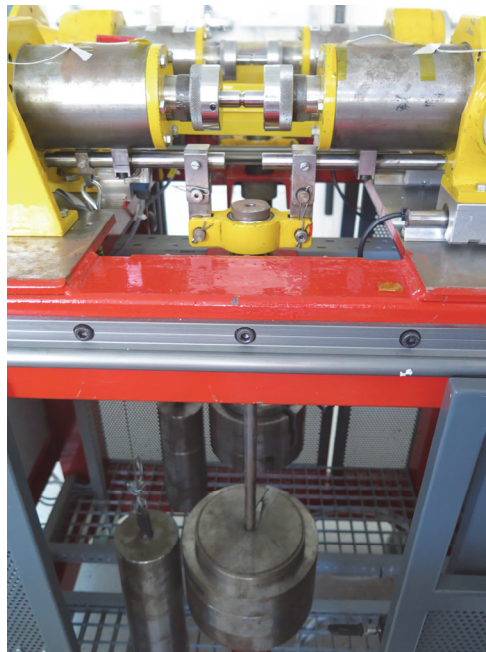Table 1: Chemical composition in percent by weight (wt%, EN 10088-3).

Figure 4: Test setup for rotating bending tests, a constant bending moment is applied over the cross section

Bending loading fatigue tests were carried out on a testing rig which was developed by the Chair of Mechanical Engineering at the Montanuniversität in Leoben. The setup provides a constant bending moment over the whole cross section of the specimen geometry. Two different specimen sizes (testing diameter 4mm and 7.5mm) were used to examine the influence of the stress gradient. A fillet radius of 50mm was used at both specimens as displayed in the technical drawing in Fig. 5.
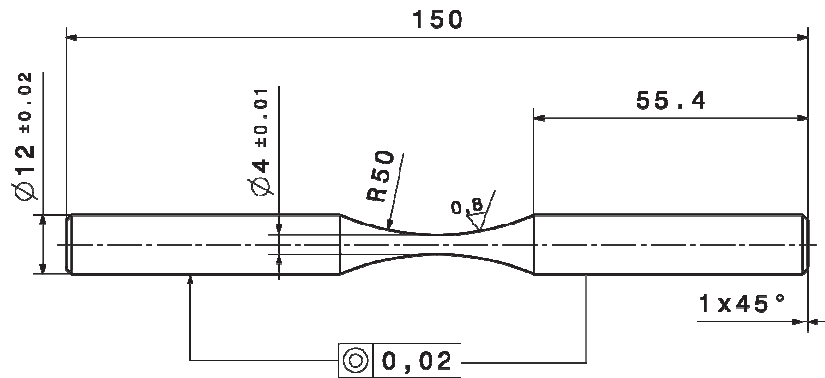
Figure 5: Shape of the tested specimens, D=4mm.

LIFETIME VALUATION

The FEA calculations were carried out through Abaqus/CAE. According to the sketch above the specimen geometry was built up and the boundary conditions were modified. Bending loading was applied on the modelled geometry. For a sufficient stress gradient calculation different parameters had to be adjusted to guarantee accurate results. Best results at the stress assessment process were achieved through the usage of quadratic elements without reduced integration (C3D8). High distortion of the elements should be prevented otherwise poor results occured. The most critical parameter was the number of elements used in this simulation. Altogether 3200 elements should be used to reach a stabilized (more elements - no significant improvement) stress level [7].

	D4	D7.5
χ'	0.511	0.279

Table 2: Calculated stress gradients at the surface of different specimen sizes.

In Tab. 2 the calculated stress gradients can be see depending on the specimen diameter. The stress gradient decreased with increasing specimen size nearly being halfed. Both specimens were applied with a nominal stress (direction in the axis of the specimen) of 1.0 MPa which also showed no real value of K_t.

The fatigue calculations were carried out with FEMFAT 5.2a. Modifications were done according the FEA results and the appropriate material parameters from testing results. Especially the material parameters had to be adjusted to the actual material properties in order to evaluate the fatigue calculations. A good estimation can be done by using the proposed parameters from the FKM guideline (section 4.2.1, [8]). A rough guide is suggested by literature data where ultimate tensile strength (UTS) values are given in a range from 1300 up to 1450 MPa. The standard values were optimized after testing to improve results.

The modifications, which can be applied with respect to the actual stress gradient, are chosen within the FEMFAT influence parameters. Mainly three different approaches are implemented where one possibility approach was to neglect the stress gradient influence which represents a conservative assessment of the lifetime calculation. The fatigue limit was adjusted by picking option 2 and the fatigue limit and the slope were adjusted by picking option 3.

