NUMERICAL INVESTIGATION OF LOW CYCLE FATIGUE MECHANISM IN NODULAR CAST IRON


M. Lukhi*, M. Kuna¹, G. Hütter¹

The failure mechanism in ductile cast iron under static loading is nucleation, growth, and coalescence of voids. It is known from the literature that elastic-plastic porous materials under strain controlled cyclic loading show an increase of void volume fraction called void ratchetting effect. From this observation, we suggest that void ratchetting is the relevant mechanism for low cycle fatigue in nodular cast iron as well. The low cycle fatigue process in the microstructure of ductile cast iron has been simulated cycle by cycle using unit cell models. The strain-life approach for fatigue is followed in this work. The matrix material behavior is modeled as an elastic-plastic one. From the simulations, void ratchetting is identified as a potential mechanism of low cycle fatigue in nodular cast iron which finally leads to failure. The lifetime of different load ratio and different matrix material behavior is extracted from the simulations. The simulated strain-life curves are compared with experimental data from literature.

1. Introduction

Nodular cast iron (NCI) or ductile cast iron is an iron-carbon alloy. In NCI, the shape of graphite particles is nearly spherical that makes NCI's properties unique as compared to the other types of cast iron. NCI has mechanical properties like steels. However, in comparison to steels, NCI reduces manufacturing costs. For these reasons, NCI is widely used in transportation, nuclear and energy industries. A few examples of the application of NCI are gearboxes and crankshafts in automobile industry, wind turbine rotor hubs in energy industry and nuclear storage and transportation casks [1].

The properties of NCI are dependent on the material's microstructure, the form, size, and distribution of graphite particles and the defects present in the matrix due to the casting process. A ferritic matrix leads to ductile behavior of NCI, whereas a pearlitic matrix not only increases the strength but also brittleness. The combination of two phases shows the intermediate material behavior.

The material fatigue under cyclic loading is the relevant damage cause in most practical applications since most structural components are exposed to alternating service loads. Thus, a better understanding of fatigue failure is very important. Murakami [2] has mentioned previous studies related to the effect of shape and size of graphite nodules and microstructure on the fatigue strength of NCI. No information is mentioned regarding extremely low cycle fatigue in NCI.

To gain information about low cycle fatigue (LCF), experimental and computational approaches can be used. With significant advancements in the computational power, the simulation approach becomes more popular and efficient to understand the interaction between microstructure and material behavior [1].

As NCI is mostly used in high cycle fatigue (HCF) applications, there is scarcity of literature reporting on extremely low cycle fatigue (ELCF) of NCI. Komotori et. al [3] have experimentally observed void growth and coalescence in the ferritic NCI material. The schematic diagram of this process is shown in Figure 1. In another article, Komotori et al. [4] have mentioned that the fracture mode is depended on the applied strain amplitude. The fracture mode can be surface mode or internal mode. Although, this

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behavior is observed for ferritic-pearlitic steel, it is supposed to be equally applicable to nodular cast iron also. Mottitschka et al. [5] conducted LCF experiments on ferritic cast iron GJS 400 using round tensile bars at load ratio $R_e = -1$. The SEM picture of the fracture surface is shown in Figure 2. It is clearly visible that fatigue starts at graphite particles in the interior of the cross section. The ligaments between the particles experience severe plastic deformations with dimple structure.

Figure 1 Void coalescence in NCI under cyclic loading (schematic after [3])

Figure 2 Fracture surface in GJS 400 after LCF (private communication from T. Mottitschka)

