Effect of Hardness and Stress Ratio on Threshold Stress Intensity Factor Ranges for Small Cracks and Long Cracks in Spheroidal Cast Irons^{*}

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Abstract

Threshold stress intensity factor ranges, ΔK_{th} s, of spheroidal cast iron, which are composed of ferritic, ferrite-pearlitic, or pearlitic structures, have been estimated by ΔK -increasing tests for small cracks and by ΔK -increasing and ΔK -decreasing tests for long cracks at several stress ratios. With respect to the effects of the hardness and stress ratio, ΔK_{th} estimated by the ΔK -decreasing tests for long cracks is evidently different from that for small cracks, while ΔK_{th} estimated by the ΔK -increasing tests for long cracks is similar to that for small cracks. Moreover, in the case of long cracks, the values of ΔK_{th} estimated by the ΔK -decreasing tests were larger than those estimated by the ΔK -increasing tests, irrespective of the type of matrix structures. These tendencies are attributed to the fact that the crack closure stress of the long cracks in the ΔK -decreasing tests is relatively higher than that of the long cracks in the ΔK -increasing tests. On the fracture surface of the long cracks in the ΔK -decreasing tests, oxide layers produced by fretting are observed at sites around the crack tip, although such layers are not observed on the fracture surface in the ΔK -increasing tests.

Key words: Fatigue Limit, Vickers Hardness, Stress Ratio, Threshold Stress Intensity Factor Range, Effective Stress Intensity Factor Range, Crack Closure, Small Crack, Long Crack, Spheroidal Cast Iron

1. Introduction

The fatigue strength of spheroidal cast irons is generally lower than that of steels, whose hardness is nearly equal to that of the spheroidal cast irons. This is because the structure of spheroidal cast irons contains graphite and various types of defects. In particular, it is difficult to predict fatigue limit of spheroidal cast irons with cast surfaces due to the complex effects of surface roughness, transitional layers, defects, and residual stress. To solve this problem, we have conducted plane-bending and tension-compression fatigue tests⁽¹⁾⁽²⁾ by using specimens with cast surfaces whose residual stress is relieved by annealing in a vacuum. We have also quantitatively evaluated the effects of the above factors excluding the residual stress on the fatigue limit by using the $\sqrt{area}$ parameter model proposed by Murakami et al⁽³⁾⁻⁽⁵⁾. However, with respect to the actual parts, the effect of the residual stress on the fatigue strength must be considered in addition to these factors. Based on the $\sqrt{area}$ parameter model, the threshold stress intensity factor range, ΔK_{th} , and fatigue limit, σ_w , at a stress ratio of $R = -1$ are expressed using the defect size, $\sqrt{area}$, as follows:

$$\left[\sqrt{area} < 1000 \mu\text{m} \right]$$

$$\Delta K_{th} \cong 3.3 \times 10^{-3} (HV + 120) (\sqrt{area})^{1/3} \dots\dots\dots (1)$$

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$$\sigma_w = C \times (HV + 120) / (\sqrt{area})^{1/6} \quad \dots\dots\dots (2)$$

$$C = \begin{cases} 1.43 \text{ (surface defects)} \\ 1.56 \text{ (subsurface defects)} \end{cases} \quad \dots\dots\dots (3)$$

$$[\sqrt{area} \geq 1000 \mu\text{m}]$$

$$\Delta K_{th} = \Delta K_{th,\infty} = \text{material constant} \quad \dots\dots\dots (4)$$

$$\sigma_w = \frac{\Delta K_{th,\infty}}{2F \times \sqrt{\pi \sqrt{area} \times 10^{-6}}} \quad \dots\dots\dots (5)$$

$$F = \begin{cases} 0.65 \text{ (surface defects)} \\ 0.50 \text{ (subsurface defects)} \end{cases} \quad \dots\dots\dots (6)$$

