

Influence of Microstructure Discontinuities on the Fatigue Strength of Metallic Materials

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Abstract This paper presents the results of fatigue investigations under rotating bending loading for the determination of the critical inclusion sizes in different high-strength steels. All fatigue cracks initiated at non-metallic inclusions, whose size, form and position were determined and subsequently statistically evaluated. A comparison with the determination of the degree of purity derived from microscopic evaluation of cross sections – the commonly used method of quality assurance in steel production – shows a significant underestimation of the inclusion sizes. Finally, a procedure to derive allowable stresses depending on the size of inclusions is shown, based on rotating bending tests and using the methods of fracture mechanics. A safety factor is derived, taking into account statistical size effect and scatter of internal defects. The methods presented facilitate higher utilization of the fatigue strength of high strength steels, as well as an optimized quality assurance process, thus minimizing the risk of failure during service life.

Keywords non-metallic inclusions, rotating bending test, microstructure metallographic specimen, endurance limit, safety factor

1. Introduction

Non-metallic inclusions or other microstructure discontinuities are often the origin for fatigue cracks, particularly in the case of weakly notched components made of high-strength steels. The dimension, number, shape and distribution of these discontinuities therefore have a significant influence on both local fatigue strength in the region of high cycle fatigue and the scatter of the mechanical strength properties. The scatter of the endurance limit is also directly correlated to the scatter of the inclusion size [11], [12], [15]. Specifically, this again depends on the kind and size of the primary material as well as the position where the non-metallic inclusions were detected. Knowledge of the size distribution of non-metallic inclusions in the basic material is of enormous importance for the definition of local allowable stresses, in order to produce components with the desired, very low failure probability. The influence of internal defects on fatigue strength rises with the increasing strength of the material used. In [1], comprehensive investigations of different high-strength materials used for the manufacture of vehicle springs showed a systematic correlation between local inclusion size and endurance limit. In the following, the terms “endurance limit” and “threshold value” will be used without regard to the effects of strength reduction in the range of very high cycle fatigue. This influence on the endurance limit shows that the potential of high-strength steels only can be fully exploited if it can be guaranteed that a certain size of non-metallic inclusions is not exceeded. Fig. 1 illustrates this for passenger car springs. The outlier in the Wöhler diagram was caused by a large non-metallic inclusion (Fig. 1, right, exemplarily). In the context of this publication, the usual procedures for the detection of non-metallic inclusions and the influence of these defects on HCF characteristic values, like the endurance limit, are examined and the possibilities for incorporating these findings in the stress analysis of components is presented.

