THESIS BOOKLET

EFFECT OF SURFACE DEFECTS ON THE FATIGUE LIFE OF NODULAR CAST IRON COMPONENTS

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CONTENTS

ABBREVIATIONS

Abbreviation	Designation
DSG	Defect Stress Gradient Approach
EIM	Equivalent Inclusion Method
FE-	Finite Element Method/Analysis
HCF	High-Cycle Fatigue
LEFM	Linear Elastic Fracture Mechanics
NCI	Nodular Cast Iron
SEM	Scanning Electron Microscopy

1. INTRODUCTION

The current thesis investigates the phenomenon of the defect induced fatigue process and is focused on the high-cycle fatigue behaviour of nodular cast iron (NCI) components. Considering that high-cycle fatigue is known for being strongly linked to the surface condition, the fatigue life reduction effect of the various surface discontinuities is a fundamental question. From the standpoint of creating as-precise-as-possible fatigue life assessment for the components, the role of defects is nonnegligible as they are usually the initiators of the fatigue cracks and their presence is almost inevitable in the subsurface region of castings. NCI components have numerous advantages compared to their forged and machined counterparts, such as the efficient mass production of complicated shapes with mechanical properties comparable to steel. Due to their beneficial properties, they are widely used in different industrial branches, amongst them the transportation industry. The main price to pay for their advantageous behaviour is the inhomogeneity of material properties yielding from many various phenomena, including the characteristics of the flow in the casting form and the solidification process. Both the inevitable presence of the casting skin and the different types of casting defects lead to large scale scatter of the fatigue properties of NCI material.

Figure 1.1 displays surface defects on NCI components found during the visual quality control process. A detailed consideration of these inhomogeneities leads to more accurate service life calculations, which allows for the application of reduced safety factors without compromising reliability. Important decisions must be made to differentiate between the various phenomena affecting the fatigue strength. Specific type of inhomogeneities having criticality above a given threshold are to be assessed individually during the quality control process, preferably with the application of a proven assessment method that can predict their impact on the service life. The expected effect of the uncontrolled and imperfect microstructure is to be considered during the design phase of the components.

From the standpoint of engineering system manufacturers, the classification process of castings supplied by various foundries poses several difficulties. System manufacturers usually apply quality control guidelines for material strength based on the testing of monotonic testing properties of test specimens machined from randomly selected castings. However, high cycle fatigue being a surface linked failure mode, the measurement of the monotonic bulk behaviour does not ensure the expected fatigue performance for a cyclically loaded component.

There are internationally applied standards which define examination rules for the surface condition of castings (such as the European standard EN 1370 [1] and the ASTM A802 [2]). However, none of them presents a quantitative approach for the description of fatigue strength based on the inspected surface conditions. The current research was initiated and supported by the Knorr-Bremse Rail System Budapest to gain first-hand theoretical and experimental knowledge related to the defining factors of defect induced fatigue. These can be utilised to create a quantitative design and quality control guideline for the surface examination of safety-critical castings.

The pre-existing published methodologies for defect induced fatigue often make significant simplifications and are rarely aimed at providing generally applicable theories focused on the component scale. The lack of experimental fatigue test data for the ISO 1083 500-7 [3] grade of interest hinders the reliable application of published methodologies.

The thesis aims to consider the impact of surface defects, which have been detected during the visual quality control process, on the high cycle fatigue life. First, the defects must be characterised with relevant parameters containing the necessary information to evaluate their criticality. The fatigue life and strength need to be calculated based on these parameters for complex components and multiaxial stress states.

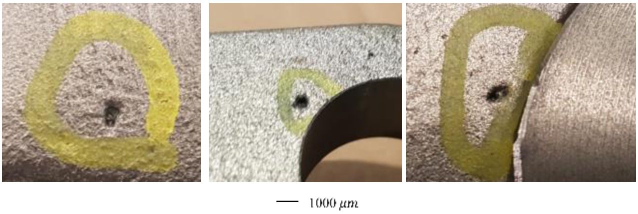

Figure 1.1. Examples for surface defects on nodular cast iron components.

1.1. Necessity of research

Several methodologies have been developed for the modelling of defect induced fatigue over the recent years; however, most of them have many shortcomings if one tries to apply them in an industrial environment. There is no commonly accepted methodology for the assessment of notches, while the effect of defects has significantly more unknown factors.

The notch and defect sensitivity research have been generally limited to the effect of circumferentially machined notches and hemispherical defects in contrast to natural ones. Only a limited number of studies [4,5] tried to analyse the impact of the defect shape on the fatigue life. Understanding the effect of the defect shape is an essential step towards the description of the effect of natural surface defects having complex shapes.

