Coupling of Simulation Tools for Obtaining Local Fatigue in Combination with Experimental Data

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Abstract. Cast iron components have a good strength to weight ratio. This leads to their frequent use in the wind industry. The design of cast iron components is currently based on the use of individual simulation tools and material data that is common to all components. In order to better exploit the lightweight potential of cast iron components, it is necessary to link the simulation software tools and thus take into account local material properties already in the design phase. This is described in this paper using the example of a large casting for the wind industry.

Introduction

Designers of castings are increasingly using simulation tools. There are typically three steps involved: (1) The designer creates a geometry based on the requirements and calculates the stresses resulting from the applied static operating loads and inertia forces using FEM simulation with structural analysis. In an optimisation loop, the component can be optimised to minimise the stresses under certain constraints. (2) The casting process simulation is preformed based on the 3D CAD model. The entire casting process from pouring to solidification of the melt is analysed in the form of a CFD simulation and the casting system (feeder, material allowance, etc.) is defined. (3) Based on the CAD data and, if necessary, the local material properties, the fatigue life is assessed and potential local weak spots in the component are identified. A number of sub-steps are required before a final design is achieved.

The use of simulation programmes for casting process, structural and fatigue analysis is currently still carried out independently. If several calculation tools are used, there is no exchange of all relevant data, partly due to the lack of software interfaces. There is no holistic view of the simulation data.

Cast iron components are often subjected to high mechanical loads. To ensure the safe operation of plant and machinery, the fatigue life of the component must be guaranteed under the assumed operating conditions over the planned service life. New or expanded applications and increased safety requirements increase the need for detailed life prediction. From this point of view, the following question arises How can casting process simulation and structural analysis contribute to the fatigue life calculation?

In addition to simulation-based fatigue analysis, the fatigue life of a component can also be determined experimentally, but these tests are time consuming and expensive. They also require extensive laboratory equipment. In addition, component tests of this magnitude are almost impossible to perform experimentally. Therefore, this route is only taken in a few cases, and experimental validation of simulation results is also too costly in most cases. The present work is the first attempt to take into account the experimental data obtained at great expense in simulation-based fatigue analysis. These data have been obtained from samples of large castings.

1 Simulative Determination of Local Fatigue Limits

In the following chapter, two different approaches are presented from a methodological point of view. The first approach describes the calculation of fatigue limits based on a homogeneous material definition, i.e. the material definition is identical for the whole component.

Locally varying material parameters are not taken into account. The second approach describes the integration of casting process simulation data into the fatigue analysis. Here the local material properties are defined on a common FE mesh. Both approaches have already been mentioned in [1, 2, 3]. This paper describes in detail the technical realisation of the data using an example.

1.1 Procedure with Global Material Data

FEMFAT is the world's leading solver for FE-based fatigue analysis and calculates the structural durability of statically and dynamically loaded components based on the results of FE calculations. As an FE post-processor, FEMFAT requires not only the structural analysis data (FE mesh and loads) but also the material data (strength values). The figure 1 shows the typical procedure for calculating local fatigue limits in FEMFAT.