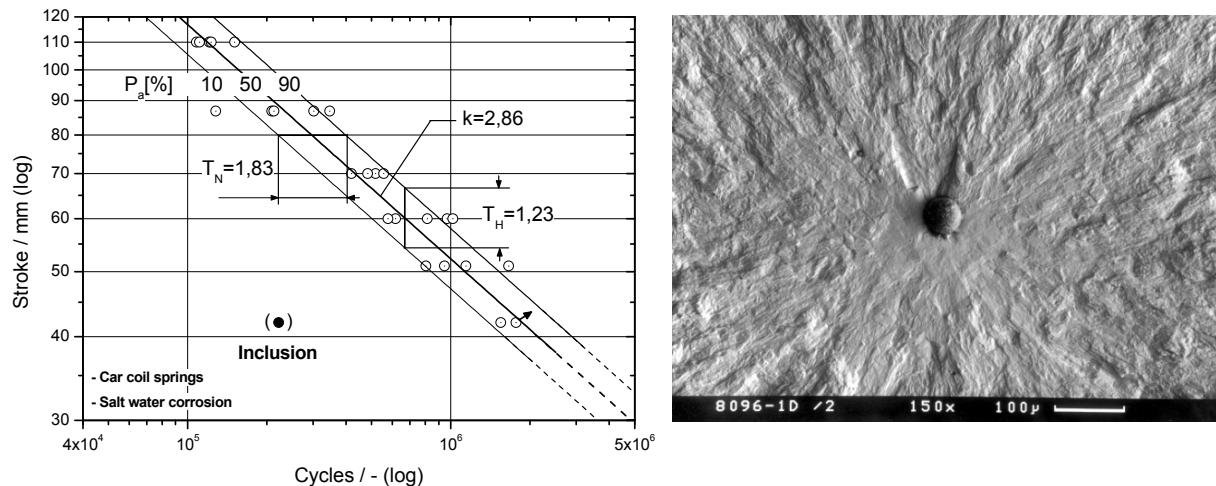


Figure 1: (Left) Influence of an inclusion on durability; (right) Example of a non-metallic inclusion in an SEM micrograph [4]

2. Methods for the detection of microstructure discontinuities

In order to consider existing microstructure discontinuities at the scatter of fatigue limit values, the purity of the material has to be known. There are a variety of procedures available for determining the size distribution of internal defects. The most common procedures are the microscopic evaluation of cross sections and computed tomography (CT) – both investigative methods used in materials science – and the rotating bending test for detection of microstructure discontinuities as a mechanical procedure. In the following, the above-mentioned procedures are described and briefly compared with one another.

2.1. Microscopic evaluation

The very frequent application of photo-optical methods for the determination of the surface portion of microstructure characteristics in steel – designated as degree of purity (DIN EN 10247) – is ascribed to the historical development of quantitative materialography. The detection limits requirements for non-metallic inclusions, formulated in standards like DIN EN 10247, are thus based on the resolution potential of optical microscopes. The procedure described below is based on the light-microscope evaluation of a cross section surface with given size and constitutes a representative determination for the entire material. The cross section surfaces are usually scanned fully automatically and the microstructure discontinuities are detected using grey scale value analyses on the basis of arising contrast differences [6]. The defects identified are classified using standardized methods, e.g. DIN EN 10247 or ASTM-E45, and the statistical distribution of the position, kind and size of the defects is determined for the entire material. Given a sufficiently large measuring field, it is assumed that under this procedure the surface portion of a microstructure characteristic corresponds to the volume fraction.

2.2. 3D-x-ray-computed tomography (μ CT)

μ CT analysis is based on the principle of x-ray radiographic inspection and is used as a non-destructive testing method for the verification of volume defects. The analysis takes place indirectly through the intensity attenuation of the penetrating x-ray at internal defects and the surrounding material. The measurement results can be resolved three-dimensionally by rotation of

the test volume or the radiation source. The intensity attenuations caused by density variations of the microstructure discontinuities to the surrounding material are measured by a detector and converted into a gray scale picture. The resolution achieved by this method depends on the absorption behavior of the examined sample and thus on material thickness and density as well as the energy level of the radiation source. Due to the required positioning of the sample in relation to the detector, the attainable local resolution is defined to a very large extent by the size of the sample: the larger the component, the smaller is the maximum resolution. In the case of a steel cylinder with a diameter of 10mm, the maximal attainable resolution amounts to nearly $5\mu\text{m}$. However, for a test specimen with a thickness of 200mm, the resolution is already reduced to $100\mu\text{m}$. Using this procedure, microstructure discontinuities of smaller samples can be determined in number, size and form and evaluated statistically.

2.3. Rotating bending test

This method is based on the fact that due to the notch effect, internal defects become the starting point for fracture. In general, fracture results from microscopic incipient cracks forming at the component or sample surface. In order to be able to initiate the crack at defects underneath the surface, a failure of the sample due to surface defects must be avoided. Additional strain hardening of the surface with shot peening in the skin layer of the samples can be used to achieve a residual stress condition, thus preventing initial cracking at the surface. In addition, hardness procedures are used to increase the strength of the material as far as possible in order to activate internal defects at higher stresses. The execution of the test takes place according to the principle of quarter-point flexure. In the volume examined, the applied bending load leads to the initiation of a crack at the most effective microstructure discontinuity. This leads to a failure of the sample and to an exposure of the defect in the fracture surface. Scanning electron microscopy is used to measure the position and size of the defect responsible for the sample failure and determine its chemical composition.