A severe question in the view of the author, which is often neglected or taken for granted, is the transferability of fatigue data obtained by the testing of polished specimens to components. This issue has been highlighted in the review of W. Schütz in 1996 [6] and is still relevant. Researchers develop and validate methods solely on specimen data, leaving the issue of transferability to the engineering praxis. Practising engineers often do not have the time and resources to find and document general solutions.

Multiaxiality of the stress state, heterogeneity of material properties along the cross-section and the varying proportion of the crack initiation and propagation phases are to be considered in the processing cylindrical specimen-based experience to complex components. Another factor supporting the importance of the current research is that experience and knowledge related to the cyclic material, and fatigue strength properties are limited for the ferritic-pearlitic ISO 1083 500-7 [3] NCI grade. It is interesting to note that there are significantly more experimental results are available for the mainly ferritic 400-18 and the mainly pearlitic 600-3 classes.

1.2. Research aim

The current research aims to provide transferable answers between the specimen and component scales of defect induced high-cycle fatigue with the ISO 1083 500-7 [3] ferrite-pearlitic grade castings in focus. Throughout this research, the Defect Stress Gradient approach has been found to cover the technical constraints of the research program, which is why this work follows on with further development for this approach compared to its previous formulations. A fatigue testing experimental campaign is summarised in this work, whereas the new theoretical and experimental findings are compared with each other.

From a scientific standpoint, this work aims to assess the high-cycle multiaxial fatigue life of NCI material with surface defects based on the critical characteristics, such as defect shape, size, orientation, location and surrounding microstructure. The influence of defect shape is investigated detail in the work since that is an often-neglected factor in the literature. Furthermore, a transfer of experimental data from small test specimens to the scale of industrial components is aimed for a general understanding of the problem.

From an engineering standpoint, the aim of this work to derive a methodology based on scientific results. This method should be able the decision-making process of engineers to decide, whether a given component (with its unique surface conditions) would meet the design requirements based on the post-processing of the fatigue assessment results for the idealised state of the component. There are technical constraints for the research for it to be applicable for the fatigue design of castings of the transportation industry:

1) the initiation of microstructurally long fatigue crack is usually considered as a failure criterion in the transportation industry, since regular inspections are not necessarily ensured for all safety critical components,
2) components are mainly designed for high-cycle fatigue life, often against the fatigue limit,
3) complex geometries and stress state combined with a large number of load cases.

Based on the review of the literature related to the casting defects of ferrite-pearlitic nodular cast irons and a visual inspection campaign conducted on components with surface defects, the defect size range of particular interest has been designated to be 50 – 2500 μm.

1.3. Research method

The goal to assess components with surface defects is reached systematically, starting from the analysis of test specimen behaviour and validating the findings on component tests.

The complexity of the defect induced fatigue phenomenon can be reduced with the control of the defect size, shape, morphology and surrounding microstructure. The subsurface defects cannot be detected with visual inspections; therefore, they have been identified on the fracture surfaces of the specimens after the testing. The effect of natural subsurface defects is evaluated through a comparison with the artificially machined ones of the same equivalent size.

Figure 1.2 illustrates the experimental approach of the research. From an experimental viewpoint, the detected surface defects were modelled as hemispherical and half-ellipsoidal notches machined on the surface of pulsating tension and 4-point bending fatigue test specimens. Through the controlled parameters of the defects the lowest possible difference between simulations and the tests was ensured.

Figure 1.3 displays a schematic of the theoretical approach of the research. From a general viewpoint, the high-cycle fatigue behaviour of defective components is in focus of the current work. However, under positive mean stress state, the structural stress reaches into the elastoplastic regime for a portion of the full load cycle for NCI test specimens having fatigue lives near the fatigue limit. In the presence of stress concentrators, the local cyclic plasticity at the tip of the defect is expected to have a significant effect. The crack initiation and propagation phases of the whole fatigue life are investigated separately in the thesis for a thorough understanding of the fatigue process.

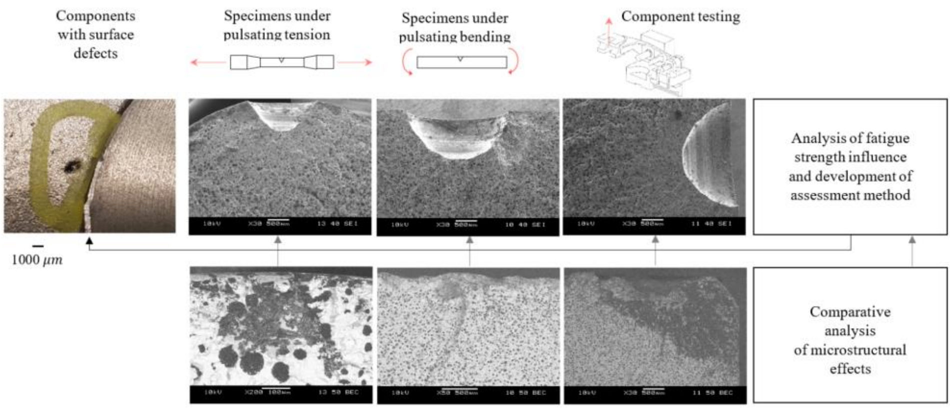

Figure 1.2. Experimental approach of the research.

