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Fatigue crack growth in nodular cast iron - Influences of graphite spherical size and variable amplitude loading

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Abstract. Investigations of constant and variable amplitude loading, including a variety of overloads, were carried out experimentally as well as numerically in order to characterize the fatigue crack growth behaviour of nodular cast iron with a ferritic matrix. Under constant cyclic loading the crack growth rate, which depends on the graphite size can be described well by the NASGRO equation. The mean distance between the graphite particles and the shape factor also influence the fracture behaviour. The experimental investigations show that overloads yield to acceleration effects in fatigue crack growth. The calculation of the a-N curves based on different usual life prediction models yields non-conservative results. Therefore, a modified strip yield model is presented which allows the prediction of the crack growth acceleration after overloads in nodular cast iron.

1. Introduction
During use, a component is often subjected to variable amplitude loadings, which influence the lifetime. Therefore, fracture mechanics assessment of fatigue crack growth behaviour under variable amplitude plays an important role in many areas of applications of nodular cast iron especially in the case of components made for wind turbines. In order to quantify load history effects in ductile cast iron, fatigue crack growth experiments were carried out under constant and variable amplitude loading. The acceleration effects observed in fatigue crack growth of nodular cast iron significantly affect the accuracy of life predictions. Therefore, an extended strip yield model was developed to simulate the fatigue crack growth in nodular cast iron under variable amplitude loading.

2. Experimental setup
A ductile cast iron EN-GJS-400-18LT with a ferritic matrix and two specific adjusted graphite spherical sizes was studied. The cast test material variants G10 and G50 are produced from one slab by using different cooling rates to adjust specific graphite sizes \(d_c\). Higher cooling rate leads to finer spherical graphite size (G10) using a chill-mould. Lower cooling rate leads to larger spherical graphite size (G50) by means of sand mould. The graphite morphology of both test materials was statistically evaluated by quantitative structural analysis. Stroppa et al. found that the mean distance \(\lambda\) between the graphite particles and the shape factor \(f\) influence the fracture behaviour of cast iron with a ferritic
matrix [1]. The deviation from the spherical size is described by the shape factor (for an ideal sphere $f=1$). Table 1 gives the mechanical properties and the graphite morphology for both materials.

Table 1: Mechanical properties and graphite morphology of both tested materials [7]

| Material | $T$ [°C] | $R_m$ [MPa] | $R_{p0.2}$ [MPa] | $A_S$ [%] | $E$ [GPa] | $d_G$ [µm] | $\lambda$ [µm] | $f$ [-] |
|----------|----------|-------------|------------------|----------|-----------|-----------|------------|-------|
| G10      | RT       | 388         | 247              | 23,5     | 176       | 13        | 21         | 0,75  |
| G50      | RT       | 374         | 242              | 22,9     | 179       | 41        | 58         | 0,53  |

The experiments were performed with SENB-specimens of dimensions 10 mm x 20 mm x 100 mm. The fatigue crack growth experiments under constant amplitude loading were carried out at constant stress ratios of $R=0.1, 0.3$ and $0.5$ according to ASTM E 647-08 [2] using a resonance testing machine RUMUL. The compliance method was used to determine the crack length. The investigations of load history effects with variable amplitude loading were carried out using a MTS servo-hydraulic testing machine under load-controlled conditions, in which the crack length were measured by using crack gauges. Fatigue crack propagation under variable amplitude loading was realized by:

- Constant cyclic load with various tensile overload ratios ($R_{OL}=1.25…2.25$)

$$R\text{-ratio during a single overload defined by } R_{ol} = \frac{P_{ol}}{P_{Bl,max}}$$

where $P_{ol}$ is the maximum force during the overload and $P_{Bl,max}$ is the maximum force of the baseline-level loading.

- Block loading (low-high-low sequences) with various block loading ratios ($R_{block}=1.25…2.0$)

$$R\text{-ratio during the block loading was defined by } R_{block} = \frac{P_{block}}{P_{Bl,max}}$$

where $P_{block}$ is the maximum force during the block loading and $P_{Bl,max}$ is the maximum force of the baseline-level loading.