2.4. Comparison of the methods

With the cross section procedure, evaluation of the defect content – and thus the purity of the entire material – is based solely on examination of a cut surface of an inclusion under a light microscope. Fig. 2 shows this schematically for two spherical, differently sized inclusions. In this cross section evaluation both defects appear to have the same inclusion size. Furthermore, inclusions that lie outside the cross section level cannot be determined. Thus, in this procedure a statistical evaluation of the size of the spherical non-metallic inclusions systematically leads to an underestimation.

Therefore, [3], [7] and [8] suggest procedures for the conversion of the radius distribution of the defects in the examined polished sections into the corresponding ball radius distribution.

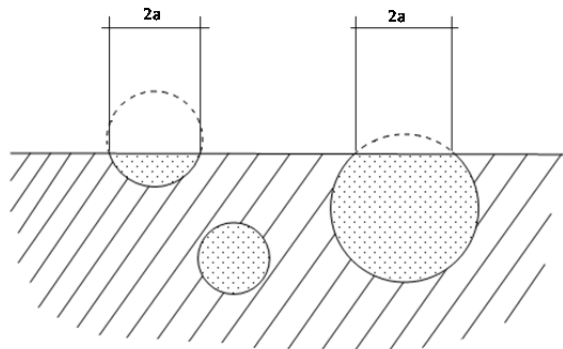


Figure 2: Determination of the cross-section of two inclusions by means of a metallographic specimen

The 3D-X-ray computed tomography (μ CT) method allows a three-dimensional representation of microstructure discontinuities and their distribution. Due to the reduction of resolution during the application to large material volumes, this procedure shows considerable weaknesses. Even with small samples, microstructure discontinuities with a size smaller than $50\text{ }\mu\text{m}$ can no longer be resolved. Moreover, due to the small number of voxels in the grey scale pictures, the type of the defect cannot be differentiated, e.g. cavities or inclusions may appear similar. In contrast, when the appropriate sample treatment is used, the rotating bending method activates the microstructure discontinuity most conducive to crack initiation in the damaged sample volume. Using this experimental technique with an appropriate number of samples, a statistically reliable result for the size and the position of the inclusions relevant for crack initiation is obtained. Due to the effective stresses microstructure discontinuities smaller than $30\text{ }\mu\text{m}$ can be examined.

Direct comparison of the cross section procedure with the rotating bending and CT methods reveals a substantial difference in the size distribution and absolute magnitude of the determined defects identified. Additionally, with the application of the conversion procedures presented in [3], [7] and [8], the results for the cross section method strongly underestimate the maximum sizes of the defects which can be expected. The assumptions about fatigue strength characteristics derived from the cross section procedure thus can be strongly non-conservative [9]. Therefore, the ASTM E 45 standard states that the application of this method may not be used as a condition of acceptance for relevant steel qualities. The investigation by means of CT provides a realistic size distribution, but due to the low resolution for large specimens [10], the investigation of larger sample volumes is not possible.

3. Evaluation of the results for fracture mechanics

In [4], extensive investigations were conducted to determine the influence of internal defects on the fatigue strength of eleven high-strength spring and ball bearing steels. The method used for the determination of the defects relevant for crack initiation was the rotating bending test described in the preceding chapter. Fig. 3 shows the distribution of the inclusion sizes in the probability net for the examined materials. The defect sizes were described by an area equivalent diameter $2a$ in the sense of fracture mechanics. The standardized characteristics were evaluated for a total of 175 inclusions and each illustrated in a probability net.