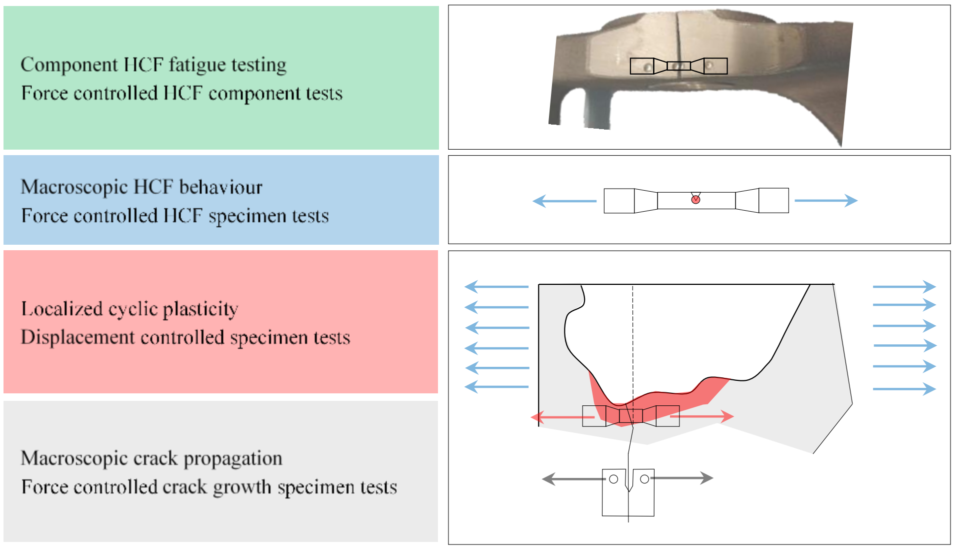

Figure 1.3. Theoretical approach of the research.

2. BRIEF SUMMARY OF THE RESEARCH

The impact of the various material defects is generally expressed in the form of a Kitagawa type plot (based on the pioneering work of Kitagawa and Takahashi [7]). The Kitagawa diagram displays the fatigue strength for a given number of cycles (generally corresponding to the fatigue limit) as a function of the equivalent defect size. The results of the polished cylindrical test specimens having different types of machined defects tested in pulsating tension ($R = \sigma_{min}/\sigma_{max} = 0.05$) are presented in connection to the equivalent defect size of the defect responsible for the initiation of the detrimental fatigue crack. Figure 2.1 displays the Kitagawa diagram for the pulsating specimen tests, where the equivalent size of a defect is the square root of its cross-sectional area projected in a plane perpendicular to the first principal direction of the acting stress tensor $(\sqrt{area})$, and the fatigue limit is determined experimentally as the fatigue strength at 10^6 load cycles (this corresponds to the interpretation of the fatigue limit in the FKM 2012 Guideline).

The experimental results are displayed in Figure 2.1 with schematics aiding the interpretation and curves highlighting the different trends. For the polished specimens the natural subsurface defects (yielding from the characteristics of the casting process; inclusions and degenerated graphite) located at the initiation of the crack propagation process have been identified by the means scanning electron microscopy. Without proper SEM characterization their effect is considered within the random scatter of the fatigue strength; however, on a Kitagawa plot this shows a clear trend: the subsurface defects above approximately 150 μm start to decrease the fatigue strength. The milled artificial defects with different shapes (hemispherical, transversal ellipsoid, longitudinal ellipsoid and tilted ellipsoid) have larger equivalent defect sizes compared to the natural subsurface ones. The behaviour of hemispherical defects shows an interesting trend, it lies below the data points for the ellipsoidal defects, even though some of the ellipsoidal defect shapes have a larger linear elastic stress concentration effect. Based on this experience, it becomes apparent that methods using linear elastic stresses will not be able describe the criticality of the defect shape. The $\sqrt{area}$ parameter from Murakami [8] has been known to be proportional to the K_I mode I stress intensity factor for a given surface crack. This leads to the conclusion, that the methods based on the theory of linear elastic fracture mechanics will neither be able to describe these results, since the $\sqrt{area}$ parameter was not able to align the datapoints on a single trend.

