Influence of mean stress on fatigue strength of ferritic-pearlite ductile cast iron with small defects

T Deguchi[1], H J Kim[2,3], T Ikeda[4] and K Yanase[2,3]

[1] Graduate School of Engineering, Fukuoka University, 8-19-1, Nanakuma, Jonan-ku, 814-0180, Japan
[2] Department of Mechanical Engineering, Fukuoka University, 8-19-1, Nanakuma, Jonan-ku, 814-0180, Japan
[3] Institute of Materials Science and Technology, Fukuoka University, 8-19-1, Nanakuma, Jonan-ku, 814-0180, Japan
[4] R&D Center HINODE, Ltd., Iwasaki, Harakoga, Miyaki-cho, Miyaki-gun, Saga, 849-0101, Japan

E-mail: td160004@cis.fukuoka-u.ac.jp

Abstract. Because of their excellent mechanical properties, low cost and good workability, the application of ductile cast iron has been increased in various industries such as the automotive, construction and rail industries. For safety designing of the ductile cast iron component, it is necessary to understand the effect of stress ratio, *R*, on fatigue limit of ductile cast iron in the presence of small defects.
Correspondingly in this study, rotating bending fatigue tests at R = –1 and tension-compression fatigue tests at R = –1 and 0.1 were performed by using a ferritic-pearlitic ductile cast iron. To study the effects of small defects, we introduced a small drilled hole at surface of a specimen. The diameter and depth of a drilled hole were 50, 200 and 500 μm, respectively.
The non-propagating cracks emanating from graphite particles and holes edge were observed at fatigue limit, irrespective of the value of stress ratio. From the microscopic observation of crack propagation behavior, it can be concluded that the fatigue limit is determined by the threshold condition for propagation of a small crack. It was found that the effect of stress ratio on the fatigue limit of ductile cast iron with small defects can be successfully predicted based on $\sqrt{area}$ parameter model. Furthermore, a use of the tensile strength, σ_B, instead of the Vickers hardness, *HV*, is effective for fatigue limit prediction.

1. Introduction

Because of their excellent workability, low cost as well as good mechanical properties, ductile cast irons are widely used for industrial application such as crankshafts, railways and gas pipes. Correspondingly, a number of researches have been conducted on the fatigue limit prediction to employ the ductile cast irons in the structural components. However, in essence, the fatigue limit prediction for ductile cast irons is difficult because it has intrinsic defects such as graphite and casting defects in the structure.

The fatigue strength of ductile cast iron is affected by the size and distribution of casting defects and graphite particles and by the phase distribution of matrix materials. It is known that the fatigue limit of many metallic materials with small defects can successfully be predicted with the $\sqrt{area}$ parameter model by using $\sqrt{area}$ as a geometrical parameter of defect and the Vickers hardness, *HV*, as a material parameter [1]. Several researchers [2-6] 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. However, ductile cast irons have a vast number of graphite particles in the complex matrix structure. The measurement of *HV* of ductile cast iron is affected by soft graphite particles. Furthermore, when a ductile cast iron contains two-phase matrix, the measurement of *HV* of the matrix is rather 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 [7-9], we proposed a fatigue limit prediction for ferritic-pearlitic ductile cast iron with small and large defects based on the $\sqrt{area}$ parameter model by using the tensile strength, σ_B, as material parameter, instead of *HV*, for stress ratio $R = -1$ [7, 8]. The fatigue limit of ferritic-pearlitic ductile cast iron specimens with small defects could successfully be predicted by using σ_B. In addition, the fatigue limit for larger defects could be predicted based on the conventional fracture mechanics approach. 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 effects of small defects and 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 small defects 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 procedure

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. The ultimate tensile strength, σ_B, and 0.2% yield strength, σ_Y, were 552 and 335 MPa, respectively. The shapes and dimensions of test specimens are shown in Figure 2(a) and 2(b). After lathe turning of specimens, the surface was finished with an emery paper up to #1000 and then by buffing with an alumina paste. Thereafter, a small hole was introduced at the specimen surface, as shown in Figure 2(c). Before fatigue test, the surface layer of about 10 μm in thickness was removed from the specimens by electro-polishing.