3. Experimental results and numerical simulation

3.1. Fatigue crack growth behaviour under constant and variable loading

The crack growth curves for both materials G10 and G50 are illustrated in Fig. 1 for all investigated $R$-ratios. In Fig. 1a the crack growth curves are only given for lower and middle crack growth rates, whereas Fig. 1b compares the complete crack growth curve of G10 and G50 for $R=0.3$. The fracture mechanical properties for both materials at various stress ratios are given in Table 2. Fatigue crack growth under constant amplitude loading can be described well by the NASGRO equation, as seen in Fig. 1b. This equation is an extended Paris equation, which describes all three ranges of the crack growth curve in dependency of the stress ratio. For further information it is referred to [3, 4]. The results in Table 2 and Fig. 1 show that fatigue crack growth depends on the graphite size. With increasing spherical graphite size, higher threshold values $\Delta K_{th}$ (see Table 2) and higher critical cyclic stress intensity factors $\Delta K_{fc}$ are obtained (see Fig. 1). Examples for the extensive analysis of the fatigue crack growth under variable amplitude loading to investigate load history effects on nodular cast iron are given in Fig. 2. For G10 the influence of a 1.5-fold single tensile overload is presented in Fig. 2a. No crack growth retardation occurs. The crack growth rate shortly increased up to about 1E-03 mm/cycle and then returned to the previous crack growth rate level. As a result of one tensile overload the crack required about 440 cycles to level off to its previous crack growth rate. Fig. 2b shows the influences of block loading (low-high-low sequence) with two different block loading ratios $R_{block}=1.25$ and 1.50 on G10, whereby higher block loading ratios lead to higher crack growth rates. The transition from a low to a high sequence shortly induces higher crack growth.
acceleration before the crack growth rates settle down. The transition from high to low does not yield retardation effects.

Table 2: Results of the fatigue crack growth behaviour under constant amplitude loading

| Material | R-ratio | $\Delta K_{th}$ [MPam$^{1/2}$] | m     | C     |
|----------|---------|---------------------------------|-------|-------|
| G10      | 0.1     | 10.1                            | 6.0   | 5.1E-12|
|          | 0.3     | 8.1                             | 5.0   | 1.5E-10|
|          | 0.5     | 5.1                             | 5.0   | 2.8E-10|
| G50      | 0.1     | 10.2                            | 6.1   | 3.3E-12|
|          | 0.3     | 8.5                             | 5.0   | 2.0E-10|
|          | 0.5     | 5.5                             | 4.6   | 3.1E-10|

Fig. 1: Influence of stress ratio a) and graphite spherical size b) on fatigue crack growth

Fig. 2: Influence of a single tensile overload a) and block loading b) on fatigue crack propagation of G10

Scanning electron microscopy was applied to investigate the damage behaviour during crack propagation in nodular cast iron under variable amplitude loading. It could be shown that overloads lead to debonding the nodular graphite from the ferritic matrix and also micro crack initiation was observed on the specimen surfaces in a region forms ahead of the crack tip. This damage behaviour can lead to crack growth acceleration [4].
3.2. Numerical simulation of load history effects with an extended Strip Yield Model (SYM)

In order to be able to simulate the acceleration effects occurring during fatigue crack growth of nodular cast iron an extended strip yield model (SYM), based on the work of Newman [5] and Wang [6], was developed. The basic equations of the strip yield model arise from a modified Dugdale model, where the crack is fictitiously extended by the length of the plastic zone. Within the plastic zone there are elastic ideal-plastic bar elements of length $L_i$, which are separated by crack advance and which further carry the residual plastic deformation on the crack surfaces. The extension of the strip yield model regarding the acceleration effects is realised by an additional boundary condition for the plastic deformation $L_i^*$ of the bar elements within the plastic zone. If a critical value $L_i^*$ is reached, the corresponding element is separated at once and the crack advances.

$$L_i \geq L_i^* : \quad \sigma_i > 0 \Rightarrow \sigma_i = 0, \quad \sigma_i < 0 \Rightarrow \sigma_i = 0$$  \hspace{1cm} (3)

The crack growth rate is calculated by the NASGRO equation, using parameters identified for EN-GJS-400-18LT by Hübner et al. [3]. Accelerated crack growth in nodular cast iron after single overloads can be described with the extended strip yield model, see Fig. 3. In order to identify the microstructure dependent parameter $L_i^*$ for crack growth acceleration the evaluation of systematic experiments with single overloads is currently under progress.

Fig. 3: Comparison of crack length $a$ and crack growth rate $da/dN$ versus cycle plot under constant amplitude loading (CA) and one integrated overload (OL-general SYM, OL*-extended SYM)

4. Conclusions

Within the scope of this work, systematic investigations of constant and variable amplitude loading were carried out by experiments as well as numerical studies in order to characterize the fatigue crack growth behaviour of nodular cast iron. The fatigue crack growth behaviour depends on the graphite size. Increasing graphite size leads to higher thresholds values $\Delta K_{th}$ and higher critical cyclic stress intensity factors $\Delta K_{fc}$. The experimental investigations under variable amplitude loading always show acceleration effects in fatigue crack growth and no retardation effects have been obtained. The presented numerical simulations show that accelerated crack growth after a single tensile overload can be described with the extended strip yield model.

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