Fatigue limit prediction of ferritic-pearlilite ductile cast iron considering stress ratio and notch size

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Abstract. The mechanical behavior of ductile cast iron is governed by graphite particles and casting defects in the microstructures, which can significantly decrease the fatigue strength. In our previous study, the fatigue limit of ferritic-pearlitic ductile cast iron specimens with small defects (\(\sqrt{\text{area}} = 80 \sim 1500 \mu m\)) could successfully be predicted based on the \(\sqrt{\text{area}}\) parameter model by using \(\sqrt{\text{area}}\) as a geometrical parameter of defect as well as the tensile strength as a material parameter. In addition, the fatigue limit for larger defects could be predicted based on the conventional fracture mechanics approach. In this study, rotating bending and tension-compression fatigue tests with ferritic-pearlitic ductile cast iron containing circumferential sharp notches as well as smooth specimens were performed to investigate quantitatively the effects of defect. The notch depths ranged 10 ~ 2500 \(\mu m\) and the notch root radii were 5 and 50 \(\mu m\). The stress ratios were \(R = -1\) and 0.1. The microscopic observation of crack propagation near fatigue limit revealed that the fatigue limit was determined by the threshold condition for propagation of a small crack emanating from graphite particles. The fatigue limit could be successfully predicted as a function of \(R\) using a method proposed in this study.

1. Introduction

Because of their low cost as well as excellent workability, ductile cast irons have been used for various machine parts and structural components such as crankshafts, railways and gas pipes. Ductile cast irons have good monotonic strength and high ductility compared to gray cast irons and malleable cast irons. However, the fatigue strength of ductile cast irons is relatively lower than those of the steels and alloys with the same level of monotonic strength because of their peculiar microstructure containing graphite particles and casting defects.

The fatigue strength of ductile cast iron was affected by the size and distribution of casting defects and graphite particles and by the phase distribution of matrix materials. Many researchers investigated the effect of casting defects on the fatigue strength and assessed the fatigue limit of ductile cast iron using matrix hardness such as Vickers hardness, \(HV\). Nodat et al. [1] and Shiota et al. [2] reported that fatigue strength was decreased with the increase of the size of graphite particles and casting defects. Further, the distribution of graphite particles and casting defects affected the fatigue strength of ductile...
cast iron [3-5]. Noguchi et al. [6] assessed the effects of defects in ductile cast iron based on the fracture mechanics and the nondestructive method. It was shown that the matrix hardness had a remarkable effect on the fatigue strength of ductile cast iron. Sofue [7] investigated the effect of matrix hardness on the fatigue strength of ductile cast iron with single-phase matrix. It was reported that the fatigue limit was increased with the increase of matrix hardness. Several researchers [3, 8-11] proposed the fatigue limit predictions using HV for ductile cast iron with single-phase matrix. The prediction using HV of the matrix showed a good agreement with the experimental data. Therefore, the fatigue limit prediction using HV of ductile cast iron with single-phase matrix is possible. However, when a ductile cast iron contains two-phase matrix, the measurement of HV of the matrix is impossible. This is because ferrite and pearlite phases are evenly distributed within the matrix structure, in addition to the influence of interference by graphite particles.

In our previous study [12, 13], we proposed a fatigue limit prediction for ferritic-pearlitic ductile cast iron based on the $\sqrt{\text{area}}$ parameter model by using the tensile strength, $\sigma_B$, as material parameter, instead of HV, for stress ratio $R = -1$. This was because, in the case of ductile cast iron with two-phase matrix, the measurement of correct value of HV was quite difficult, as mentioned above. Alternatively, the prediction using $\sigma_B$ as a material parameter shows a reasonably good agreement with the experimental data. However, ductile cast iron is frequently used under the condition where the mean stress is applied (i.e., $R \neq -1$). Accordingly, for safety designing of the products with ductile cast iron, it is necessary to understand the effect of stress ratio, $R$, on the fatigue limit.

In this study, we investigated the fatigue limit of a ductile cast iron with a two-phase matrix of almost evenly distributed ferrite and pearlite phases by using the specimens containing circumferential notches with a wide range of sizes at $R = 0.1$ in addition to $R = -1$. The purpose of this study is to present a simple yet useful method for prediction of the fatigue limit as a function of $R$.