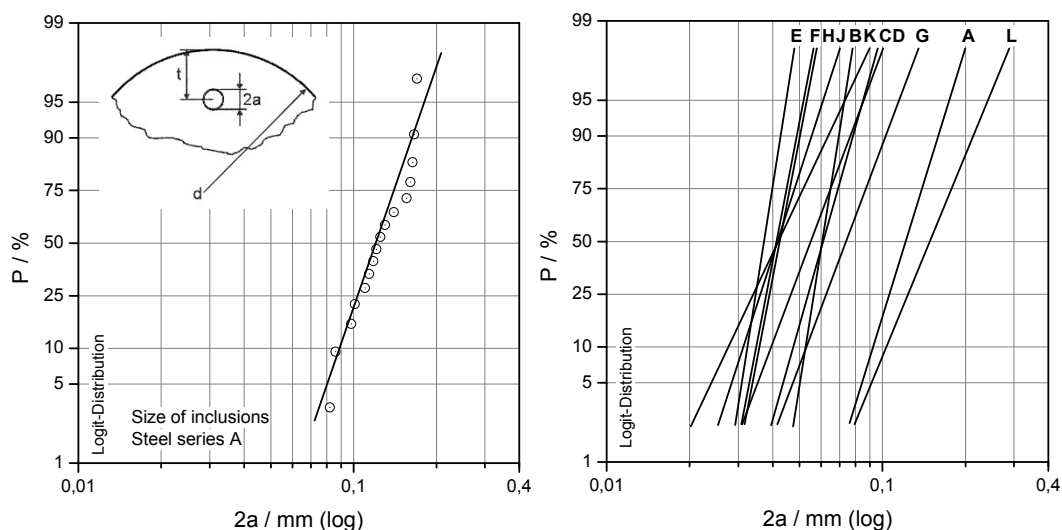


Figure 3: Size distribution of internal defects in different high-strength steels (A-K)

The inclusion sizes determined and extrapolated using the cross section procedure for the same samples were up to an order of magnitude smaller than the results achieved with the rotating bending test. Therefore from the point of view of the authors, the cross section procedure is not suitable for reliable detection of inclusions.

In a further step for the purposes of comparative statistical evaluation, the diameters of the crack initiating defects determined at different depth have to be converted into a diameter with equal stress intensity at a reference depth. In order to take account of the statistical size effect it was also necessary to effect a conversion of the diameters to a standardized reference volume, depending on the critically stressed volume of the respective sample (see also [13]). In Fig. 3 a very large range in the diameter of the arising inclusions can be seen.

The illustration of the converted test results in a Wöhler diagram (Fig. 4, left) shows no correlation between the applied nominal stress and the number of load cycles until fracture for the cracks arising from internal defects.