RESULTS AND DISCUSSION

In the following, the results are presented with respect to testing and simulation results. The S/N data concerning the base material is described as "Material" which can be seen in Fig. 6. This is used as reference for further calculations where every S/N curve being clearly defined by the fatigue limit σ_f, the slope k and the cycles to the fatigue limit N_D.

As described in Eq. (3) – (6) the local fatigue limit is calculated where different parameters of the S/N curve were adjusted. As expected the calculations showed increasing values of certain parameters. In Fig. 6 two different S/N curves representing

different specimen sizes were marked as D4 (red) and D7.5 (blue) lines. The curve marked as broken-dotted line represents the option 2 adjustment. Just the fatigue limit was adjusted according to the present stress gradient. The option 3 adjustment of the parameters is done by modification of the fatigue limit, the slope and the cycles to the fatigue limit. It can be seen that with increasing stress gradient the local fatigue limit $\sigma_{t,2/3}$ increases and N_D decreases.
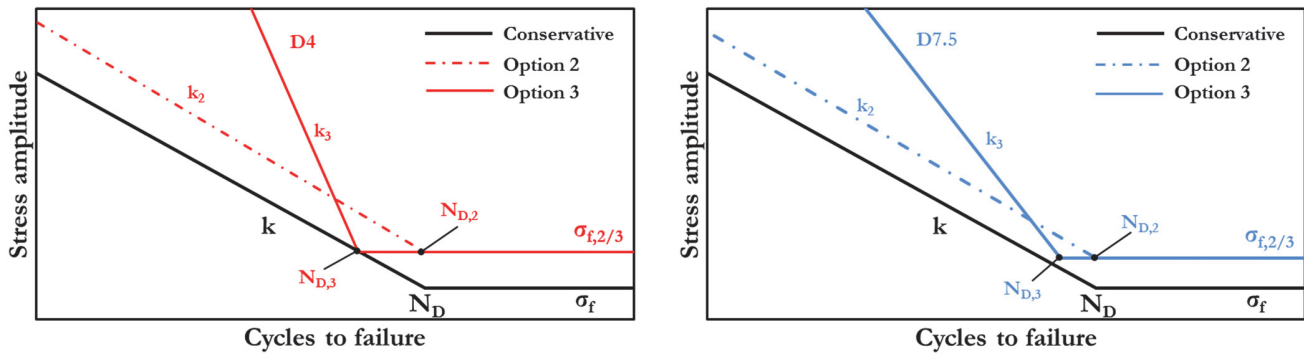

Figure 6: Comparison of different local S/N curves modified by the stress gradient approach.

Attention should be attracted to the region near N_D in Fig. 7 where smaller specimens having apparently lower lifetimes. Through the modification of S/N parameters, such an aggressive behaviour was observed. Tested specimens (D4 and D7.5) showed the same result in this particular load area. Although it's commonly known that smaller specimen sizes tend to have higher lifetimes it could be observed that in the region of the fatigue limit bigger specimens showed higher lifetimes. In this case, the gradient approach could be applied very well.

A material model, which is implemented into FEMFAT, was parameterised and simulations were made to observe the validity of the stress gradient approach from a standardized specimen (D7.5) to a smaller specimen size (D4). In Fig. 8 and Fig. 9 the testing life and the simulation life were compared depending on option 2 and option 3 stress gradient approach. In both figures, there are three groups of data included. The circular shaped data points represent calculations without applying the stress gradient approach (conservative) to the lifetime estimation process. The quadratic shaped data points represent option 2 calculations and the triangular shaped data points represent option 3 calculations where all mentioned parameters were modified.
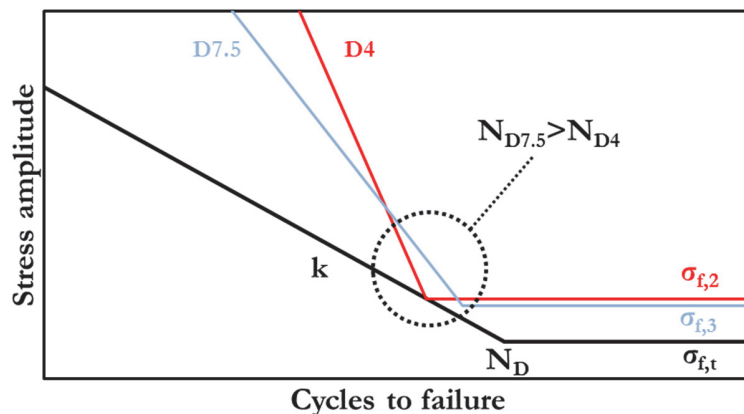

Figure 7: Location of the area where the stress gradient concept showed identical results as the rotating bending tests.