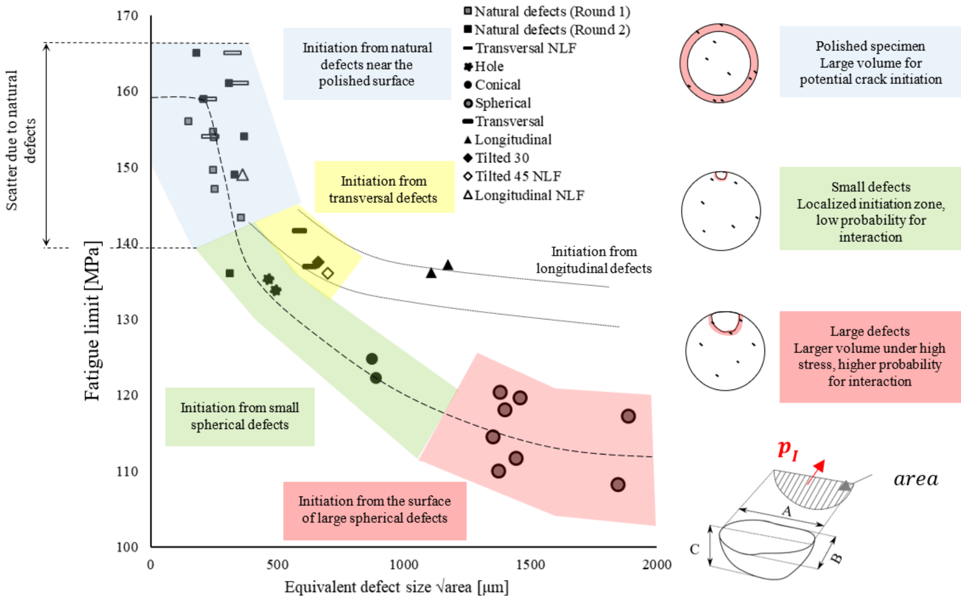

Figure 2.1. Kitagawa type plot of the fatigue test results for different defect sizes and shapes for ISO 1083 500-7 NCI specimens tested under pulsating tension (R0.05).

2.1. Development of the Defect Stress Gradient (DSG) approach

The Defect Stress Gradient approach [5] is one of the actively researched methodologies for the prediction of defective fatigue life and strength, and it is able to describe the Kitagawa relationship of various metallic materials (cast aluminium and titanium alloys, rolled steel and nodular cast iron).

Multiple adjustments have been presented in the thesis to its formulation and its application coupled with FEA, with the aim of reaching general industrial applicability and improved prediction accuracy. Figure 2.2 presents the outline of the DSG method, where the improved parts of the approach are highlighted with bold.

Figure 2.3 presents the simulated Kitagawa curves obtained with elastoplastic DSG calculations in comparison to the a) cylindrical specimen and b) component fatigue test results. The min/max designations for the simulated curves of the different defect shapes (hemispherical, transversal-, longitudinal- and titled ellipsoid) correspond to the lowest and highest value of the computed elastoplastic multiaxial stress concentration factor, where the difference is due to the individual nature of each tested specimen. In view of the results, the DSG method is applicable for the precise description of the fatigue strength influenced by artificial defects on cylindrical test specimens and components as well. The simplified linear elastic method provides conservative results in comparison to the elastoplastic one; however, it has the advantage of not needing additional FE-computations for the consideration of the defect influence.

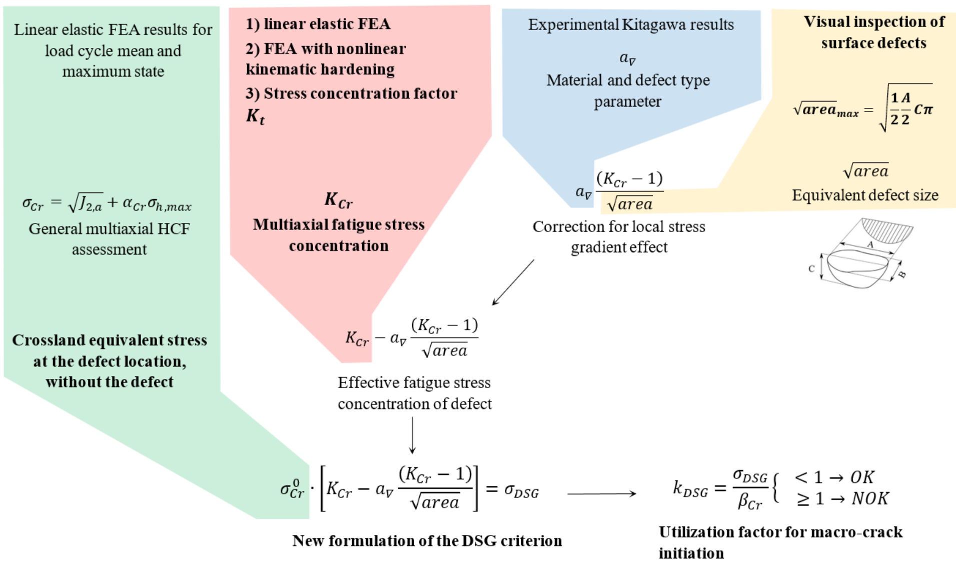

Figure 2.2. Outline for the new formulation of the Defect Stress Gradeint approach, with the improved part of the methodology highlighted with bold.