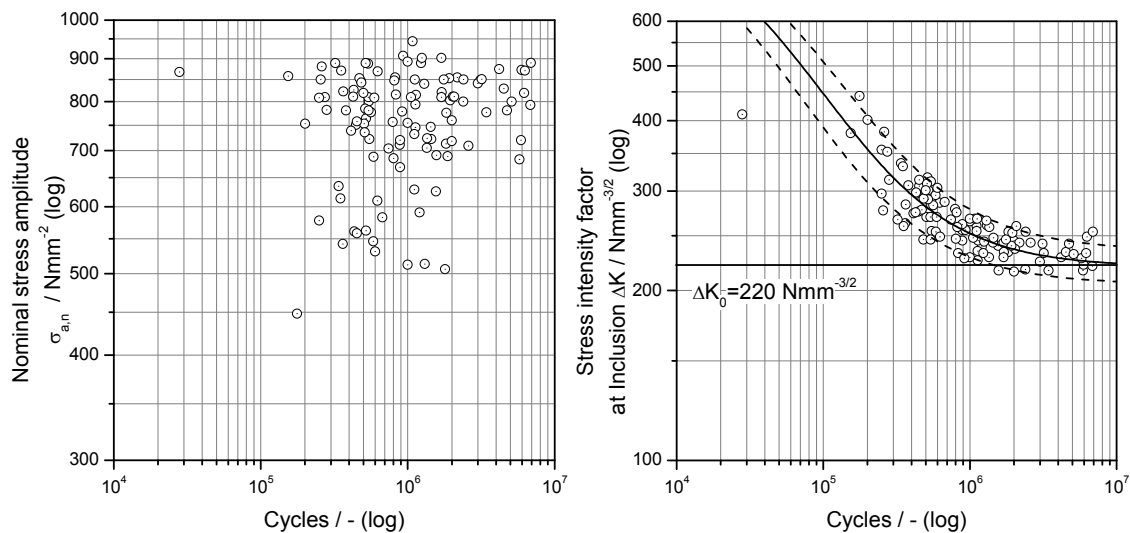


Figure 4: Durability of samples with internal defects, in terms of fracture mechanics

This can be attributed to the fact that in different samples with the same nominal stress amplitude, the local effective load in the vicinity of the defects responsible for crack initiation is different, depending on the location of the respective inclusion. Again, the load depends on the size of the inclusion and the local stresses at the inclusion. This suggests a description of the stress condition in terms of the stress intensity factor in the sense of fracture mechanics. Publications by Heckel [11] and El Haddad, Smith, Topper [14] describe this unification of Wöhler concept and fracture mechanics. In these concepts, the crack origin is approximated by a fictitious crack describable by the means of fracture mechanics. With the conversion of the nominal stress amplitudes into the stress intensities at the inclusion, all results can be described in the Wöhler diagram (Fig. 4, right) and a threshold value of $\Delta K_0 = 220 \text{ Nmm}^{-3/2}$ can be determined within the endurance limit range. This threshold value appears to be independent of the steel grade and can be used to evaluate the fatigue strength if the defect distribution is well known. This result is confirmed by further investigations in [15] and [16].

Based on the equation for the stress intensity factor [17] and using the local stresses, the correlation between maximum inclusion size and allowable local stress (2) can be determined:

$$\Delta K = 2 \cdot \sigma_{a,l} \cdot \sqrt{\pi \cdot a} \cdot \frac{2}{\pi} \quad \text{with } \sigma_{a,l} = \sigma_{a,n} \cdot \left(\frac{d-2t}{d} \right) \quad (1)$$

$$\sigma_{a,d} = 0,63 \cdot \frac{\Delta K_0}{\sqrt{2a}} \quad \text{with } \Delta K_0 = 220 \text{ Nmm}^{-\frac{3}{2}} \quad (2)$$

Using this threshold value of the local stress intensity at the inclusion ΔK_0 , it is possible to estimate an upper limit of the usable local fatigue strength with a defined limiting number of load cycles from the middle diameter of the potentially crack initiating defects $\overline{2a_f}$ of the investigated material [3].

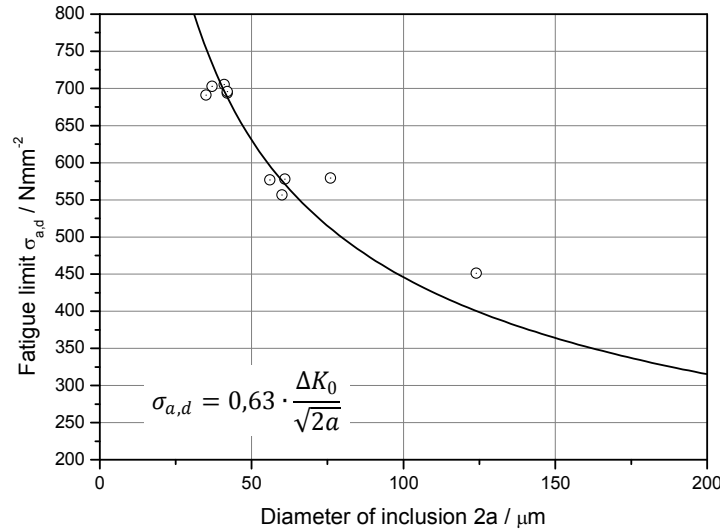


Figure 5: Estimation based on the rotating bending test of local durability in respect of the average crack initiating inclusion size

The endurance limit values of several steels determined in tests from [4] show a very good agreement with computed values of the upper limit of the usable endurance limit under consideration of existing microstructure defects (Fig. 5). This correlation is confirmed for different steels by investigations in [3].