2. Experimental procedures

The material investigated was an as-cast ductile cast iron. The chemical composition is listed in Table 1. The microstructure is shown in Figure 1. The area fractions in the microstructure were 10.5% for graphite, 45.3% for ferrite and 44.2% for pearlite, respectively. The ultimate tensile strength, $\sigma_B$, was 552 MPa. The shapes and dimensions of test specimens are shown in Figure 2(a) and 2(b). After lathe turning of specimen, the surface was finished with an emery paper up to #1000 and then by buffing with an alumina paste. Thereafter, a circumferential notch shown in Figure 2(c) was introduced into a specimen. Before the fatigue test, the surface layer of about 10 µm in thickness was removed from the specimens by electro-polishing.

The rotating bending fatigue tests were carried out using a machine of uniform moment type, and its capacity was 100 Nm and operating frequency was 50 - 67 Hz. The tension-compression fatigue tests

| Table 1. Chemical compositions (wt.%.). |
|----------------------------------------|
| C   | Si  | Mn  | P   | S   | Cu  | Mg  |
|-----|-----|-----|-----|-----|-----|-----|
| 3.84| 2.5 | 0.66| 0.017| 0.009| 0.21| 0.043|

Figure 1. Microstructure.
Carried out using a uniaxial hydraulic fatigue test machine at a frequency of 35 Hz. The stress ratios, $R$, were $-1$ and 0.1. Concerning the shallow-notched specimens ($t = 10, 100$ and $200 \mu m$), the nominal stress was calculated with the average diameter of specimen, $D$. On the other hand, concerning the deep-notched specimens ($t = 1000$ and $2500 \mu m$), the nominal stress was calculated with the minimum diameter of specimen, $D - 2t$. The fatigue limit was defined by the maximum stress amplitude, $\sigma_a$, for which a specimen endured $N = 10^7$ cycles without failure.

### Results and discussion

#### 3.1. Crack growth and non-propagation behavior

Figure 3 shows the $S$-$N$ diagram of smooth and notched specimens at the stress ratios of $R = -1$ and 0.1. The results for notched specimens for $t = 2500 \mu m$ at $R = -1$ and those for $t = 100 \mu m$ and $2500 \mu m$ at $R = 0.1$ were obtained by the tension-compression fatigue tests. The results of other specimens were
obtained by the rotating bending fatigue tests. The fatigue strength decreases significantly with an increase in notch size at $R = -1$ as well as 0.1. Especially, the fatigue strength of notched specimen with $t = 100 \mu m$ at $R = 0.1$ ($\sigma_w = 125$ MPa) decreased significantly compared to that of the identical specimen tested at $R = -1$ ($\sigma_w = 195$ MPa). On the other hand, the fatigue strength of notched specimens with $t = 2500 \mu m$ at $R = 0.1$ ($\sigma_w = 45$ MPa) was slightly lower than that of the identical specimen tested at $R = -1$ ($\sigma_w = 52.5$ MPa).

The non-propagation of cracks was observed at the root of shallow- and deep-notched specimens at fatigue limit, irrespective of notch sizes and stress ratios, as shown in Figures 4 and 5. In the case of notched specimens, a lot of fatigue cracks initiated from graphite particles at the notch root, and they stopped the propagation before $N = 10^7$ cycles. In the case of smooth specimens, several fatigue cracks emanated from different graphite particles at the specimen surface and they coalesced, but they ceased propagation before $N = 10^7$ cycles [13]. Consequently, all those cracks can be regarded as a non-propagating crack and it is concluded that the fatigue limit is determined by the threshold condition for crack propagation, regardless of notch sizes and stress ratios.

3.2. Prediction of fatigue limit of ductile cast iron

![Figure 4. Non-propagating cracks emanating from the notch at the fatigue limit for $R = -1$ [13].](image)

![Figure 5. Non-propagating cracks emanating from the notch at the fatigue limit for $R = 0.1$.](image)