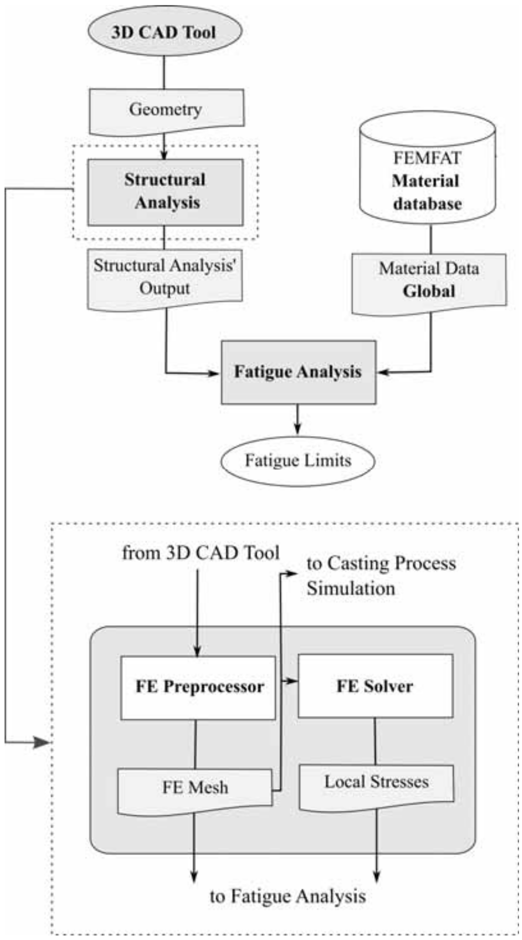

Figure 1: Calculation of fatigue limits with global material data.

The following example of a large wind turbine casting illustrates the process in more detail. The *poll end* or *canister* (the cast iron box on the end of the wind shaft through which the sails stocks pass) of a wind turbine has to withstand high cyclic loads. It is therefore extremely important to ensure fatigue limits in areas of high stress.

The determination of fatigue limits starts with the import of the component geometry into the structural analysis pre-processor to generate an FE mesh. This step has been performed in VisPER, a component of the structural analysis tool PERMAS 18.00.404.

Simulations to calculate the static stresses were carried out using the PERMAS FE solver. For the poll end, the resulting stresses for the different rotor positions were investigated for a complete poll end revolution at a distance of 45°. For the resulting 8 positions, the mechanical stresses were determined with PERMAS (Figure 2).

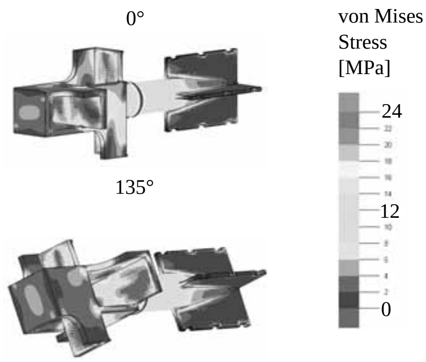

Figure 2: Simulated distribution of mechanical stresses at two different angular positions.

The TransMAX module from FEMFAT was used to calculate the locally endurable stresses. This provides the user with the ability to analyse structural durability based on load-time histories. Prior to this, a material had to be defined for the fatigue analysis model. Typically, the option of a homogeneous material definition from the internal FEMFAT database is used.

A material class is selected from the material database. Based on pre-programmed ratios, the following missing material parameters are added to a predefined tensile strength for the calculation to be automatically generated:

- Young's modulus
- Yield strength
- Elongation at break

At the FE node, local fatigue limits are calculated from material parameters that are additionally influenced by local component properties (e.g. notch effect) and loads. The basic procedure for calculating fatigue limits is based on the influencing factors that increase or decrease the fatigue strength. The FKM (Forschungskuratorium Maschinenbau) standard describes these factors [4].

1.2 Integration of a Casting Process Simulation

The casting process simulation determines the local microstructure formed by the manufacturing process. A microstructure is formed as the metal solidifies and consists of different microstructural phases with different shape, size and distribution (grains, dendrites, lamellae, pores) [5]. Figure 3 illustrates the distribution of a microstructural phase - pearlite - at the poll end.

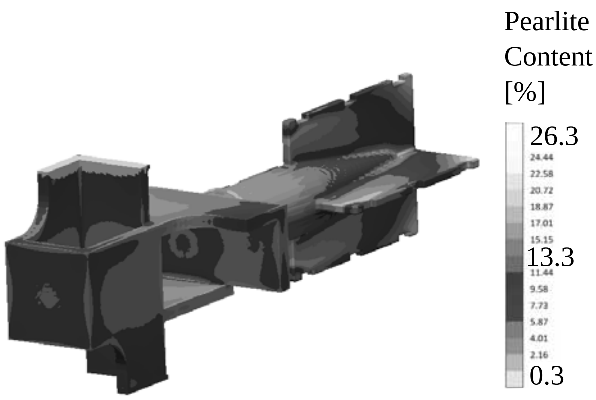

Figure 3: Simulated microstructure fraction in the component at room temperature.