Fig. 5 shows that the maximum usable endurance limit is reduced by the factor of two by an inclusion of 150 μm in relation to a material condition with technically undetectable inclusions ($< 30 \mu\text{m}$ [4]). This illustrates the necessity for the reliable consideration of microstructure discontinuities in the dimensioning and validation of cyclically loaded, high-strength components.

4. Extrapolation of the distribution of microstructure discontinuities with regard to statistical size effects

The rotating bending method used for determining the distribution of microstructure discontinuities is a very economical means of testing, due to the high testing frequencies and its low energy consumption. One disadvantage, however, is the stress gradient arising in the sample during quarter-point flexure (Fig. 6, right). In order to estimate an allowable defect size on the basis of a given probability of failure of a component, the defect distribution determined in the rotating bending test must therefore be converted to an equivalent, uniformly stressed volume. Based on the stress integral, the equivalent volume V_0 without stress gradient results in:

$$V_0 = \int_V \left[\frac{\sigma_{xyz}}{\sigma_{\max}} \right]^{\frac{1}{m}} dV \quad (3)$$

For rotating bending of a cylindrical sample with diameter of $d_0 = 2 \cdot r_0$ and a steady stressed length l_0 (circular bend line under quarter-point flexure), the following simplification applies:

$$V_0 = \int_V \left[\frac{r}{r_0} \right]^{\frac{1}{m}} dV \quad \text{where} \quad \frac{r}{r_0} = \frac{\sigma_{xyz}}{\sigma_{\max}} \quad (4)$$

using the scatter index of the Logit-distribution (index L):

$$m = 0,524 \cdot \lg T_{L,a} \quad (5)$$

with $T_{L,a}$ = scatter band (10% / 90%) of the defect distribution.

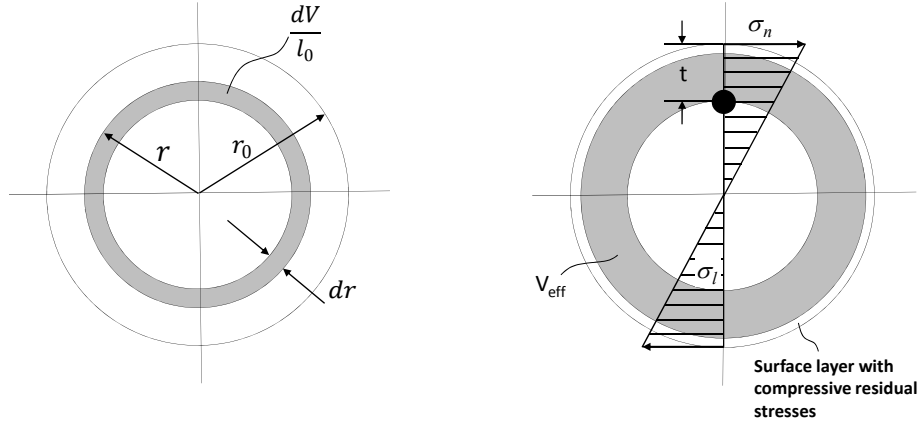


Figure 6: Model for the derivation of the effective volume

In Fig. 6, the volume element of the integral for round samples is derived to:

$$dV = 2\pi \cdot r \cdot l_0 \cdot dr \quad (6)$$

Considering that defects in the vicinity of the approximately 0.22 mm thick compression stress layer originating from the shot peening are ineffective, then the integration results in:

$$V_0 = \frac{2\pi \cdot l_0}{2 + \frac{1}{m}} \cdot r_0^{-\frac{1}{m}} \cdot (r_0 - 0,22)^{2 + \frac{1}{m}} \quad (7)$$