Numerically, Gilles et al. [6] have first time observed void ratchetting under cyclic loading in ductile materials. In their study, they have created a cylindrical unit cell and carried out finite element calcula-
tions under cyclic loading at constant triaxiality. The results of these simulations show an initial spherical void experiencing deformation that leads to increasing of the mean void volume fraction after every cycle which is defined as void ratchetting. The void ratchetting due to hardening and residual stresses after each loading cycle was observed by Leblond [7] as well. Devaux et al. [8] have studied void growth in ductile metals due to applied cyclic loading. They have investigated void ratchetting effect in a material having isotropic hardening behavior. Ristinmaa [9] has also studied void growth under cyclic loading and compared these results with Gurson model results. Cell model simulations of voids under cyclic loading in NCI were conducted by Rabold and Kuna [10]. They studied the effect of hardening on the void growth rate. In this study, the void ratchetting due to plastic deformation could be observed as well. However, only few loading cycles were simulated. Steglich et al. [11] have investigated the cyclic response of metals incorporating damage with the help of cell models. They confirmed the void ratchetting behavior. The effect of cyclic loading on an elastic-plastic porous material was investigated by the Mbiakop et al. [12]. When a unit cell is subjected to cyclic deformations, change of the void shape and size are observed. Lacroix et al. [13] have studied the void growth in porous materials subjected to cyclic loading using an improved Leblond-Perrin-Devaux (LPD) model. Recently, Nielsen et al. [14] have performed a numerical study which includes void coalescence under combined tension and large amplitude cyclic shear loading. When the material is subjected to intense cyclic shear loading, voids are flattened. Thereafter flattened voids experience rotation and elongation. Now, neighboring voids interact with each other and void coalescence happens. When void coalescence happens, the material loses its load carrying capacity.

The conclusion from the literature review is, elastic – plastic porous materials show void ratchetting under cyclic loading condition. The question arising from these observations is, whether this void ratchetting might be the relevant mechanism of LCF of NCI. Void ratchetting leads to cyclic necking and ultimately void coalescence which are major arguments justifying it as basic mechanism for low cycle fatigue in NCI. This is underlying idea and working hypothesis of the present study. However, this has not been proved by numerical simulations before. In contrast to previously mentioned studies, in the present study cell model simulations are carried out until final failure of the cell model instead of few cycles only.

In the present work, an axisymmetric cell model is used for modeling of the mechanisms of LCF in nodular cast iron. In chapter 2, brief information about NCI is mentioned, the numerical approach is explained in chapter 3. The strain-life curves obtained from the simulations are presented in chapter 4. A comparison with experimental data from literature and the possible influence of parameters are also discussed. A summary and outlook of the present work are given in chapter 5.

2. Nodular cast iron

Micrograph of NCI is shown in Figure 3. In the micrograph, black spots are the graphite nodules surrounded by grains of the 100% ferritic ductile matrix.

![Figure 3 Micrograph of nodular cast iron](image-url)
From the close inspection of the micrograph, it can be said that the particles are not perfect spheres or circles in 2D. To account for this information, it is necessary to model the graphite particle with a shape other than a sphere. The roundness of the graphite particle is commonly described by the shape factor

$$S = \frac{4\pi A}{U^2}. \quad (1)$$

Therein, $A$ is the area of particle and $U$ is the circumference of a particle in the micrograph. If the shape factor is equal to 1, then the particle is a perfect sphere and 0 means it is a plane flake. Now, it is important to quantify the lower limit of shape factor as a quality feature for nodular cast iron. Brocks et al. [16] have considered two different types of nodular cast iron material having shape factors $S = 0.85$ and $S = 0.70$. Imasogie et al. [17] have mentioned that minimum roundness (aspect ratio) of the graphite particle is 65% to be called nodular particle. The aspect ratio is defined as the ratio of the semi-minor axis to the semi-major axis of a graphite particle.

Shirani et al. [18] have summarized the type of cast iron according to the shape of graphite particle and aspect ratio. This summary is shown in Figure 4. In the standard ISO 945-1 [19] different forms of the cast iron are classified according to the graphite particles shape. For nodular and spheroidal cast iron, form V and VI are considered according to ISO-945.