Given the demands on the accuracy of today's simulations in the foundry industry, local material differences must be taken into account in the fatigue analysis. One way of dealing with this is to use the local material data from the casting process simulation. From the microstructure, the casting process simulation can determine local material values (tensile strength, Young's modulus, yield strength, elongation at break) in the casting in the next step (Figure 4).

Figure 5 shows the schematic description of the approach to calculate the local fatigue limits with integration of the local material data from the casting process simulation:
For the calculation of the local material data of the poll

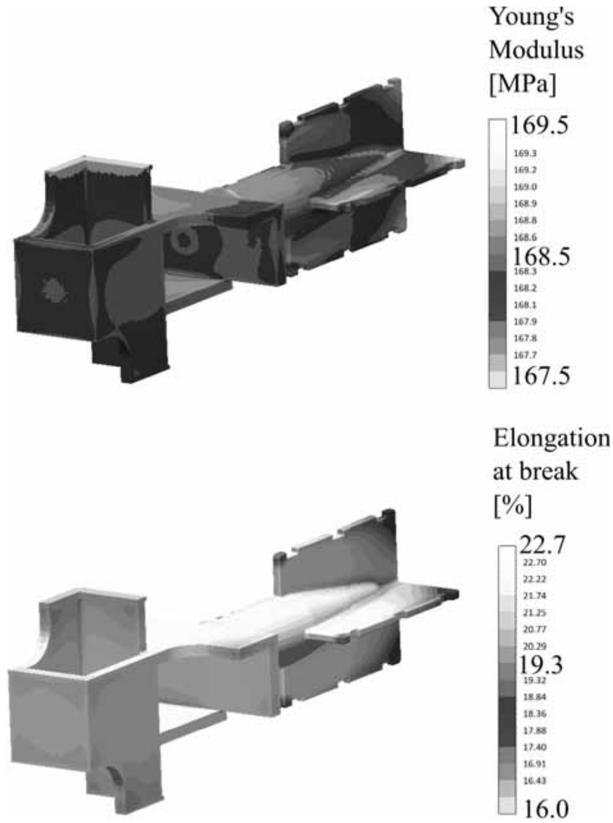

Figure 4: Simulated local material properties in the component at room temperature.

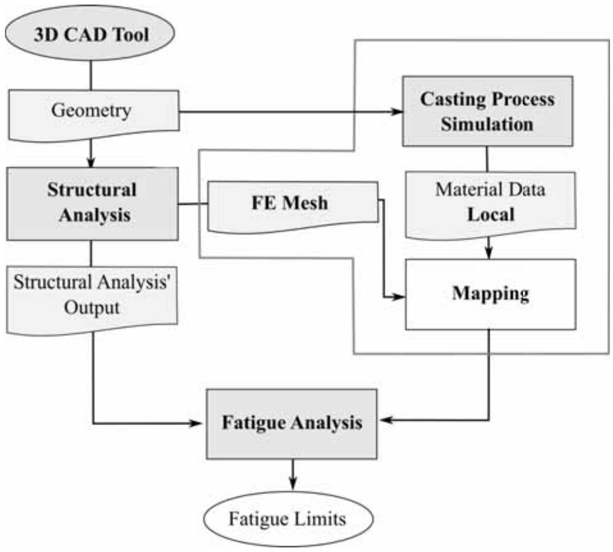

Figure 5: Calculation of fatigue limits with local material data from casting process simulation.

end, the casting process simulation was carried out in the commercial software package MAGMASOFT®5.4.

The discretisation for the numerical solution algorithm in the casting process simulation on the one hand and in the fatigue/structural analysis on the other hand is different: in MAGMASOFT® the discretisation is based on the Finite Volume Method (FVM) and in the fatigue/structural analysis on the Finite Element Method (FEM). There is a need to map the results from the casting process simulation to the FE mesh generated in the structural analysis. The mapping is realised by MAGMAlink, a casting process simulation module. This makes the results of the casting process simulation available for further processing in the fatigue analysis.