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

The rotating bending fatigue tests were carried out at $R = -1$ using a machine of uniform moment type, and its capacity was 100 Nm and the operating frequency was 50-67 Hz. The tension-compression

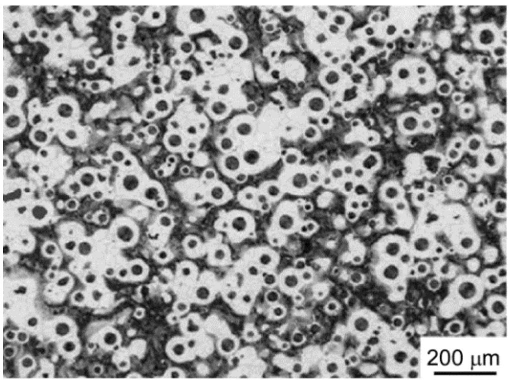
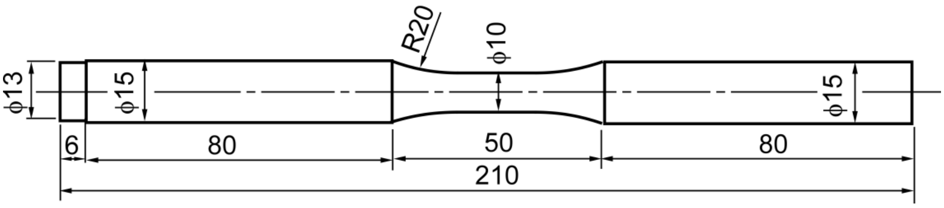
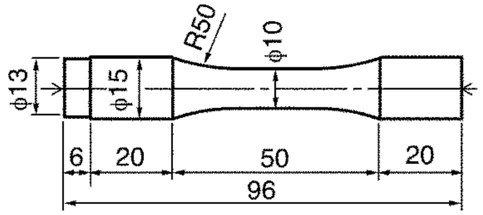


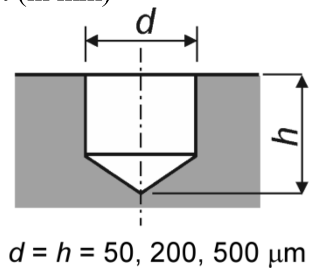
Figure 1. Microstructure.

IOP Conf. Series: Journal of Physics: Conf. Series **843** (2017) 012049 doi:10.1088/1742-6596/843/1/012049



(a) Specimen for rotating bending fatigue test (in mm)





(b) Specimen for tension-compression fatigue test (in mm) (c) Drilled holes

Figure 2. Shapes and dimensions of test specimens and artificial defects.

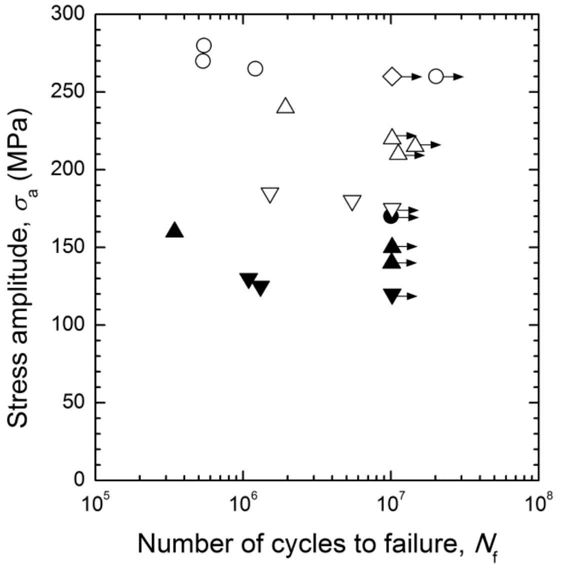
fatigue tests were carried out at $R = 0.1$ using a uniaxial hydraulic fatigue test machine and the operating frequency was 35 Hz. The fatigue limit was defined by the maximum stress amplitude, σ_a, for which a specimen endured $N = 10^7$ cycles without failure.