3. Methodology

A unit cell model is widely used for microstructural material modeling. The microstructure of NCI can be idealized by the regular arrangements of graphite nodules in the ductile matrix. For the modeling of NCI microstructure, the regular arrangement of the hexagonal prism cylinder with graphite particle at body center position is a common assumption. This is shown in Figure 5.
The hexagonal structure can be approximated as a cylinder which is a suitable assumption [10], [16]. There is a weak interface between the graphite nodules and ductile matrix [20]. Due to this, there is decohesion of the graphite nodules and ductile matrix. Considering easy decohesion of graphite nodule and ductile matrix, the graphite nodule is modeled either as a void or as a rigid particle in the cell model. Taking advantage of the rotational symmetry, the cell model is discretized by axisymmetric finite elements of linear shape functions (CAX4 from the finite-element program Abaqus library). The NCI model at a different length scales can be seen in Figure 5. The initial void volume fractions (v vf) of cell model with ellipsoidal particle are defined in Eq. (2) [16].

\[ f_0 = \frac{2a_0^2 b_0}{3R_0^2 L_0} \] (2)

Therein, \( a_0 \) is semi-major axis and \( b_0 \) is semi-minor axis of the graphite particle. \( R_0 \) and \( L_0 \) are dimensions of the unit cell which are shown in Figure 5. If \( a_0 = b_0 \) then, the unit cell is with the spherical graphite particle. The considered volume fractions of the graphite particle are 8.86% and 11%. From the volume fraction of voids, the size of the void in the cell model is determined using Eq. (2). Apart from the axisymmetric conditions, additional kinematic boundary conditions are applied. The right and top surfaces are constrained to remain plane. Both surfaces can move in a normal direction and remain straight throughout the analysis. The right surface is free of loading. The cyclic deformation is imposed by homogenous displacements \( u \) of the top plane. Two different load ratios (displacement ratio) \( R_\varepsilon = \frac{u_{\min}}{u_{\max}} \) for cyclic displacements are assumed (\( R_\varepsilon = -1 \) and \( R_\varepsilon = 0 \)). The resulting engineering strain amplitude is given by Eq. (3).

\[ \Delta \varepsilon = \frac{u_{\max} - u_{\min}}{L_0} = \frac{\Delta u}{L_0} \] (3)

The macroscopic strains and stresses of the cell model can be calculated using the following equations [10].

\[ E_Z = \ln \frac{L}{L_0}; \quad E_R = \ln \frac{R}{R_0}; \quad E_V = E_Z + 2E_R \] (4)

\[ \Sigma_Z = \frac{F_Z}{\pi R_0^2}; \quad \Sigma_R = \frac{F_R}{2\pi R_0 L_0} = 0; \quad T = \frac{\Sigma_Z^2 + 2\Sigma_R}{\Sigma_{eq}} = \frac{1}{3} \] (5)
Where, \( E_L \) is longitudinal, \( E_R \) is radial and \( E_V \) is volumetric logarithmic strains. \( \Sigma_L \) and \( \Sigma_R \) are macroscopic stresses in longitudinal and radial direction and \( \Sigma_{eq} \) is the equivalent von Mises stress.

The macroscopic stresses are the result of the applied boundary conditions and the cyclic deformations. They are measured as an average reaction forces on the top and the right planes. For uniaxial loading, the stress triaxiality \( T \) defined in Eq. (5) has the value \( T = 0.33 \) due to vanishing radial macroscopic stresses. A large displacement analysis has been carried out in the commercial FEM code Abaqus/Standard.

The ferritic matrix can be represented as an elastic – plastic material. The considered material behavior is elastic – plastic one. The constitutive material model for the ferritic matrix is based on the J2 flow theory of plasticity. The considered hardening types are isotropic hardening and isotropic/non-linear kinematic combined hardening.

4. Simulation results and Discussion

4.1 Isotropic hardening

The isotropic hardening is defined by the rate-independent power law of Eq. (6). The isotropic hardening has been implemented using user subroutine UHARD in Abaqus.

\[
\frac{\sigma_y}{\sigma_0} = \left( \frac{\sigma_y}{\sigma_0} + \frac{E \varepsilon^{pl}}{\sigma_0} \right)^n
\]  

(6)

Here, \( \sigma_y \) is yield stress, \( \sigma_0 \) is initial yield stress and \( n \) is hardening exponent.