According to the state of the art, FEMFAT can read in the local material data from the casting process simulation and use the output from the structural analysis (FE mesh and local loads) to calculate the fatigue limits for each FE node. Comparing the two approaches (Figure 6), it can be seen that when the casting process simulation is included, the fatigue limits are on average between 10 % and 20 % higher. The difference at the edge of the poll end is significantly larger, up to 50 %.

2 Consideration of Experimental Data.

The described simulative approaches start from the component geometry and the determination of the fatigue limits is computer-aided. However, the fatigue life analysis tool FEMFAT also offers the possibility of directly importing already existing local fatigue data in order to perform a more specific calculation.

Ut has already been shown in several publications that the microstructure has an influence on the fatigue life [6, 7, 8, 9]. In particular, the ratio of pearlite to ferrite and nodularity have been shown to be important microstructural parameters. In this context, a high pearlite content and a high nodularity have a positive effect on the endurable stresses and thus on the component fatigue. However, nodularity is not calculated by the casting process simulation and is therefore consequently not considered further.

The casting process simulation does not require the local mechanical properties as in the purely numerical approach, but the local microstructure.

If experimental data on the microstructure and the associated fatigue limit are now available in a material database, the microstructure resulting from the casting process simulation can be used to generate local fatigue limits (Figure 7).

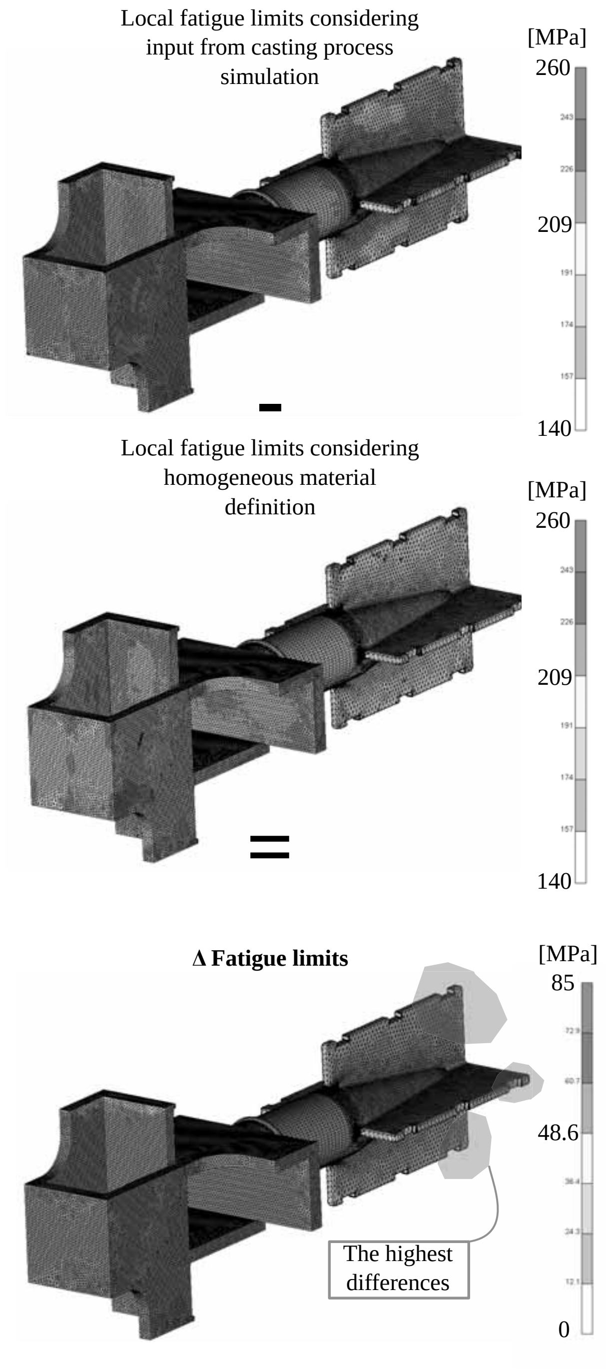

Figure 6: Fatigue limits with homogeneous material data and incorporating casting process simulation data