V_0 is the reference value for the component volume V_B , determined from the rotating bending test. This can be calculated from the stress integral of the component V_e and the series amount n_B .

$$V_B = n_B \cdot V_e \quad (8)$$

To compute the stress integral of the component, the distribution data of the microstructural discontinuities determined in the rotating bending tests are used.

These distribution data (average value a_0 and scatter range $T_{L,a}$) are the basis for the derivation of allowable stresses. Thus the experimentally determined distribution of the microstructural discontinuities is extrapolated on the basis of the volume ratio of the sample and the component.

$$P_A = \frac{1}{1 + \frac{V_0}{n_B \cdot V_e}} \quad (9)$$

The critical diameter $2a_z$ of the microstructure discontinuities for the allowable, fatigue endurable stress in one of n_B components is determined from the extrapolation equation

$$\lg a_z = \lg a_0 + k \cdot s_{lg} \quad (10)$$

$$\text{yielding} \quad a_z = a_0 \cdot 10^{k \cdot s_{lg}} = a_0 \cdot T_{L,a}^{\frac{k}{2,42}} \quad (11)$$

where a_0 = average defect size with a statistical reliability of 50%
 s_{lg} = standard deviation of the distribution of the inclusion sizes

Under consideration of the confidence (statistical reliability S), the standardized parameter k can be calculated [18]:

$$k = \frac{2 \cdot (n_p - 1)}{2 \cdot (n_p - 1) - u_s^2} \cdot \left[u_p \pm u_s \cdot \sqrt{\frac{2 \cdot (n_p - 1) + n_p \cdot u_p^2 - u_s^2}{2 \cdot n_p \cdot (n_p - 1)}} \right] \quad (12)$$

where n_p = number of the microstructural discontinuities determined with rotating bending test
 u_p = fractile for the extrapolation to $2a_z$
 u_s = fractile for the necessary single sided statistical reliability S

For the applied Logit distribution, both fractiles result in the expressions illustrated in equation (13) and (14):

$$u_p = \frac{\sqrt{3}}{\pi} \cdot \ln \frac{n_B \cdot V_e}{V_0} \quad (13)$$

$$u_s = \frac{\sqrt{3}}{\pi} \cdot \ln \frac{S}{1-S} \quad (14)$$

On the basis of these considerations, the fatigue endurable local stress amplitude σ_{zul} with the expected defect size of $2a_z$ for one of n_B components can be calculated under the assumption of a defined statistical confidence using equation (2).

Under the assumption that microstructural discontinuities can cause the failure of a large volume component of high-strength steel, a reduction of the allowable design stress can be derived for a given microstructure defect in the material with regard to the statistical size effect. Since the fracture mechanics threshold value ΔK_0 is independent of the material and its tensile strength, the equations presented here apply to all steel grades [4].