The material parameters have been taken from Rabold et al. [10]. The material parameters are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (E)</td>
<td>210000 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio (( \nu ))</td>
<td>0.3</td>
</tr>
<tr>
<td>Hardening exponent (( n ))</td>
<td>0, 0.05, 0.1, 0.2</td>
</tr>
<tr>
<td>Initial yield stress (( \sigma_0 ))</td>
<td>230 MPa</td>
</tr>
</tbody>
</table>

Firstly, graphite is modeled as a spherical void. The model has been simulated cycle by cycle as per the above-mentioned material parameters and boundary conditions. The load ratio of applied cyclic deformation is \( R_L = -1 \). The macroscopic stress vs cycles response of the model is shown in Figure 6(a). The applied strain amplitude for this curve is \( \Delta \varepsilon = 5\% \) and hardening exponent \( n=0.2 \). All the points in the diagram represent the maximum values of the macroscopic stress during the cycle, i.e. at points of reversal.

In Figure 6(a), the curve starts with zero stress at the beginning of the simulation. As the simulation progresses, the macroscopic stress increases due to isotropic hardening of the matrix. The macroscopic stress reaches a peak level. After the peak point, the macroscopic stress starts decreasing. The overall behavior of the curve can be described as initial cyclic hardening followed by geometric softening behavior. The plastic strain accumulation with each cycle leads to an increase in the overall volumetric strain \( E_V \) of the unit cell which is attributed to void growth, since the plastic matrix is incompressible. This void ratcheting is shown in Figure 6(b). The initial perfect spherical void is now distorted. The void ratchetting leads to a cyclic necking of the cross-section of the unit cell. This leads to initiation of cyclic softening. When this plastic strain accumulation reaches a critical limit, there is a drop in the macroscopic stress response. After the peak point, geometric softening begins, which is defined as the failure point of the unit cell. This point is marked as point “C” in Figure 6. As mentioned in the introduction, the cyclic necking is associated with coalescence of voids and it leads to the formation of the macroscopic crack. In a real material with many graphite particles, the softening would lead to localization of the deformation and complete failure within the next few cycles. The point C can be treated as a
transition to the cyclic void coalescence. That is why this point is defined as the failure point in this study. In the experiments, degradation of macroscopic stress or stiffness of 1% or 2% is considered as a criterion of fracture initiation.

![Figure 6](image1)

**Figure 6** (a) Macroscopic stress vs cycles; (b) Volumetric strain vs cycles

![Figure 7](image2)

**Figure 7** Void ratchetting due to plastic strain accumulation

The void distortion process is shown in Figure 7. Figure 7(A) shows perfect spherical void at the beginning of the simulation. Figure 7(B) shows the distorted void and Figure 7(C) represents the void shape at the model failure. Interesting is the concentration of accumulated plastic strain at the deformed void, see Figure 7 (C). The maximum local equivalent plastic strain $\varepsilon_{\text{max}}^{pl}$ is plotted in Figure 8 vs number of cycles for different
strain amplitudes. The x-axis scale is logarithmic and y-axis scale is linear. The failure points for different strain amplitudes are marked with crosses in Figure 8. For lower strain amplitudes $\Delta \varepsilon$, the maximum accumulated plastic strain $\bar{\varepsilon}^{pl}_{\text{max}}$ reaches higher values. This tendency is in contradiction to classical fatigue laws like Coffin – Manson, which would predict failure at equal values of $\bar{\varepsilon}^{pl}_{\text{max}}$. It is again an indication that another mechanism, namely void ratchetting is responsible for failure of NCI under cyclic loading at large strain amplitudes $\Delta \varepsilon$. In case of small strain amplitudes, the formation of fatigue cracks in the matrix becomes more likely, however.

The effect of different hardening exponents $n$ on the macroscopic stress response has been studied using the simulations. The compiled results are shown in Figure 9. The hardening exponent $n=0$ represents the elastic – ideal plastic material behavior. As expected the macroscopic stress increases with the increase in hardening exponent. The full line shows strain amplitude $\Delta \varepsilon = 2\%$ and the dotted line shows strain amplitude $\Delta \varepsilon = 1\%$. The macroscopic stress also increases with the increase in applied strain amplitude.