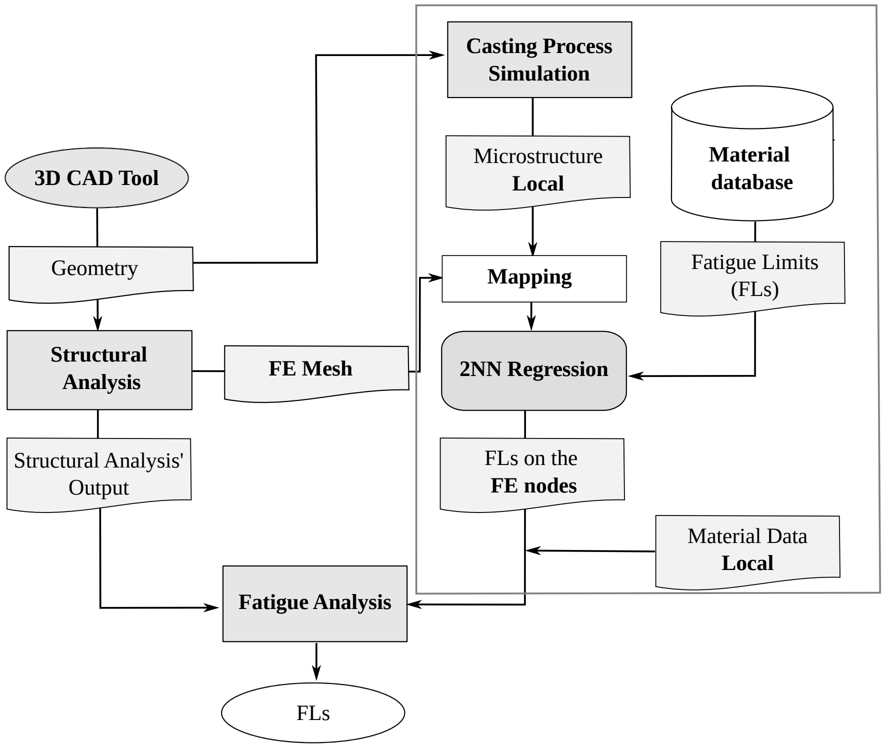

Figure 7: Calculation of local fatigue limits using experimental data.

Since the experimental determination of microstructure/fatigue limits data is very costly, only a few data sets are available. In order to determine the associated fatigue limits for all the microstructure data from the casting process simulation, these must be approximated from the available experimental data.

Using the k-nearest neighbour algorithm (kNN) as a regression method [10], an individual fatigue limit can be generated for each FE node (Figure 8). Here, the value at a FE node is weighted by the distances d of the 2 nearest neighbours proportional to their distance. In the present work, the regression method is implemented in the form of in-house developed MATLAB code.

The fatigue limit $FL(x)$ for a node x is obtained from the experimentally determined fatigue limits of the two nearest neighbours x_1 und x_2 (both calculated nodewise from the casting process simulation) according to the equation 1:

$$FL(x) = \frac{d(x,x_1) \cdot FL(x_1) + d(x,x_2) \cdot FL(x_2)}{d(x,x_1) + d(x,x_2)} \quad (1)$$

In the equation 1 the $d(x,x_1)$ and $d(x,x_2)$ represent the distances from the FE node to the two two neares neigh-

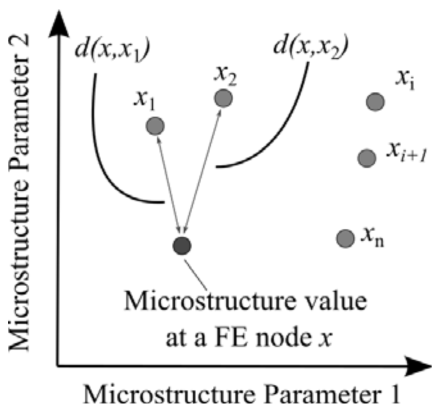

Figure 8: 2NN regression of fatigue limits from microstructure values.

bours (experimental data) in two-dimensional space consisting of two positive real numbers, the values for microstructure parameter 1 (x-axis) and microstructure parameter 2 (y-axis).

Finally, the fatigue limits obtained are modified by FEMFAT's internal algorithm using the stresses from the structural analysis. This allows a comparison of the fatigue limits from the three approaches described.