3. Results and discussion

3.1. S-N diagram and non-propagation behavior

The *S-N* diagram of smooth and holed specimens at the stress ratios of $R = -1$ and 0.1 are shown in Figure 3. The fatigue strength decreases with increase in the defect size at $R = -1$ as well as at $R = 0.1$. However, the fatigue strength of the holed specimen with $d = h = 50$ μm was not decreased. It means that the critical size of defect that does not affect the fatigue strength of ferritic-pearlitic ductile cast iron exists.

Figures 4 and 5 show the non-propagating cracks observed at the hole edge of holed specimens at fatigue limit. Figures 4(c) and 5(c) show the non-propagating crack observed at $N = 10^7$ cycles. In the



Specimen		Fatigue limit (MPa)		Loading Type	Symbol
Smooth	R = -1	-	260	RB	○
	R = 0.1	-	170	TC	●
Notched	R = -1	d = h (μm)			
		50	260	RB	◇
		200	220	RB	△
		500	175	RB	▽
	R = 0.1	200	150	TC	▲
		500	120	TC	▼

RB : Rotating bending, TC : Tension-compression

Figure 3. *S-N* curve.

case of holed specimens, the fatigue cracks emanated from the hole edge, 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 [8]. Consequently, all those cracks can be regarded as non-propagating crack and it is concluded that the fatigue limit of ferritic-pearlitic ductile cast iron is determined by the threshold condition for crack propagation, regardless of hole sizes and stress ratios.

3.2. Fatigue limit prediction for ductile cast iron

In our previous study [7-9], the fatigue limit prediction for ferritic-pearlitic ductile cast iron based on the $\sqrt{area}$ parameter model by using ultimate tensile strength, σ_B, instead of the Vickers hardness, *HV*, was proposed. The relationship between the fatigue limit of smooth specimen, σ_{w0}, and σ_B was obtained by linear regression [7]. A predictive equation of fatigue limit for smooth specimens, σ_{w0}, was rendered as:

$$\sigma_{w0} = 0.25\sigma_B + 110 \tag{1}$$

where σ_{w0} and σ_B are in MPa. Further, the following form of a predictive equation for the fatigue limit in the presence of small defect, σ_w, for ductile cast irons was proposed by taking advantage of the $\sqrt{area}$ parameter model:

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

where F_{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 [1]. Here, σ_w is in MPa and $\sqrt{area}$ is in μm. Further, based on the $\sqrt{area}$ parameter model, it is expected that the effect of stress ratio,

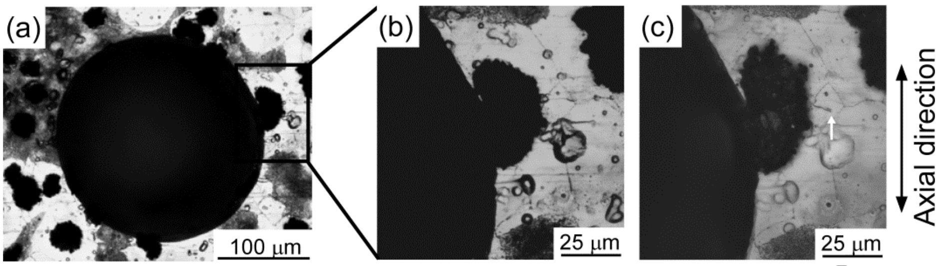


Figure 4. Non-propagation cracks emanating from the hole at the fatigue limit (σ_a = 150 MPa) at R = 0.1