Figure 8 The maximum local equivalent plastic strain $\bar{\varepsilon}^{pl}_{\text{max}}$ evolution with number of cycles
Different strain amplitudes $\Delta \varepsilon$ have been imposed on the cell model. The obtained cycles to failure $N_f$ are extracted from the simulation results. This data is plotted on logarithmic scale for the different hardening exponents $n$ in Figure 10. The strain-life curve is approaching monotonic failure on the left-handed side of the diagram. When the applied strain amplitude is very high, the cell model fails immediately. It is evident from Figure 10 that the number of cycles to failure is decreasing with the increase in hardening exponent. With increase in hardening exponent $n$, the slope of strain-life curve is decreasing.

Furthermore, Figure 10 shows corresponding experimental data from literature [3], [21]–[27] for ferritic NCI GJS-400. All the experimental data lie within a narrow band. The metallographic characteristics of NCI are mentioned in Appendix A. From the comparison of the experimental and simulation strain-life curves, it can be concluded that the simulation results are in qualitative agreement with the experimental results but there is a quantitative mismatch between them. The simulations overestimate the lifetime by an order of magnitude. The potential reasons of overestimation will be discussed below. The effect of load ratio $R_\varepsilon$ on the strain-life diagram is shown in Figure 11. It can be observed that an increase in the load ratio increases the number of cycles to failure. In the low strain amplitudes region, the predicted influence of load ratio $R_\varepsilon$ is negligible.

![Figure 9 Macroscopic stress vs cycles for different hardening exponents](image)
**Figure 10** The strain-life plot from the simulation results contrasted with experimental data.

**Figure 11** Effect of Load ratio $R_e$ on strain-life diagram.
This simple model uses just four material parameters to predict the above-mentioned results. The quantitative mismatch between the simulation and experimental results provided additional motivation to carry on this study to find out the potential reasons that might be responsible for the mismatch:

1. Type of hardening
2. The interaction between graphite particle and ferritic matrix
3. Non-spherical shape of graphite particle
4. Damage inside the matrix due to the presence of defects

These potential reasons are explained in detail and their influence on the strain-life behavior is investigated.

4.2 Combined hardening

The experiments indicate a Bauschinger effect in the hardening behavior of the ferritic matrix [10]. To accommodate the increase in yield stress due to the accumulated plastic strain and Bauschinger effect, the combined hardening has been employed, based on the work of Lemaitre and Chaboche [10]. The yield function for the combined hardening is

\[ \phi = \frac{3}{2}(\sigma^{\text{dev}} - \alpha) : (\sigma^{\text{dev}} - \alpha) - \sigma_y. \]  

(7)

Therein, \( \sigma^{\text{dev}} \) is the deviatoric part of the stress tensor and \( \alpha \) denotes the back-stress tensor. The isotropic hardening is included in the evolution of the yield stress \( \sigma_y \) as

\[ \sigma_y = \sigma_0 + Q_\infty(1 - e^{-b\dot{\varepsilon}^\text{pl}}). \]  

(8)

Therein, \( Q_\infty \) is the maximum change allowed until yield stress reaches its saturation level. The parameter \( b \) defines the evolution rate of yield stress with plastic strain accumulation. For the kinematic hardening, the evolution of the back-stress tensor is defined as

\[ \dot{\alpha} = C \dot{\varepsilon}^\text{pl} \frac{1}{\sigma_y} \left( \sigma^{\text{dev}} - \alpha \right) - \gamma \alpha \dot{\varepsilon}^\text{pl}. \]  

(9)

Therein, \( C \) is the initial kinematic hardening modulus and \( \gamma \) represents the decrease in backstress with plastic strain accumulation (recall term).

The parameters required for the isotropic/nonlinear kinematic hardening can be obtained from the cyclic stress-strain curves. In the present study, the proven parameters \( \sigma_0 \), \( Q_\infty \), \( b \), \( C \) and \( \gamma \) are taken from Rabold et al. [10]. The material parameters were identified in Rabold et al. [10] from a special ferritic steel charge, which has similar composition and microstructure like matrix material of nodular cast iron GJS-400.