where, ΔK_{th} , is the threshold stress intensity factor [$\text{MPa}\sqrt{\text{m}}$]; HV , the Vickers hardness [kgf/mm^2]; $area$, the area projected on the principal plane [μm^2]; σ_w , the fatigue limit [MPa]; $\Delta K_{th,\infty}$, the threshold stress intensity factor for long cracks [$\text{MPa}\sqrt{\text{m}}$]. Since the fatigue cracks of spheroidal cast irons with cast surfaces sometimes begin from a cast defect with $\sqrt{area} > 1000 \mu\text{m}$, a quantitative evaluation of their fatigue limit must be performed using the accurate value of $\Delta K_{th,\infty}$. In addition, it is important to clarify the applicable range of Eq. (1) with respect to $\sqrt{area}$. Although the value of $\Delta K_{th,\infty}$ is generally estimated by ΔK -decreasing tests, several studies have reported that this value is different from that obtained by the ΔK -increasing tests ⁽⁶⁾⁽⁷⁾. Therefore, the value of $\Delta K_{th,\infty}$ should be estimated by ΔK -increasing tests. Thus far, however, the value of $\Delta K_{th,\infty}$ estimated by ΔK -decreasing tests has hardly been compared with that estimated by ΔK -increasing tests.

Furthermore, we focus on the effect of the stress ratio on the fatigue strengths of specimens with small cracks ($\sqrt{area} \leq 1000 \mu\text{m}$) and long cracks ($\sqrt{area} > 1000 \mu\text{m}$). Since the actual parts have compressive residual stresses at sites near the cast surfaces produced by shot blasting, we must clarify not only the usefulness and the applicable defect sizes of Eq. (1) but also the effect of the stress ratio on the fatigue strength. Based on the $\sqrt{area}$ parameter model, the fatigue limit of specimens with small cracks considering the effect of the mean stress is expressed as follows:

$$\sigma_w = C \times (HV + 120) / (\sqrt{area})^{1/6} \cdot [(1 - R) / 2]^\alpha \quad \dots\dots\dots (7)$$

$$\alpha = 0.226 + HV \times 10^{-4}$$

The error in Eq. (7) is reported to be within $\pm 15\%$ for materials with $HV = 100 - 740$ ($\alpha = 0.236 - 0.3$). However, Kondo et al. ⁽⁷⁾ have reported that the values of α for S25C and SCM435 tend to be larger (S25C: $\alpha = 0.3$, SCM435: $\alpha = 0.8$) than those calculated using Eq. (7), although experimental data are insufficient. Therefore, it is also necessary to verify the accuracy of Eq. (7). On the other hand, several evaluation equations using $\Delta K_{th,R=0,\infty}$, i.e., $\Delta K_{th,\infty}$ with $R = 0$, are proposed ⁽⁸⁾⁻⁽¹¹⁾ for specimens with long cracks. The value of α for long cracks estimated by ΔK -decreasing tests is in the range of 0.7–1.0 ⁽⁸⁾⁽⁹⁾⁽¹²⁾⁽¹³⁾ and these values are considerably larger than those for small cracks.

From this viewpoint, the purpose of this study is to verify the effects of the hardness and stress ratio on the values of ΔK_{th} for several types of spheroidal cast irons with small or long cracks and clarify the difference in the values obtained by ΔK -increasing and ΔK -decreasing tests. To achieve this purpose, we conduct tension-compression fatigue tests using specimens with an artificial defect ($\sqrt{area} \approx 300 - 4000 \mu\text{m}$) or a pre-crack and crack growth tests using specimens with a center crack. Moreover, the crack closure behavior of specimens subjected to the ΔK -increasing and ΔK -decreasing tests is observed by applying the unloading elastic compliance method.