R, can be accounted for by using a term of $\{(1-R)/2\}^{\alpha}$ as follows:

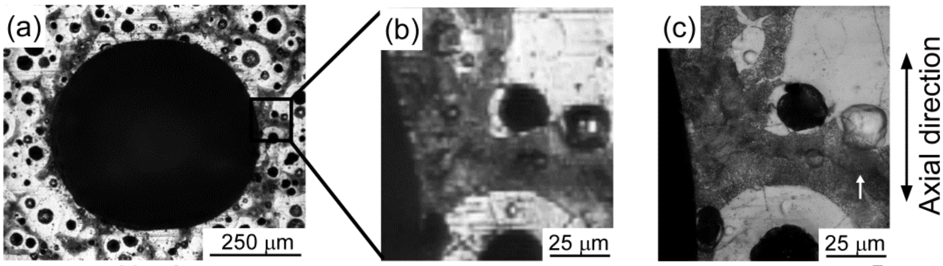


Figure 5. Non-propagation cracks emanating from the hole at the fatigue limit (σ_a = 120 MPa) at R = 0.1

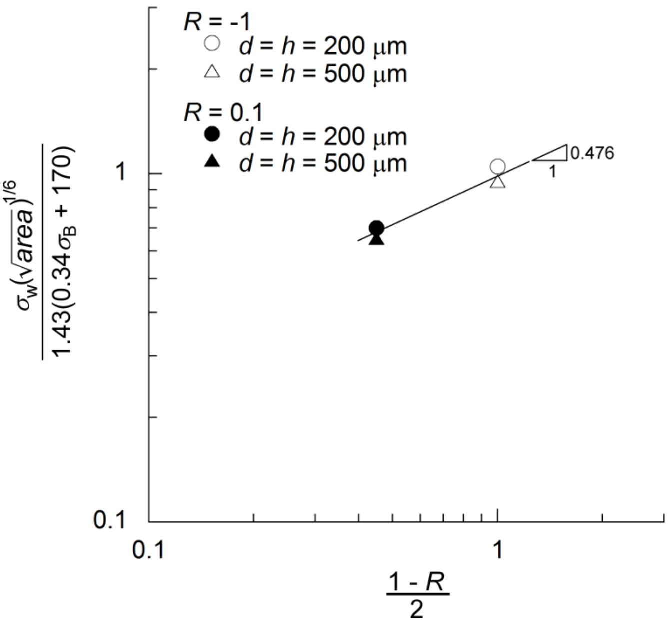


Figure 6. Influence of stress ratio on the fatigue limit.

$$\sigma_{\mathrm{w}} = \frac{F_{\mathrm{loc}}(0.34\sigma_{\mathrm{B}} + 170)}{(\sqrt{area})^{1/6}} \cdot \left(\frac{1-R}{2}\right)^{\alpha} \tag{3}$$

where α is a correction coefficient that depends on the material. Figure 6 shows the values of σ_{w} $(\sqrt{area})^{1/6}/\{F_{\mathrm{loc}}(0.34\sigma_{\mathrm{B}} + 170)\}$ as function of $(1–R)/2$ on a logarithmic graph. The slope of line in Figure 6 represents the value of α. In Figure 6, the results for the hole specimens with $d = h = 200$ μm and $d = h = 500$ μm were plotted. The slope indicated the values of $\alpha = 0.476$ and this value was adopted for the prediction of fatigue limit.