This combined hardening model is used in the axisymmetric cell model and simulations for the different strain amplitudes have been performed. The results of simulations are plotted in Figure 12. It shows that the type of hardening does not affect LCF lifetime. The cyclic ratchetting of voids under strain-controlled loading seems to be a rather kinematic mechanism. In this study, the strain controlled low cycle fatigue test has been performed. It is possible that due to strain-controlled loading, the kinematic hardening does not have any significant effect on the strain-life behavior. But, if the cell model is subjected to a cyclic stress-controlled loading, then an effect of combined hardening on the stress vs life curve is expected.
4.3 Interaction between matrix and graphite particle

For the micromechanical modeling of NCI, most of the investigators assumed graphite particle as a void [28], [29]. In contrast, Rabold et al. [10], Bonora et al. [30] and Collini et al. [31] have modeled graphite particle as a rigid particle.

In the previous sections, the graphite particle has been modeled as a void. Now, the graphite is modeled as a rigid particle as shown in Figure 13. The black arc represents the graphite particle which is modeled as a rigid line. The cell model with graphite particle is subjected to the cyclic loading of load ratio $R_e = -1$ and material property is elastic – plastic with isotropic hardening ($n = 0.2$). The deformation of the matrix can be seen in Figure 13. The interaction between the graphite particle and matrix is defined as a frictionless contact. The graphite particle is fixed at the lines of symmetry.

![Figure 12 The effect of combined hardening on strain-life curve](image)

![Figure 13 Graphite modeled as a rigid particle](image)
The strain-life curve resulting from the simulations is shown in Figure 14 in comparison to the previous results with graphite as a void and compared with experimental data. If the graphite particle is modeled as a rigid particle, then it requires a lower number of cycles to failure in comparison of graphite as a void. The reason for this behavior can be explained by the interaction of the matrix with the rigid particle. If the graphite particle is a rigid inclusion (in the cell model), then it favors void growth [10]. This faster void growth leads to fewer cycles to failure than the cell model without rigid graphite inclusion. The effect of modeling graphite as a rigid particle is encouraging but there is still a quantitative mismatch between the experimental and the simulation results.

4.4 Graphite particle shape
It can be observed from Figure 3 that not all the graphite particles in the matrix are perfectly spherical. To consider a graphite particle as nodular, classification by shape factor can be used as mentioned earlier. Here, the cell model with the non-spherical shape of the particle shall be used as shown in Figure 5. The orientations of semi-major and semi-minor axes are also given in Figure 5. The major axis of ellipsoidal void is normal to the direction of loading.
The unit cell model is simplified by assuming that all the particles are non-spherical in shape and have same orientations of major and minor axes. The results of strain-life studies are shown in Figure 15. It is evident that the cell model with ellipsoidal void predicts the strain-life behavior of NCI more accurately than the cell model with a spherical void. This approach is conservative for fatigue life prediction. Another observation from Figure 15 is that the shape of graphite has a high influence on the strain-life behavior.

If the non-spherical shaped graphite particles would be considered as rigid, then it may give even more realistic strain-life behavior. Considering $S=0.70$ and rigid graphite particles, an improved cell model is prepared. The results of this model are shown in Figure 16. It can be stated that the combination of non-spherical shape and rigid graphite gives the most realistic results in comparison with experimental data.

Canzar et al. [32] have shown that size, shape and distribution of the graphite nodules has no significant influence on cyclic hardening of the material but they play a great role in the fatigue crack initiation and propagation process. These experimental observations further support predictions done in the present numerical studies.
5. Conclusion

In this study, a micromechanical model was prepared for the understanding of low cycle fatigue mechanism in nodular cast iron. This cell model was subjected to cyclic deformations and cycle by cycle simulations have been carried out in Abaqus. Different material behaviors such as elastic - ideal plastic, elastic - isotropic hardening with a power law and elastic – isotropic/nonlinear kinematic hardening have been used for modeling of the matrix material. To predict low cycle fatigue failure, the suggested model and methodology rely only on material parameters defining hardening behavior of the matrix and geometrical quantities of the microstructure. There is no need to provide additional input parameters to specify the failure behavior.