2. Materials, specimens, and experimental method

2.1 Materials

Table 1 shows the conditions for conducting the fatigue tests on the cast materials. Three types of spheroidal cast irons are employed whose matrices are composed of ferrite (F), ferrite-pearlite (FP), and pearlite (P) structures. A flat plate ($40 \times 200 \times 10.5^t$ mm) and Y-block specimens were cast as a row material. Table 2 shows the mechanical properties of these materials. In the case of the F and P materials, the flat plate specimens can be considered to be the same as the Y-block specimens because their mechanical properties and the amount of graphite in their microstructures are nearly the same. In the case of the FP material, although the proof stress, tensile strength, and hardness of the flat plate specimens are approximately 10% higher than those of the Y-block specimens, the amount of graphite in the flat plate specimens is equivalent to that in the Y-block specimens. Therefore, for convenience, these specimens considered to be the same.

2.2 Specimens

Figure 1 shows the specimens for the crack growth tests and tension-compression fatigue tests. All the specimens have a smooth surface finish achieved by buffing after emery polishing. The artificial defects shown in Figs.1 (a) and (b), and (c) have been introduced by machining, while those shown in Fig. 1 (c) have been introduced by electrical discharge machining. Then, residual stresses produced by machining are relieved by annealing in a vacuum at 550 °C for 2 h.

2.3 Experimental method

2.3.1 Crack growth test

The crack growth tests were conducted with a stress ratio of $R = -1$ and a frequency of 15–30 Hz under loading control, based on ASTM E647–95a⁽¹⁴⁾. In order to eliminate the bending stress generated in the crack growth tests, strain gages were attached to both sides of the specimens, and the alignment was carefully adjusted. The values of ΔK_{th} were measured by decreasing ΔK gradually, after the introduction of a pre-crack at a length of approximately 2 mm by the application of stress that did not exceed K_{max} at the beginning of the tests. The crack growth tests with $R = -1$ began at the same level of K_{max} under the consideration that the values of ΔK_{th} depend on those of K_{max} at the beginning of the tests⁽¹⁵⁾. The crack length was measured using a movable microscope. By employing the secant method, the crack growth rate was estimated from the number of cycles that are required for crack propagation over a length of 500 μ m. The ΔK -decreasing tests were conducted under the conditions that satisfy Eq. (8), and we inferred that crack propagation stopped when $da/dN < 1 \times 10^{-10}$ [m/cycle].

Table 1 Condition of fatigue tests

Cast material		Crack growth test* ¹	Tension-compression fatigue test	
			Artificial defects	Single edge crack* ¹
FP	Flat plate	No* ²	$R = -4, -2, -1^{*3}, 0, 0.3$	No
	Y block	$R = -1.5, -1, 0.05$	No	$R = -1.5, -1$
F	Flat plate	No	$R = -1$	No
	Y block	$R = -1$	No	
P	Flat plate	No	$R = -1^{*3}$	No
	Y block	$R = -1$	No	

*1: Crack closure was observed by the unloading elastic compliance method.

*2: The “No” means that a test was not conducted.

*3: These data were taken from an early study.⁽¹⁾

Table 2 Mechanical properties

Cast material		0.2% P.S. [MPa]	T.S. [MPa]	Elong. [%]	HV0.1 [kgf/mm ²]
FP	Flat plate	363	555	8	227
	Y block	337	512	14	207
F	Flat plate	292	430	23	166
	Y block	290	424	26	160
P	Flat plate	462	743	6	286
	Y block	469	761	5	292

Fig.1 Shape and dimensions in mm of specimens

$$\frac{1}{\Delta K} \frac{d(\Delta K)}{da} = -0.08 \pm 0.01 [\text{mm}^{-1}] \quad \dots \dots \dots (8)$$

After measuring the values of ΔK_{th} , crack growth tests accompanied by the application of a constant stress were conducted until the crack length satisfied the condition of small scale yielding expressed in Eq. (9), and the data for middle crack growth rates were measured:

$$W - 2a \geq 1.25 \frac{P_{\max}}{B\sigma_y} \quad \dots \dots \dots (9)$$

where $P_{\max}$ is the maximum load [N] and σ_y is the yield stress [MPa]. The crack closure load, P_{cl} , was measured by the unloading elastic compliance method in which strain gages were attached at lengths of 3 mm and 7 mm from the tip of the notch and these strain gages are different from those used for adjusting the alignment. Figure 2 shows an example of a compliance curve. A variation point of this curve was considered as the value of P_{cl} . The strain gages for obtaining the compliance curve were used under minimum loading to prevent them from slackening.

