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Influence of notches on the mechanical properties of machine parts

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1. Introduction

The design of machine parts and machines is associated with the use of appropriate types of materials and thus the determination of their physical and mechanical properties. Usually these are metallic materials (high-strength steels, pure alloys, etc.), in recent decades also other non-traditional materials, such as composites (particle or fiber composites, hybrid materials). Each real part is characterized by its geometric shape, which is adapted to the functionality of structure and also to operational loading and stresses. Each part is also made by a specific technology. This forms its future structural and mechanical properties including static, dynamic and fatigue resistance in relation to operational loads. Designers should be able to optimize and correctly design the so-called "notch effect" of a part. In this sense, a notch means a local stress and strain concentrator. Locations with high local stress concentration usually form critical points in mechanical structures where a static failure occurs or where a fatigue crack begins to spread. Notches can be categorized from different criteria. Let us mention here geometrical, structural or technological notches. The first group is unambiguously described by its geometric shape and dimension. Structural notches, such as inclusions or inhomogeneity in material, also create local deformation concentrations. Their real shape is usually replaced by a simplified geometry. Also, various technological treatments of materials can cause a notch effect, for example on the transition of two layers of material of different structural and mechanical properties, etc. Here we will focus on geometric notches and description of stress in the notch root as well as description of prediction methods to evaluate durability of notched parts using nominal stress approach or local stress approach by using of calculations with finite element method (FEM).

2. Stress concentration and the stress gradient effect in the notches

It is known that the concentration of nominal stress, σ_n, to the local elastic (virtual) stress, $\sigma_{\max}$, which are at the root of geometrical notches can be described using a stress concentration factor (also shape factor) defined as

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

The so-called exposed material volume in which a significant part of the local damage occurs, can be described using the relative stress gradient at the notch root, G, where

$$G = \left[\frac{\Delta\sigma_y}{\Delta x}\right]_{x\to 0} \cdot \frac{1}{\sigma_{\max}} \qquad [\text{mm}^{-1}]. \tag{2}$$

If the stress peaks occur along the entire *L* region (as, for example, in Fig. 1, where *L* represent the sample thickness), the *L/G* ratio characterized the exposed region. All these quantities can be determined in the notch locality from the results of the FEM calculations, also during complex loading conditions, when the condition of the multicomponent strain is usually assessed using equivalent stress values according to strength hypotheses, for example, σ_{HMH} .

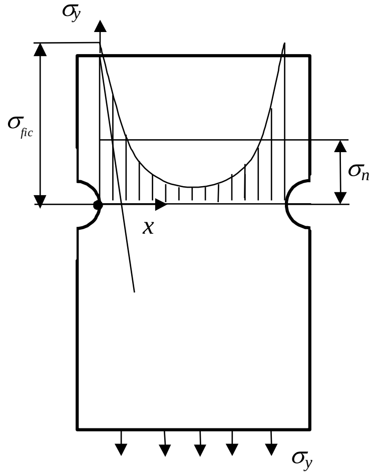

Fig. 1. Stress in the notch specimen

3. The effective notch effect on the fatigue strength

It is also known that the effect of the stress peaks on the notch fatigue strength is not as significant as it would correspond to the theoretical stress concentration. Experiments define the effective notch effect on the fatigue limit by a notch factor,

$$K_f = \frac{\sigma_C}{\sigma_C^*} . \tag{3}$$

In the past, several relations were proposed for the computational estimation of the notch factor, which are reviewed, for example, in Ref. [5]. Let us define the ratio of the shape and notch factor by the fatigue ratio, $n = \frac{K_t}{K_f}$. The methods for expressing the *n* quantity can be split into two major groups, see Table 1.