Compared to the calculation using the local material properties from the casting simulation, the fatigue limits with the regression from the microstructure data increase again by between 10 % and 20 %. Figure 9 shows the areas with the highest differences between the approach based on experimental data and the approach based on the local material properties. The differences are located at the blade bearings and the contact vials to the shaft.

Conclusion and Outlook

In this article, three possibilities for the simulative determination of the fatigue limit have been presented on the basis of a large cast component used in wind turbine technology. The integration of experimental data represents a new way of combining information from simulation and experiment. It is shown that the determined fatigue limits are lower with the purely numerical approaches than with the consideration of experimental data, which supports the application of purely numerically determined fatigue limits in industrial practice.

The complexity of the study for the numerical determination of local fatigue limits is explained by the purposeful coupling of software tools in the foundry industry which have not been connected up to now. In order to combine the different software modules, a number of interfaces are required. Table 1 shows the formats of the respective interfaces used in the three fatigue limit calculation approaches.

The integration of experimental data into the numerical process chain could be realized by a 2NN regression. Since the acquisition of experimental data on fatigue limits is very time-consuming, the algorithm is currently based on very little data. The incorporation of more experimental data will improve the prediction accuracy. These should also cover significantly more microstructure classes with the associated fatigue limits. An evaluation of the method presented here is only possible if the fatigue limit of a component is determined both experimentally and numerically.

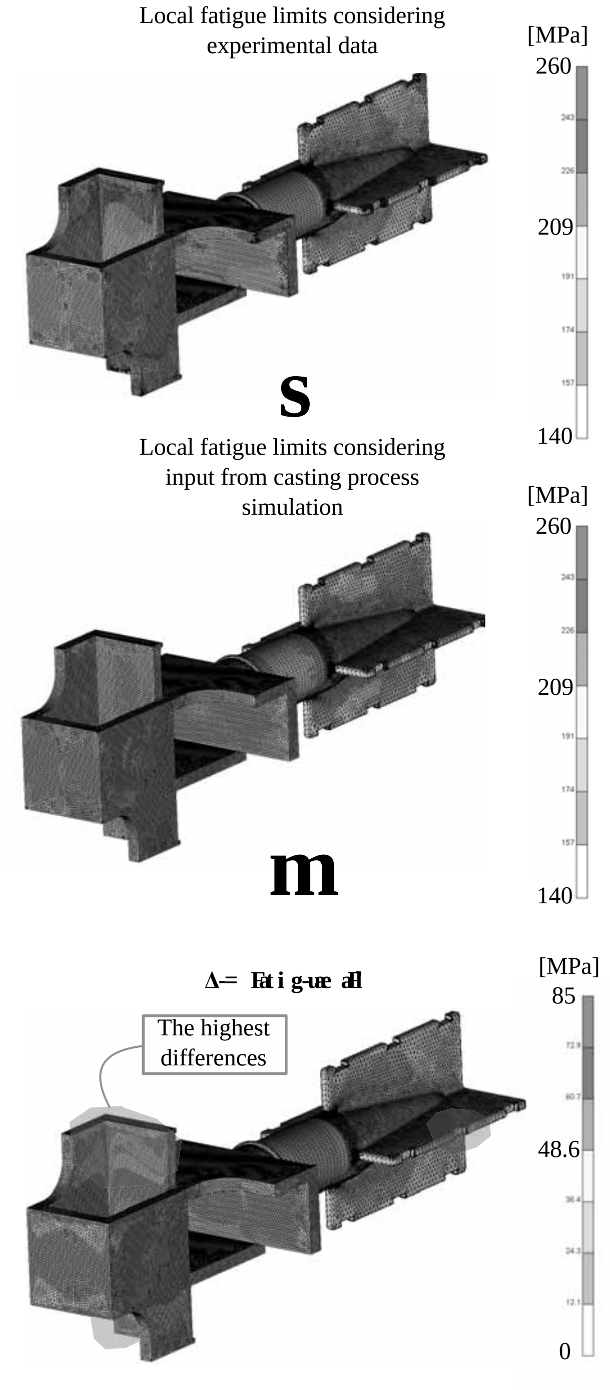

Figure 9: Fatigue limits considering data from casting process simulation and considering experimental data.