Fig.2 Measurement of crack closure load P_{cl} by the unloading elastic compliance method (Notch depth $t = 1$ mm , Load $P = \pm 9$ kN)

2.3.2 Tension-compression fatigue test

The tension-compression fatigue tests were conducted on the specimen at the stress ratio of $R = -1$ and a frequency of 10–35 Hz under loading control, as shown in Figs.1 (b) and (c). Strain gages were applied on both sides of the specimens and the alignment was carefully adjusted. The fatigue limit of the specimen shown in Fig.1 (b) was defined as the maximum value of the stress amplitude applied to the specimens at which a non-propagating crack was observed at $N = 1 \times 10^7$. The non-propagating crack in the specimen with a drilled hole was observed by using an optical microscope. On the other hand, the specimen with a notch was compulsorily fractured at room or liquid nitrogen temperature and the existence of a non-propagating crack was determined by observing its fracture surface using a scanning electron microscope. The fatigue limit of the specimens in which the non-propagating crack cannot be observed was defined as the average of the minimum stress amplitude for broken specimens and the maximum stress amplitude for unbroken specimens.

The tension-compression fatigue tests were conducted on the specimen shown in Fig. 1 (c) after the introduction of a pre-crack at the tip of the notch. To prevent any increase in the crack closure load, the pre-crack was introduced under a high compressive mean stress. The length of the pre-crack for the 200 μm notch was 70 μm , while that for the 1 mm notch was 150 μm . Moreover, the crack growth behavior during the fatigue tests was observed using replicas. The values of P_{cl} were measured by applying the unloading elastic compliance method.

3. Calculation of stress intensity factor ranges

The value of ΔK [$\text{MPa}\sqrt{\text{m}}$] for each specimen was calculated as follows:

【Specimen with a center crack】⁽¹⁴⁾

$$\Delta K = \frac{\Delta P}{B} \sqrt{\frac{\pi \beta}{2W} \sec \frac{\pi \beta}{2}}, \quad \beta = \frac{2a}{W} \quad \dots\dots\dots(10)$$

【Specimen with a drilled hole】⁽⁵⁾

$$\Delta K = 0.65 \times 2\sigma_a \sqrt{\pi \sqrt{\text{area}} \times 10^{-6}} \quad \dots\dots\dots(11)$$

【Specimen with notches on both sides】⁽¹⁷⁾

$$\begin{cases} \Delta K = F(\chi) \times 2\sigma_a \sqrt{\pi t}, & \chi = \frac{2t}{W} \\ F(\chi) = \{1 + 0.112 \cos^2(\frac{\pi \chi}{2})\} \sqrt{\frac{2}{\pi \chi} \tan \frac{\pi \chi}{2}} \end{cases} \quad \dots\dots\dots(12)$$

【Specimen with a notch】⁽¹⁷⁾

$$\begin{cases} \Delta K = F(\eta) \times 2\sigma_a \sqrt{\pi t}, & \eta = \frac{t}{W} \\ F(\eta) = 1.12 - 0.23 \ln \eta + 10.55 \eta^2 - 21.72 \eta^3 + 30.39 \eta^4 \end{cases} \quad \dots\dots\dots(13)$$

where ΔP is the load range [N]; W , the width of specimen [m]; B , the thickness of the

specimen [m]; a , the crack length [m]; σ_a , the stress amplitude [MPa]; $\sqrt{area}$, the defect size [μm]; and t , the crack depth [m]. The value of a (or t) is equal to the crack length (or depth) that includes the notch length (or depth).