![Figure 6. Influence of stress ratio on the fatigue limit (notch depth $t = 100 \mu m$).](image)
In our previous study [12, 13], a fatigue limit prediction for ferritic-pearlitic ductile cast iron based on the $\sqrt{\text{area}}$ parameter model by using ultimate tensile strength, $\sigma_b$, instead of the Vickers hardness, $HV$, was proposed. Let us recall that a predictive equation of fatigue limit for smooth specimens, $\sigma_{w0}$, was rendered as:

$$\sigma_{w0} = 0.25\sigma_b + 110 \quad (1)$$

where $\sigma_{w0}$ and $\sigma_b$ are in MPa. Further, the following form of a predictive equation for the fatigue limit in the presence of defect, $\sigma_w$, for ductile cast iron was proposed by taking advantage of the $\sqrt{\text{area}}$ parameter model:

$$\sigma_w = \frac{F_{\text{loc}}(0.34\sigma_b + 170)}{(\sqrt{\text{area}})^{1/6}} \quad (2)$$

where $F_{\text{loc}}$ is the correction coefficient for the location of small defect being 1.43 for surface defects, 1.56 for internal defects and 1.41 for defects just in contact with the surface [14]. Here, $\sigma_w$ is in MPa and $\sqrt{\text{area}}$ is in $\mu$m. Similarly, based on the $\sqrt{\text{area}}$ parameter model, it is expected that the effect of stress ratio, $R$, is estimated by using a term of $\{(1-R)/2\}^\alpha$ as follows:

$$\sigma_w = \frac{F_{\text{loc}}(0.34\sigma_b + 170)}{(\sqrt{\text{area}})^{1/6}} \left(\frac{1-R}{2}\right)^\alpha \quad (3)$$

where $\alpha$ is a correction coefficient that depends on the material. To determine the value of $\alpha$ in Eq. (3), the value of $\sigma_w(\sqrt{\text{area}})^{1/6}/\{F_{\text{loc}}(0.34\sigma_b + 170)\}$ is shown as a function of $(1-R)/2$ on a logarithmic graph in Figure 6. A value of $\alpha = 0.557$ was determined from the slope of the line. The present value of $\alpha = 0.557$ is significantly higher than the value of $\alpha = 0.402$ for ductile cast iron reported in the literature [15]. The reason of higher value of $\alpha$ is unclear at present, and it is necessary to conduct fatigue tests with other stress ratios.

Figure 7 shows a comparison of prediction by Eqs. (1) and (3) with the experimental results for smooth specimen as well as shallow-notched specimen. The prediction of fatigue limit is in reasonable

![Figure 7. Relationship between fatigue limit and $\sqrt{\text{area}}$.](image-url)
agreement with the experimental data. Irrespective of the stress ratio, there is a critical size of defect that has no effect on the fatigue strength of ferritic-pearlitic ductile cast iron. Defects with the \( \sqrt{\text{area}} \) smaller than about 80 \( \mu \text{m} \) (region I), designated herein as \( \sqrt{\text{area}_0} \), are not harmful to the fatigue limit. Prediction with Eq. (3) shows a good agreement with the experimental results for the artificial defects with \( 80 \mu \text{m} \leq \sqrt{\text{area}} \leq 1000 \mu \text{m} \) (region II).

In the case of deep-notched specimen with \( t = 1000 \mu \text{m} \) and 2500 \( \mu \text{m} \) (cf. Figure 2 (c)), the fatigue limit can no longer be predicted by Eq. (3). This is because the notch size is sufficiently large beyond the region II. In this circumstance, the threshold stress intensity factor (SIF) range, \( \Delta K_{\text{th}} \), become a material constant, which is \( \Delta K_{\text{th},lc} \). The relationship between the fatigue limit range, \( \Delta \sigma_w = 2\sigma_w \), and the threshold range, \( \Delta K_{\text{th}} \), can be derived by using the following equation based on the linear elastic fracture mechanics analysis [15, 16]:

\[
K_{\text{Imax}} = 0.65\sigma_0 \sqrt{\pi \text{area}}
\]  

where \( K_{\text{Imax}} \) is the maximum value of SIF along the front of a three-dimensional surface crack with the arbitrary shape existing in a semi-infinite body with a Poisson’s ratio of 0.3 under remote tensile stress \( \sigma_0 \). By setting \( K_{\text{Imax}} = \Delta K_{\text{th}}/2 \), \( \sigma_0 = \sigma_w \) and \( F_{\text{loc}} = 1.43 \), Eqs. (2) and (4) render the following equation:

\[
\Delta K_{\text{th}} = 3.3 \times 10^{-3} (0.34\sigma_w + 170)(\sqrt{\text{area}})^{1/3}
\]  

where \( \Delta K_{\text{th}} \) is in MPa \( \sqrt{\text{m}} \), \( \sigma_0 \) is in MPa and \( \sqrt{\text{area}} \) is in \( \mu \text{m} \). The effect of stress ratio can be estimated by using the term of \( \{(1-R)/2\}^\alpha \), thus Eq. (5) becomes:

\[
\Delta K_{\text{th}} = 3.3 \times 10^{-3} (0.34\sigma_w + 170)(\sqrt{\text{area}})^{1/3} \left( \frac{1-R}{2} \right)^\alpha
\]  