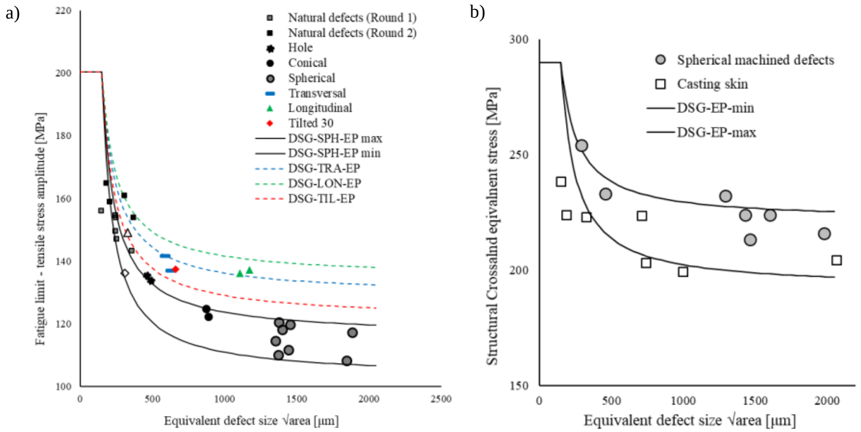

Figure 2.3. Elastoplastic DSG Kitagawa curves and fatigue test results at 10^6 cycles for a) specimens and b) components.

3. ALLOWABLE DEFECT SIZE MAPS FOR A GIVEN SERVICE LIFE GOAL

Allowable defect size maps show the value of the equivalent defect size in the form of FE-result field, which would still allow the component to reach its designated life goal in high-cycle fatigue. In the current research, the high-cycle fatigue strength is investigated at 10^6 load cycles, which corresponds to the fatigue limit by the FKM 2012 Guideline [9]. In the DSG approach the Crossland multiaxial fatigue criterion is used to create an equivalent fatigue stress type quantity for the description of the multiaxial stress state, and the load ratio effect and a stress gradient correction is applied for the precise description of the local stress concentration of the fatigue strength. The information related to the allowable defect size is highly important for the foundries aiming to produce components to meet the requirements of their customers quality control system. The casting process can be optimised for a given component based on an allowable defect size map. The same allowable defect size map can be used for the visual inspections of the quality control process. The levels of allowable defect sizes can be harmonised with the applied regulations, for example, the widely applied EN 1370 [1] standard. The current work proposes a deterministic scientific approach for the precise calculation for the effect of surface defects on the fatigue strength. The provided example for the allowable defect size can be scaled to the required level of safety, and the probabilistic nature of the fatigue phenomenon can be included in the assessment.

The allowable defect size ($\sqrt{area}^{ell}_{all}$) for a fatigue strength of the defect-free material $\beta_{Cr}(N_{lc.i})$ corresponding to a given design life (initiation life of macroscopic cracks) can be expressed with the following equation:

$$\sqrt{area}^{ell}_{all} = a_{\nabla}\frac{\sigma^{0}_{Cr}(K^{ell}_{Cr}-1)}{K^{ell}_{Cr}\sigma^{0}_{Cr}-\beta_{Cr}},$$

where a_{∇} is a microstructural parameter, σ^{0}_{Cr} is the structural Crossland equivalent stress, and the value of K^{ell}_{Cr} can be estimated with the application of the simplified DSG approach presented in the Thesis. For multiple defects located close to each other and for subsurface defects, the assumptions presented in the Thesis are to be applied. The methodology has been validated through the comparison of calculations with the experimental results. The simplified model provides conservative predictions for crack initiation for artificial surface and natural subsurface defects in the casting skin.

In the general fatigue assessment of components, first, quasi-static load cases are defined for the representation of the cyclic loading cycle. From these results, so-called solution combinations are derived with the stress fields for the stress amplitude and the mean stress state. For a given solution combination, the allowable defect size field can be calculated. For several simultaneously acting fatigue loads near the fatigue limit, the cumulated allowable defect size can be considered in a simplified manner as the local minimum of the allowable defect sizes. The allowable defect size maps can be derived from the FE-simulation results with the post-processor. Calculations results can be harmonised with the determinative regulations, such as the EN 1370 [1] standard. It is also useful to derive directly comparable dimensions for the quality control personnel instead of the theoretical equivalent defect size. During the quality control process, the bounding dimensions of the defects are compared with the allowable defect size map documents leading to an OK/NOK decision for the inspected component. An example of an allowable defect size map is displayed in Figure 3.1. The investigated load state corresponds to a hypothetical design goal, which is the component fatigue limit from the component Wöhler tests corresponding to 32.33 kN in the cyclic load maximum. Results are also meaningful in the subsurface region of the components. For the current design goal, even the removal of the casting skin would be necessary for a small subsurface region to comply with the defect size map.