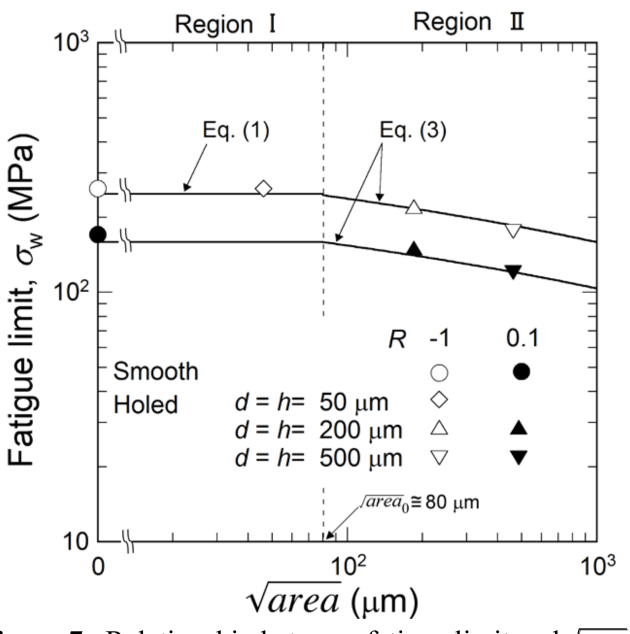


Figure 7. Relationship between fatigue limit and $\sqrt{area}$.

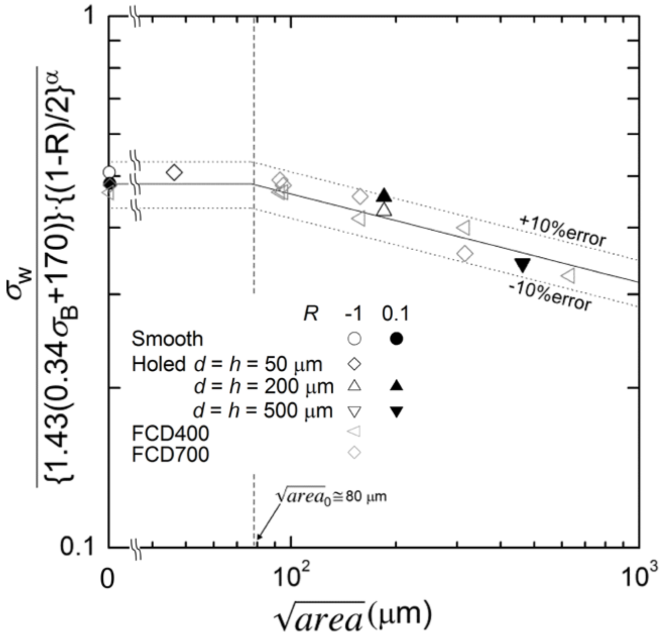


Figure 8. Relationship between normalized fatigue limit by $\{(1\text{-R})/2\}^{\alpha}$ and $\sqrt{area}$.

Figure 7 shows a comparison of prediction by Eqs. (1) and (3) with the experimental results for smooth specimens as well as holed specimens. The prediction of fatigue limit is in reasonable agreement with the experimental data. Irrespective of the stress ratio, there is a critical size of defect that has no effect on the fatigue limit of ferritic-pearlitic ductile cast iron. Defects with the $\sqrt{area}$ smaller than about 80 μm (region I), designated herein as $\sqrt{area_0}$, 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 μm ≤ $\sqrt{area}$ ≤ 1000 μm (region II).

Figure 8 shows the relationship between the fatigue limit normalized by the term of $\{(1-R)/2\}^a$ and $\sqrt{area}$. The data of FCD400 and FCD700 were taken from the previous study [5, 7]. The tensile strength