Figure 8 shows relationship between \( \Delta K_{\text{th}} \) and \( \sqrt{\text{area}} \) for \( R = -1 \) and 0.1. In the region II, the solid lines calculated by Eq. (6) shows the variations of \( \Delta K_{\text{th}} \) for small defect. Prediction line shows a reasonably good agreement with the experimental results for the small defects. In the region III, where \( \Delta K_{\text{th}} \) is constant, the fatigue limit can be estimated by the conventional fracture mechanics approach established for long cracks. The experiment result of the \( \Delta K_{\text{th},lc} \) with the large defects with \( t = 1000 \) and

![Figure 8. Relationship between \( \Delta K_{\text{th}} \) and \( \sqrt{\text{area}} \) for \( R = -1 \) and 0.1.](image-url)
2500 μm was 13.3 MPa $\sqrt{m}$ at $R = -1$ by using a formula [17]. The translation value of $\sqrt{\text{area}}$, termed as $\sqrt{\text{area}_{\text{min}}}$, represents the boundary between region II and III. By substituting $\Delta K_{th} = 13.3$ MPa $\sqrt{m}$, $\sigma_h = 552$ MPa and $R = -1$ into Eq. (6), $\sqrt{\text{area}_{\text{min}}} = 1500$ μm for $R = -1$ was obtained. Similarly, by substituting $\Delta K_{th} = 11.6$ MPa $\sqrt{m}$, $\sigma_h = 552$ MPa and $R = 0.1$ into Eq. (6), $\sqrt{\text{area}_{\text{min}}} = 3600$ μm for $R = 0.1$ was obtained.

For the region III, we express the relationship between $\Delta K_{th,lc}$ and $\Delta K_{th,lc | R = 1}$ by using the term of $(1-R)^{2}$ as follows:

$$\Delta K_{th,lc} = \Delta K_{th,lc | R = 1} \left( \frac{1-R}{2} \right)^{\alpha^*}$$

where $\Delta K_{th,lc}$ and $\Delta K_{th,lc | R = 1}$ are in MPa $\sqrt{m}$. By substituting $\Delta K_{th} = 11.6$ MPa $\sqrt{m}$, $\Delta K_{th,lc | R = 1} = 13.3$ MPa $\sqrt{m}$ and $R = 0.1$ into Eq. (7), $\alpha^* = 0.171$ was obtained. Accordingly, the different mean stress effect is expected for the region II ($\alpha = 0.557$) and the region III ($\alpha^* = 0.171$).

4. Conclusions

The effects of notch size and stress ratio on the fatigue limit of ferrite-pearlite ductile cast iron were investigated. The principal results and conclusions are obtained as follows:

1. From the microscopic observation of crack growth, it is revealed that the fatigue limit is determined by the threshold condition for propagation of a crack emanating from graphite particles, regardless of notch size and stress ratio.

2. The effect of defects on the fatigue limit can be classified into three regions depending on the defect size. In the region I where $\sqrt{\text{area}}$ of defect is smaller than 80 μm, the defect can be regarded as a non-damaging defect and the fatigue limit is the same as that of smooth specimen.

3. In the region II, the fatigue limit can be quantitatively predicted based on the $\sqrt{\text{area}}$ parameter model in terms of a geometrical parameter of defects, $\sqrt{\text{area}}$, and a material parameter, $\sigma_h$. Furthermore, the fatigue limit that depends on the effect of stress ratio can be described by the term of $(1-R)/2^\alpha$. The value of $\alpha = 0.557$ was obtained for the investigated ferritic-pearlitic ductile cast iron.

4. In the region III in which $\sqrt{\text{area}} > 1500$ μm for $R = -1$ and $\sqrt{\text{area}} > 3600$ μm for $R = 0.1$, the threshold SIF range, $\Delta K_{th}$, becomes a material constant ($\Delta K_{th,lc} = 13.3$ MPa $\sqrt{m}$ for $R = -1$ and $\Delta K_{th,lc} = 11.6$ MPa $\sqrt{m}$ for $R = 0.1$) and the fatigue limit can be estimated by the conventional fracture mechanics approach.

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