Table 1. Fatigue ratios calculated by different methods

Author	***Fatigue ratio n***	***Note***	***Eq.***
Neuber	$n_\rho = 1 + \frac{A}{\rho} \cdot \left(1 - \frac{1}{K_f}\right)$	where A=f(R_m) is the Neuber factor, see, *e.g.*, [5]	(2)
Peterson	$n_\rho = 1 + \sqrt{\frac{a}{\rho}} \cdot \left(1 - \frac{1}{K_f}\right)$	where *a* is the critical surface layer depth, see, *e.g.*, [5]	(3)
Heywood	$n_\rho = 1 + 2\sqrt{\frac{a'}{\rho}} \cdot \left(1 - \frac{1}{K_f}\right)$	empirical factor a' see, *e.g.*,. [5]	(4)
Siebel, Stiller	$n_G = 1 + \sqrt{c \cdot G}$	parameter *c* see, *e.g.*, [5]	(5)
Bäumel Seeger [1]	$n_G = 1 + \sqrt{G} \cdot 10^{-\left(\frac{R_e}{810} + 0,35\right)}$	where R_e is the yield strength	(6)
Eichelseder [2]	$n_G = 1 + \left(\frac{\sigma_{C,b}}{\sigma_C} - 1\right) \cdot \left(\frac{G}{2/d}\right)^k$	where $\sigma_{C,b}$ and σ_C are the bending and tensile fatigue limits, *d* is the diameter of the bending sample	(7)
Volejnik, Kogaev [7]	$n_G = 1 + \left(\frac{1}{\nu_\infty} - 1\right) \cdot \left(\frac{L/G}{L_0/G_0}\right)^\mu$	here ν_∞ is the magnitude factor for the homogeneous strength, μ is an exponent	(8)

The first group is formed by relations that are determined in dependence on the notch root radius, ρ. The second group involves expressions depending on the relative stress gradient, *G*. In Table 1, the values of the n_ρ and n_G ratio are compared for some most frequently used relations. For the FEM applications, the expression by means of the stress gradient, *G*, turns out to be more convenient. For the determination of the local fatigue limit in the notch root, $\sigma_{C,FEM}$, (*i.e.*, of the limit values of the elastic stress peaks in the FEM calculations), the following relation can be used:

$$n_G = \frac{K_t}{K_f} = \frac{K_t \cdot \sigma_C^*}{\sigma_C} = \frac{\sigma_{C,FEM}}{\sigma_C}, \text{ so that } \sigma_{C,FEM} = n_G \cdot \sigma_C,$$

where σ_C is the material fatigue limit during a homogeneous uniaxial tensile stress.

Analogously to the K_f factor introduced in the region of the unlimited fatigue life, it is possible to define the notch factor, $K_{f,N} = \frac{\sigma_A}{\sigma_A^*}$, in the region of the limited life from the fatigue test results. The fatigue ratio is modified by the relation $n_{G,N} = \frac{K_t}{K_{f,N}}$. It is then possible to obtain the fatigue curve of virtual stress values at the notch root, $\sigma_{FEM} = \frac{K_t}{K_{f,N}} \cdot \sigma_C = n_{G,N} \cdot \sigma_C$, which must lie above the smooth sample curve (see Fig. 2). In practical calculations, we can also use an opposite procedure. During the damage calculation, we use the fatigue curve of a smooth sample and correct the local stress amplitudes by calculating the quantity

$$\sigma_{cor} = \sigma_{FEM} \cdot \frac{K_{f,N}}{K_t}. \tag{4}$$

Fig. 2 also shows the main difference between the Nominal Stress Approach (NSA), used by analytical fatigue calculations and Local Elastic Stress Approach (LESA), used by FEM analysis. While the fatigue curve is corrected in the downward direction in the nominal approach with respect to the notches, and the fatigue damage is determined from the nominal stress amplitude. The local approach uses the corrected stress peak at the notches and the initial fatigue curve of the sample without notches. Let us mention, however, that all the effects of the surface quality of the actual machine part should be projected into the curve and, as the case may be, its further technological modifications. The magnitude factor is taken into account in the above-indicated similarity criterion of the stress gradient effect and exposed volume.