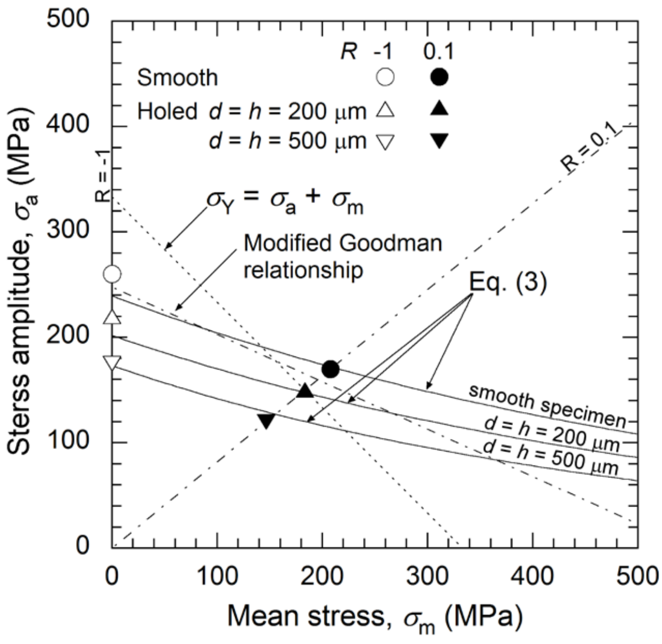


Figure 9. Effects of mean stress on fatigue limit.

of FCD400 and FCD700 were 420 MPa and 734 MPa, respectively. The prediction of fatigue limit is in reasonable agreement with the experimental data.

Figure 9 shows the effect of mean stress on fatigue limit. The solid lines calculated by Eq. (3) show the fatigue limit prediction. It is noted that to make use of Eq. (3) even for smooth specimen, we substituted $\sqrt{area}$ = 80 μm (cf. Figure 8) in Eq. (3). The fatigue limit of smooth specimen is slightly higher than the modified Goodman relationship and the yield strength at R = 0.1. Near the fatigue limit at R = 0.1, the effect of plastic yielding would be negligible because of the possible activation of elastic shake-down. As a whole, the predictions with Eq. (3) show a reasonably good agreement with the experimental results both for smooth and holed specimens.

4. Conclusions

The effects of small defects and stress ratios on the fatigue limit of ferrite-pearlite ductile cast iron were investigated. The obtained conclusions are as follows:

(1) From the microscopic observation, it is revealed that the fatigue limit is determined by the threshold condition for propagation of a crack emanating from the hole edge, regardless of defect sizes and stress ratios.

(2) In the region I where $\sqrt{area}$ is smaller than 80 μm, the defect can be regarded as a non-detrimental defect and the fatigue limit is the same as that of smooth specimen.

(3) In the region II where 80 $\mu m \leq \sqrt{area} \leq 1000$ μm, the fatigue limit can be quantitatively predicted based on the $\sqrt{area}$ parameter model in terms of a geometrical parameter of defects, $\sqrt{area}$, and a material parameter, σ_B. Furthermore, the stress ratio dependency of fatigue limit can be described by the term of $\{(1-R)/2\}^{\alpha}$. The value of α = 0.476 was obtained for the investigated ferritic-pearlitic ductile cast iron.

References

[1] Murakami Y 2002 *Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions*, (Elsevier)
[2] Yamabe J, Kobayashi M and Nakajima N 2005 *Trans. Jpn. Soc. Mech. Eng.* **71** 116
[3] Endo M 1989 *Trans. Jpn. Soc. Mech. Eng.* **38** 1139
[4] Tanaka Y, Yang Z and Miyamoto K 1995 *Mater. Trans.* **36** 749
[5] Endo M and Yanase K 2014 *Theor. Appl. Fract. Mec.* **69** 34
[6] Costa N, Machado N and Silva F S 2010 *Int. J. Fatigue* **32** 988
[7] Deguchi T, Matsuo T, Takemoto S, Ikeda T and Endo M 2016 *International Journal of Fracture Fatigue and Wear* **4** 93
[8] Deguchi T, Matsuo T, Kim H J, Ikeda T and Endo M 2016 *11th Int. Symp. on Advanced Scienc and Technology in Experimental Mechanics* Ho Chi Minh
[9] Deguchi T, Kim H J and Ikeda T 2017 *12th Int. Conf. on Damage Assessment of Structures, DAMAS2017* Kitakyushu Japan (This thesis will be presented)