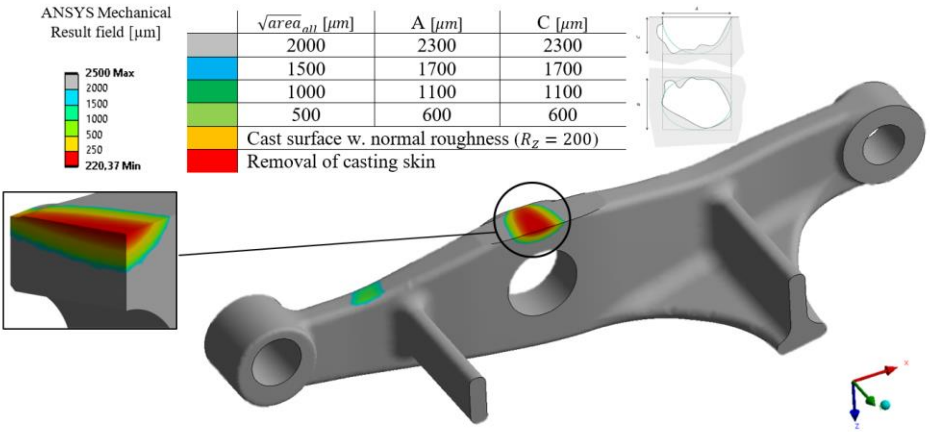

Figure 3.1. Example for an allowable defect size map based on the simplifed DSG approach.

4. NEW FINDINGS

1. New finding

Based on my experimental results and FE-based fatigue calculations I have concluded, that surface defects having equivalent sizes ($\sqrt{area}$ by the interpretation of Murakami) lead to a different impact on the high-cycle fatigue life and strength, depending on their shape, for the ISO 1083 500-7 nodular cast iron material. This difference can be traced back to the shape dependent stress concentration effect of the surface defects, which regulates the crack nucleation process.

My directly corresponding publications [I], [V]

2. New finding

I have introduced a three-dimensional half-ellipsoid based geometrical model for the description of the surface defect shape to quantify its impact on the fatigue life and strength, and I have showed through my calculations that the model can consider the shape of surface defects in the high-cycle fatigue assessment process.

The model characterizes a given surface defect with its shape parameters (B/A and C/A, which are responsible for the stress concentration effect and the nucleation of fatigue cracks), and its oriented equivalent size $\sqrt{area}_\varphi$ (which effects the stress gradient and the behaviour of the potentially initiated fatigue crack).

A surface defect in the fatigue assessment can be characterised with the following parameters:

- A $[\mu m]$ max. length on the surface,
- B $[\mu m]$ max. bounding width perpendicular to the A dimension in the plane of the surface,
- C $[\mu m]$ max. depth from the surface,
- φ $[deg]$ the angle between the normal of the plane perpendicular to the surface and containing the A dimension, and the first principal direction $\boldsymbol{p_I}$, $\varphi = \boldsymbol{n}_A \measuredangle \boldsymbol{p_I}$.

The shape of a surface defect can be described with the B/A surface- and C/A cross-sectional shape parameters. The equivalent size of an ellipsoidal defect with the A and C parameters is $\sqrt{area}_\varphi = \sqrt{\frac{1}{2}\frac{A(\varphi)}{2}C\pi}$. Figure 4.1 shows the interpretation of the geometrical parameters.

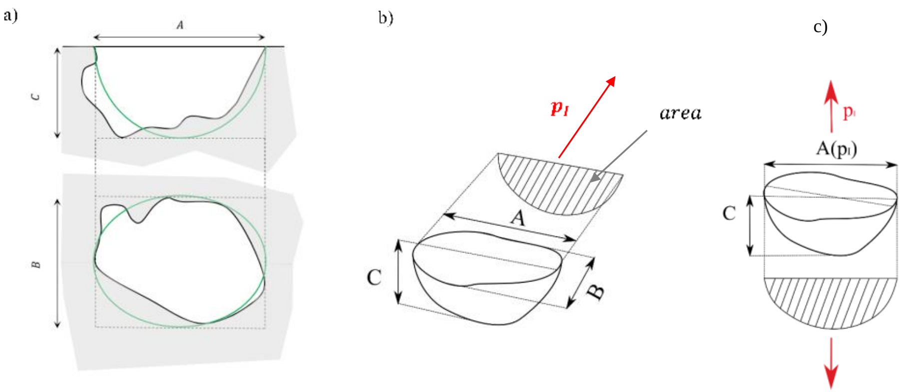

Figure 4.1. a) Interpretation of the bounding dimensions, b) Interpretation of equivlent size for defect oriented perpendicular to the max. principal direction of the stress tensor, c) interpretiation in general orientation.