The impact of different parameters affecting the predicted lifetime of low cycle fatigue failure is summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Impact</th>
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<tbody>
<tr>
<td>Hardening type</td>
<td>Low</td>
</tr>
<tr>
<td>Graphite as a rigid particle</td>
<td>Medium</td>
</tr>
<tr>
<td>Non-spherical shape of graphite particle</td>
<td>High</td>
</tr>
</tbody>
</table>

The type of hardening does hardly affect strain-life behavior under the strain (displacement) controlled loading. The rigid graphite particle in the cell model results in lower lifetime compared to model with the graphite as a void. The non-spherical shape of graphite particles gives more realistic simulation results for low cycle fatigue. The combination of rigid graphite and non-spherical shape of particle predict the best results. While studying the non-spherical shape of graphite particle, it is important to consider the orientation of the graphite particle. In the above-mentioned results with non-spherical shape, the weakest scenario is considered, which is believed to control the overall fatigue behavior. Hereby the major-axis of the ellipse is perpendicular to the direction of the applied external strain. The results extracted from the simulations are in good agreement with the experimental data from the literature with non-spherical graphite particles.
The unit cells subjected to $\Delta e < 1\%$ are run till 15000 cycles but there was no void ratchetting (no cyclic softening) observed. Surprisingly, the local accumulated strain at failure increases with lower strain amplitudes. Therefore, it is suggested that at lower strain amplitudes, the fatigue behavior of NCI is controlled by incipient crack formation in the matrix instead of void ratchetting. From the simulation results and discussions, it can be concluded that the low cycle fatigue failure can be explained by the unit cell method. This model is simple yet powerful to predict the strain-life behavior. The gradual increase of void volume due to plastic strain accumulation has been identified as a major mechanism of LCF in nodular cast iron. This so-called void ratchetting leads ultimately to internal cyclic necking and failure of the model under strain-controlled fatigue.

The direct effect of damage in the ferritic matrix is yet to be considered in the model but possibly damage of matrix is more relevant for high cycle fatigue.

6. Acknowledgment

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Appendix A. Metallographic characteristics of the nodular cast iron

Table 1 Metallographic characteristics of the nodular cast iron

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Ferritic ductile cast iron</td>
<td>Ferritic ductile cast iron (coarse grade)</td>
<td>Ferritic ductile cast iron (fine grade)</td>
<td>Ferritic ductile cast iron (cast block, Y-shaped)</td>
<td>Ferritic ductile cast iron (cast block, Y-shaped)</td>
<td>Ferritic ductile cast iron (cast block, Y-shaped)</td>
<td>Ferritic ductile cast iron (cast block, Y-shaped)</td>
<td>Ferritic ductile cast iron (cast block, Y-shaped)</td>
<td>Ferritic ductile cast iron (cast block, Y-shaped)</td>
</tr>
<tr>
<td>Nodule count (mm$^3$)</td>
<td>566</td>
<td>175</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>290</td>
</tr>
<tr>
<td>Shape factor</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Volume fraction of graphite (%)</td>
<td>9.53</td>
<td>11</td>
<td>12</td>
<td>11</td>
<td>11.9</td>
<td>12.9</td>
<td>12.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodule diameter (μm)</td>
<td>20.58</td>
<td>5-6</td>
<td>30</td>
<td>23</td>
<td>5-6</td>
<td>5-6</td>
<td>6-7</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Graphite form</td>
<td>VI</td>
<td></td>
<td></td>
<td>V (59.6 %), VI (30 %)</td>
<td>V (59.6 %), VI (38 %)</td>
<td>V (34.0 %), VI (65.3 %)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodularity (%)</td>
<td>92.5</td>
<td>76</td>
<td>78</td>
<td>73.4</td>
<td>75.4</td>
<td></td>
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</table>

The metallographic characteristic of the experimental data used for the reference have been mentioned in Table 1. The nodularity (ratio of number of nodular graphite particles to the number of graphite particles) of material varies between 73.4 % to 92.5 %. The graphite particles are in form V and VI. The volume fraction of graphite is between 10 % to 13 %. The graphite nodule diameter varies between 5 – 30 μm.
References