#	Interfaces between software tools	Transmitted data	Format (file extension)
1.	3-D CAD tool → Structural analysis	Geometry	- (STL)
2.	Structural analysis → fatigue analysis	FE stresses	PERMAS (POST)
3.	Structural analysis → fatigue analysis	FE mesh	PERMAS (DAT)
4.	Structural analysis → casting process simulation (MAGMAlink)	FE mesh	PERMAS (DAT)
5.	Casting process simulation → fatigue analysis	Local material data	- (UNV)
6.	Casting process simulation → regression	Local microstructure	PERMAS (DAT)
7.	Material DB → regression	Microstructure-dependent fatigue limits	- (XLSX)
8.	Regression → fatigue analysis	Local fatigue limits and material data	- (UNV)

Table 1: Overview of the used file formats.

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References

[1] Chen X, Engler-Pinto C, King M, Li M, Prabhu E, Su X. Aluminum Cylinder Head High Cycle Fatigue Durability Including the Effects of Manufacturing Processes. 2012; pp. 2012–01–0540. URL `https://www.sae.org/content/2012-01-0540/`

[2] Gaier C, Eberhard D, Aichberger W, Dannbauer H. Betriebsfestigkeitsanalyse mit Berücksichtigung von Ergebnissen aus der Prozesssimulation. Wiesbaden, Germany; .

[3] Puchner K, Aigner R, Rinnergschwentner L, Dannbauer H. Consideration of local material characteristics for the fatigue assessment of cast component. In: *Proceedings of the 1st Congress for intelligent Combining of Design, Casting, Computer Simulation, Checking and Cyclic Behaviour for efficient Cast Components*. Darmstadt; pp. 155–164.

[4] Rennert R. *Rechnerischer Festigkeitsnachweis für Maschinenbauteile aus Stahl, Eisenguss- und Aluminiumwerkstoffen*. FKM-Richtlinie. Frankfurt am Main: VDMA-Verl, 6th ed. 2012.

[5] Mercier JP, Zambelli G, Kurz W. Microstructures. In: *Introduction to Materials Science*, pp. 239–259. Elsevier. 2002;. URL `https://linkinghub.elsevier.com/retrieve/pii/C20090291483`

[6] Olofsson J. Local microstructure-based material performance and damage in design and finite element simulations of cast components. *Journal of Computational Design and Engineering*. 2018; 5(4):419–426. URL `https://academic.oup.com/jcde/article/5/4/419/5728982`

[7] Thomser C, Bodenburg M, Sturm JC. Optimized Durability Prediction of Cast Iron Based on Local Microstructure. *International Journal of Metalcasting*. 2017;11(2):207–215. URL `http://link.springer.com/10.1007/s40962-016-0091-x`

[8] Systemzuverlässigkeit FIFBU. Maßgeschneiderte Bauteileigenschaften durch Integration von Fertigungs- und Funktionssimulation : BMBF-Verbundprojekt MABIFF ; Abschlussbericht des Verbundprojektes.

Tech. rep., Technische Informationsbibliothek u. Universitätsbibliothek. 2011. Artwork Size: Online Ressource (103 S., 8,63 MB) Medium: application/pdf Version Number: 1.0.
URL
`https://www.tib.eu/suchen/id/TIBKAT:68815087X/`

[9] Hack M, Jung D, Egner-Walter A. Optimierter Lebensdauer-Berechnungsprozess von Eisengussbauteilen unter Berücksich-tigung des lokalen Gefüges*. *Materials Testing*. 2012;54(7-8):497–502. URL `https://www.degruyter.com/document/doi/10.3139/120.110356/html`

[10] Zhang Z, Gu GX. Finite-Element-Based Deep-Learning Model for Deformation Behavior of Digital Materials. *Advanced Theory and Simulations*. 2020;3(7):2000031. URL `https://onlinelibrary.wiley.com/doi/10.1002/adts.202000031`