My directly corresponding publication [I]

Previous interpretation by Y. Murakami [10]

3. New finding

With the application of the half-ellipsoidal defect model and the statistical analysis of the visual inspection results from 106 pcs. of ISO 1083 500-7 nodular cast iron lever arms, I have concluded that the cross-sectional shape parameter (*C/A*) and size ($\sqrt{area}_{max} = max\{\sqrt{area_{\varphi}}\}$) of surface pores and sand drops follow a lognormal distribution.

Figure 4.2 and Figure 4.3 display the empirical and fitted lognormal probability distribution function of the cross-sectional shape (*C/A* ratio) and equivalent size $\sqrt{area}_{max}$), respectively.

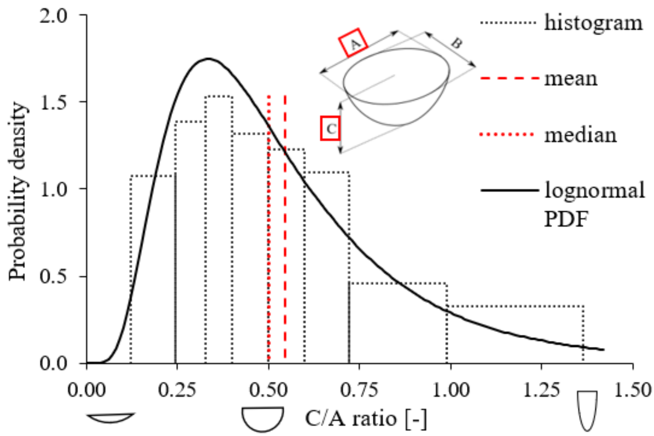

Figure 4.2. Distribution of the C/A shape parameter for surface defects displayed on histogram with the fitted log-normal probability distribution function.

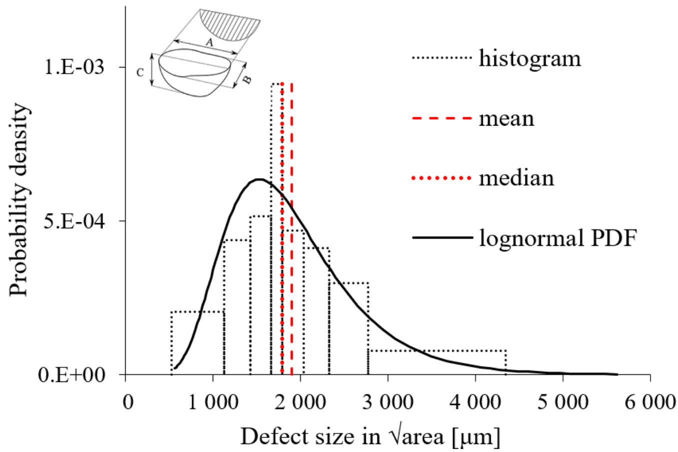

Figure 4.3. Distribution of the defect size for surface defects displayed on histogram with the fitted log-normal probability distribution function.

My directly corresponding publication [I]

4. New finding

I have interpreted and quantitatively evaluated the impact of surface defect shape on the fatigue life and strength through the modification of the Defect Stress Gradient Approach (DSG) known from the literature.

With the introduction of the defect shape related, size-independent, stress concentration effect parameter K_{Cr}, the DSG equivalent stress by the modified DSG criterion is given by:

$$\boldsymbol{\sigma_{DSG} = \sigma_{Cr}^{0} \cdot \left[K_{Cr} - a_{\nabla} \frac{(K_{Cr} - 1)}{\sqrt{area_{\varphi}}} \right] \leq \beta_{Cr}} \,,$$

where,

- σ_{DSG} is the equivalent stress type quantity defining the criterion,
- σ_{Cr}^{0} is the structural Crossland equivalent stress,
- a_{∇} the microstructural parameter,
- K_{Cr} is the shape dependent stress concentration parameter,
- $\sqrt{area_{\varphi}}$ is the oriented equivalent defect size,
- β_{Cr} is the ideal material fatigue strength for a given number of load cycles in Crossland equivalent stress.