The data points within the broken-dotted and dotted lines are located within a scatter band of two respectively five. The presented lifetime data is located in a range from 1E5 up to 1E6. The equal values of simulation and testing results were given through a red continuous line (angle of 45°) as seen in the figures. A conservative calculation was defined by lower simulation results than testing results. In the actual case data points, being located on left of the red continuous line were desirable for applying the approaches.

In case of D4 data points, it can be seen that applying option 2 calculations were more suitable than the option 3 calculations. Most of the data points are within a scatter of 2. Drifting into non-conservative calculations was observed at option 3

calculations (all parameters) where all data points were still within a scatter of five but located in the non-conservative area. The application at higher stress gradients could lead to an overestimation of the lifetime due to the modification of the gradient approach.
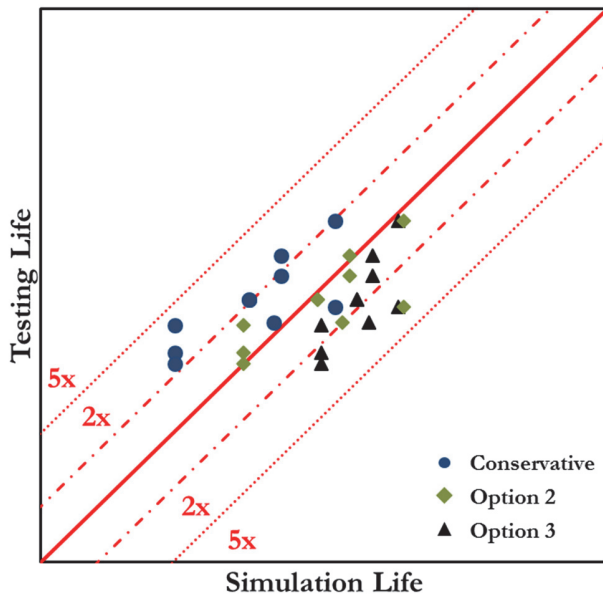

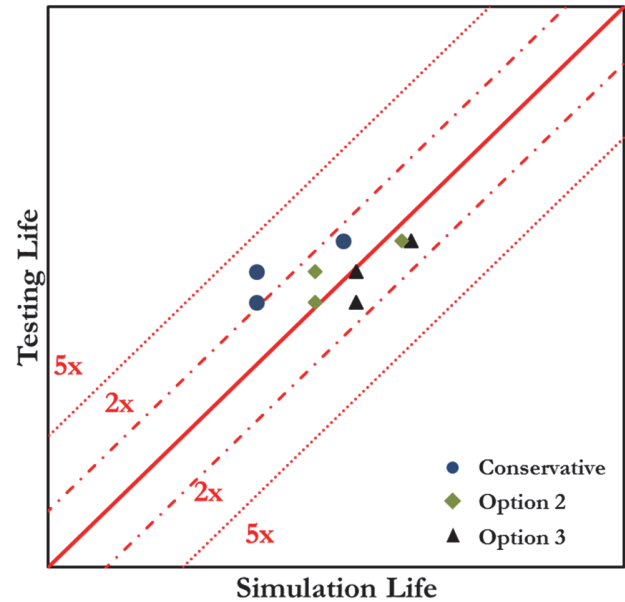Figure 8: Lifetime evaluation of D4 specimens depending on the type of stress gradient approach.

Figure 9: Lifetime evaluation of D7.5 specimens depending on the type of stress gradient approach.

CONCLUSION AND OUTLOOK

The actual work represents the involvement of the stress distribution, more precisely the local stress gradient, and the impact of application when different specimen respectively component sizes are involved. Higher stress gradients χ' lead to a significant impact on the lifetime calculation, which depends mainly on the local modification of S/N parameters.

Further investigations will focus on the applicability of actual models and the usage when even smaller component sizes are considered. Especially when the full stress gradient approach should be applied and how the over-estimation could be handled, will be analysed through further research.

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NOMENCLATURE

FEA	Finite element analysis
UTS	Ultimate tensile strength
b	Specimen thickness
σ_n	Nominal stress
σ_{max}	Maximum notch stress
K_t	Elastic stress concentration factor
K_k	Material group parameter - k
K_n	Material group parameter - N
n_χ	Notch sensitivity
χ'	Relative stress gradient
$\sigma_{f,b}$	Bending fatigue limit
$\sigma_{f,t}$	Tension/ compression fatigue limit
$\sigma_{f,l}$	Local fatigue limit
k	Slope S/N curve
$k_{max,min}$	Tested extreme values of k
N_D	Number of cycles at the fatigue limit
$N_{Dmax,min}$	Tested extreme values of N_D
K_D	Material exponent