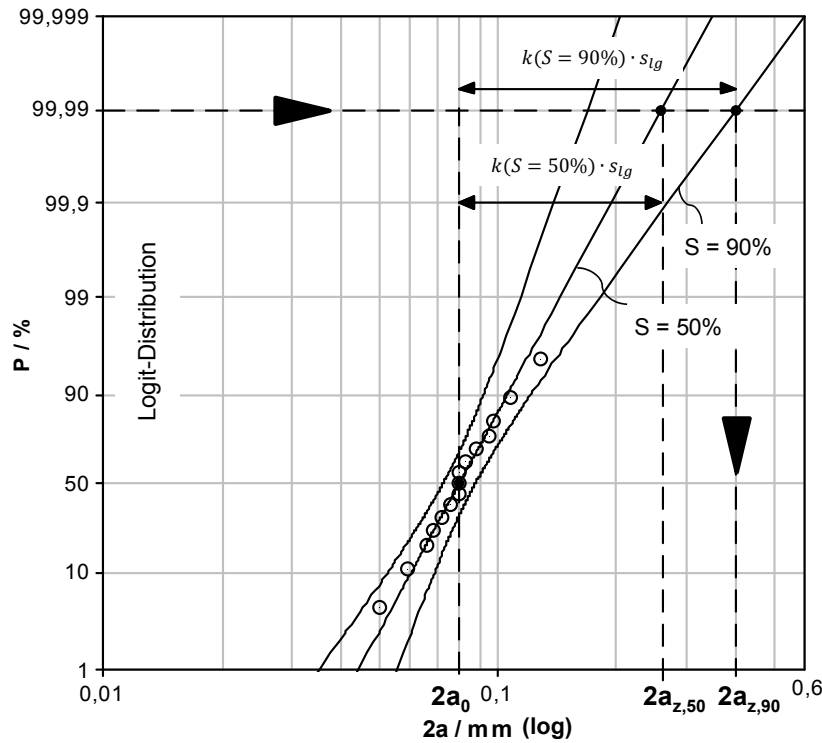


Figure 7: Estimation of the tolerable defect size with regard to the distribution of the internal defects

The experimentally determined defect distribution for an exemplary material, represented in Fig. 7, allows an extrapolation of the inclusion diameter $2a_{z,90} = 0.4$ mm for a probability of occurrence P of 99.99% and a confidence of $S = 90\%$. This means that there is a 99.99% probability that all microstructure discontinuities arising are smaller than $2a_{z,90}$, and that the probability of a defect of this size occurring is 0.01%. In a sample of components with this parameter and this volume ratio between specimen and regarded component, the probability of failure P results from (9).

According to Fig. 5, the upper limit of the maximum usable endurance limit can be determined by $\sigma_{zul} = 219$ MPa. Alternatively, the allowable inclusion size can be determined for a required endurance limit. Depending upon steel grade, this can mean a clear reduction of the dynamic stress limit used for the design. The estimated maximum size of the inclusions $2a_z$ only becomes relevant, if the endurable tolerated stresses exceed the computationally estimated stress amplitude σ_{zul} .

5. Conclusion and forecast

The investigations carried out showed that in the context of the design of components, microstructural discontinuities have to be considered as crack initiators in the highly stressed volume. Solely materials science methods for the determination of the purity of the material cannot supply reliable information on the existence and characteristics of potentially crack initiating defects and therefore do not offer a reliable criterion for process validation and quality assurance in steelmaking. An improved concept for quality assurance is suggested in the form of the determination of defects by rotating bending testing of samples. Allowable defect sizes or endurable fatigue stresses can be estimated computationally on the basis of fracture-mechanics considerations. This means that when using high-strength materials to make components it is possible to take account of strength-reducing influences due to internal defects at the design stage already. In contrast with the maximum allowable stresses, a maximum allowable defect size can be defined as a function of the required probability of failure, and thus a demand for purity for the material used can be derived. The potential of high-strength steel for vibration resistance, however, can only be exploited if it is guaranteed that a certain size of non-metallic inclusions is not exceeded. From the point of view of the authors, the determination of the defect distribution as a measure of the purity of the material used with the suggested procedure is an essential step in the design and qualification of components.

Further investigations are planned to examine, if the results presented here are relevant for lower strength materials. First test results regarding the purity of low strength materials (e.g. 42CrMo4) show internal defects with a size of more than 400 μm in the rotating bending test. The investigations clearly show the dimension of microstructural discontinuities that has to be considered in the application of these materials. Thus, reliable determination of the defects coupled with statistical analysis is essential for the design and quality assurance of components produced in large series and with the requisite low failure probability.

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