The fatigue life leading the initiation of microstructurally long fatigue cracks $(N_{lc.i})$ is:

$$N_{lc.i} = \left(\frac{\sigma_{DSG}}{A_{W.Cr}} \right)^{\frac{1}{B_{W.Cr}}}$$

where $A_{W.Cr}$ is the theoretical Crossland equivalent fatigue strength at one cycle, and $B_{W.Cr}$ is the slope of the unified Crossland Wöhler curve. The initiation life of microstructurally long fatigue cracks is a good approximation of total life in the high-cycle fatigue regime and builds an assessment criterion by itself.

The allowable ellipsoidal defect size $\sqrt{area}_{all}^{ell}$ for a given stress concentration effect by an ellipsoidal defect shape, and a given lifetime goal can be directly expressed as:

$$\sqrt{area}_{all}^{ell} = a_{\nabla} \frac{\sigma_{Cr}^{0}(K_{Cr}^{ell} - 1)}{K_{Cr}^{ell} \sigma_{Cr}^{0} - \beta_{Cr}}.$$

My directly corresponding publication	[I]
Previous formulation by M. Vincent et al.	[5]

5. SUMMARY

The thesis extended the state-of-the-art status of the fatigue research by the development of one of the current methods for the assessment of defect induced crack initiation with the analysis of the defect shape and the development of transferable methods between the test-specimen and component scales.

It has been shown that the equivalent size parameter from Murakami does not represent fully the critically of surface defects on the fatigue strength, their three-dimensional shape is a significant parameter as well. For the understanding of this effect an ellipsoidal defect model has been proposed and improvements have been implemented in the DSG method for the assessment. The impact of the defect shape has been traced back to the local cyclic elastoplastic material behaviour regulating crack nucleation and short crack growth. The thesis confirms that the crack nucleation and the propagation of microstructurally short fatigue cracks dominates the whole fatigue life in the high-cycle fatigue regime. The current research describes these phases of the fatigue life through the characterisation of the cyclic elastoplastic stress field around the defect, in which the crack nucleation and short crack propagation occurs.

The work focused on the fatigue behaviour of a ferrite-pearlitic nodular cast iron grade, for which limited fatigue test data was available at the start of this research. The experimental tests have confirmed that the influence of defects is a first-order parameter for the fatigue assessment of nodular cast iron material. The thesis investigates and then names the essential parameters regulating the effect of surface defects on the fatigue life, namely their shape, size, location, morphology and the surrounding microstructure.

From an engineering standpoint, a global approach is presented for the fatigue assessment of NCI components with surface defects and for the calculation and application of allowable defect size maps for the fatigue design and quality control process of NCI components. The nonlinear elastoplastic FE-based DSG approach is validated on the test specimen and component test showing a good description of the defect influence on the high-cycle fatigue strength. The computations and experimental studies have shown that the high-cycle fatigue strength of defective material can be modelled with high accuracy with the consideration of the cyclic elastoplastic stress state and the stress gradient effect near the defects. The simplified approach based on the estimation of the linear elastic stress concentration factors of the defects is validated to provide conservative answers.

A vital characteristic of the thesis is that the transferability of the models, test data and experience between small cylindrical fatigue test samples under pulsating tension and generally loaded industrial components have been investigated and validated. This transferability of theory and experience related to the phenomenon of fatigue between different scales is often considered self-evident and taken for granted in the scientific community. It is confirmed by this work, that it is most certainly not self-evident nor granted by the application of solid mechanics; one has to consider the heterogeneity of the material properties through the cross-section, the response of the material to cyclic loading, the effect of the structural and local stress-gradient and the initiation and propagation phases of the fatigue life to provide generally applicable methods for the assessment of the high-cycle fatigue life.

A further step could be to extend the DSG approach, which is proven to provide precise deterministic answers, to include it in a probabilistic framework. The author has already proposed advancements in the connection of the heterogeneous material properties with the probabilistic nature of the fatigue test data [VI]. However, there are years of work needed to develop a robust probabilistic model which describes the expected scatter of the fatigue life and the component size effect without compromises in accuracy and versatility.

The experiments and computations of the thesis were all conducted under constant load amplitudes. The effect of variable amplitude fatigue and damage accumulation probably the first aspect to consider for the future extension of this research. An untouched problematic of this work is the effect of environmental conditions on defective fatigue strength. Corrosive environments are known for strongly accelerating the fatigue process. The joint impact of surface defects and corrosive environments on the fatigue strength of nodular cast iron components could be an important extension of this research.

CORRESPONDING PUBLICATIONS

[I] Gróza M, Nadot Y, Váradi K. Defect size map for nodular cast iron components with ellipsoidal surface defects based on the defect stress gradient approach. Int J Fatigue 2018;112:206–15. doi:10.1016/j.ijfatigue.2018.03.025. IF 3.673, Q1.

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