The author of this paper proposed a modification of the Heywood expression (see [3]) for the description of the notch effect in the region of the limited life, *i.e.*, for the expression of the $K_{f,N}$ coefficient,

$$K_{f,N} = 1 + (1 - K_t) \cdot \mu(N), \tag{5}$$

in which the dependence on the relative stress gradient, *G*. It was expressed in the following form: $n_G = \frac{K_t}{K_f} = 1 + \sqrt{G} \cdot 10^{-\left(\frac{R_e}{K1} + K2\right)}$ and the time functions as $\mu(N) = \frac{(\log N)^{K3}}{K4 + (\log N)^{K3}}$.

Parameters *K1* up to *K4* were determined to describe best the experimental *S-N* curves of samples with a various shape factor. A bunch of the so-called synthetic fatigue curves can be generated for any general stress gradient and shape factor; these curves can represent the required areas of the structure in the NSA approach, see Fig. 3. The example of these curves is indicated in Fig. 3 according to the results in Ref. [6]. The set of these equations can also be used for correcting the elastic stress peaks according to relation (4) in the LESA approach.

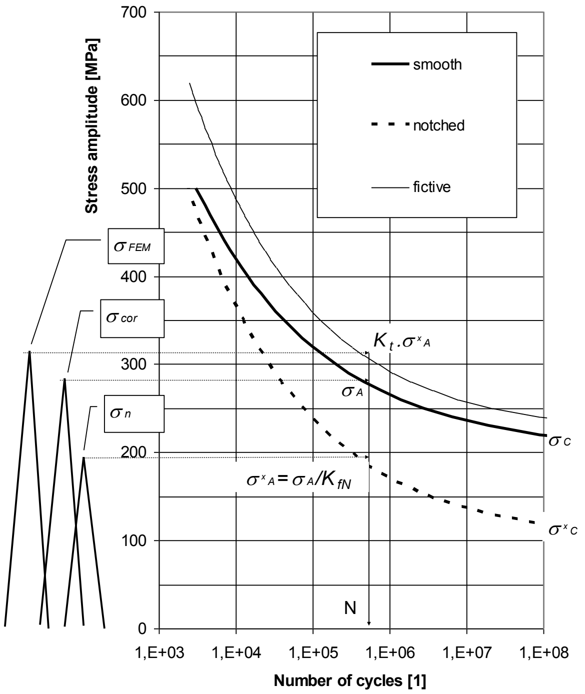

Fig. 2. Fatigue curves use for NSA and LESA

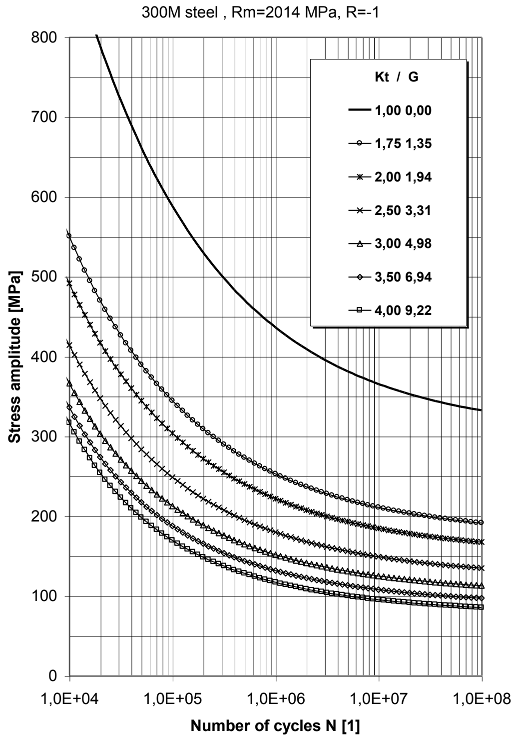

Fig. 3. Synthetic fatigue curves

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