4. Results and discussion

4.1 Crack growth test

Figure 3 (a) shows the relationship between the crack growth rate, da/dN , and ΔK . Although the values of da/dN are similar at high and middle levels of ΔK ($da/dN \geq 1 \times 10^{-8}$ [m/cycle]) for each material with $R = -1$, those at low levels of ΔK ($da/dN < 1 \times 10^{-8}$ [m/cycle]) are evidently different, i.e., the crack growth rate of the P material is the fastest and that of the F material is the slowest. Ogawa⁽¹⁸⁾ and Sugiyama⁽¹⁹⁾ have compared the crack growth behavior at low levels of ΔK by using several types of spheroidal cast irons. The tendency of our data is similar to that of Ogawa's result. Based on the data obtained in our study on the effects of the stress ratio on the crack growth behavior, we observe that the lower the stress ratio, the slower is the crack growth. The threshold stress intensity factor range, ΔK_{th} , is larger as the stress ratio is lower.

Figure 3 (b) shows the relationship between da/dN and the effective stress intensity factor range, ΔK_{eff} . The relationship between da/dN and ΔK_{eff} for all the materials is successfully shown using a single curve. Therefore, the difference in da/dN obtained from several structures and stress ratios can be explained by considering the effects of crack closure.

Figure 4 shows the relationship between ΔK_{th} , $\Delta K_{eff,th}$, and HV . For the specimens with a long crack, the values of ΔK_{th} obtained by ΔK -decreasing tests were reduced because the material was soft. In contrast, the values of $\Delta K_{eff,th}$ are almost equal for all the specimens, despite the difference in the hardness.

Figure 5 shows the relationship between ΔK_{th} , $\Delta K_{eff,th}$, and R for the FP material shown in Fig. 3. In this figure, the value of $(1-R)/2$ are plotted on the horizontal axis. For the specimens with a long crack, the values of ΔK_{th} obtained by the ΔK -decreasing tests increase with a decrease in the stress ratio, i.e., the values of $(1-R)/2$ increase. In contrast, the values of $\Delta K_{eff,th}$ hardly depend on the stress ratio. Furthermore, the values of ΔK_{th} are obtained using the following equation:

$$\Delta K_{th} \propto \left(\frac{1-R}{2}\right)^\alpha \quad \dots\dots\dots(14)$$

As for the FP material, the value of α is 0.77 for long cracks in the ΔK -decreasing tests, and it is larger than the value for small cracks, which is 0.247 ($HV = 207$) calculated using Eq. (7).

4.2 Tension-compression fatigue test

Figure 6 shows the relationship between ΔK_{th} and $\sqrt{area}$ obtained from the tension-compression fatigue tests conducted by gradually increasing ΔK ⁽¹⁾. The values of ΔK_{th} for

Fig.3 Relationship between da/dN and ΔK or ΔK_{eff}

small cracks were accurately estimated using Eq. (1), which is applicable to specimens with $\sqrt{area} > 1000 \mu\text{m}$ for all the materials. The range of $\sqrt{area}$ in which Eq. (1) can be applied increases because the material is soft.

Figure 7 shows the relationship between the fatigue limit, σ_w , and the mean stress, σ_m , for the FP material with a small or long crack. Although the amount of data is insufficient, on the basis of the stress ratio obtained from this study, it is inferred that the effect of the mean stress on the fatigue limit is successfully determined using the modified Goodman diagram.

Figure 8 shows the relationship between ΔK_{th} and HV for specimens with small cracks ($\sqrt{area} = 555 \mu\text{m}$) and long cracks ($\sqrt{area} \approx 4000 \mu\text{m}$) obtained by the tension-compression fatigue tests. The values of ΔK_{th} for small cracks are directly related to those of HV shown in Eq. (1). The values of ΔK_{th} for long cracks are also directly related to HV , and their tendency differs from that of values for long cracks obtained by the ΔK -decreasing tests, as shown in Fig. 4. For the specimen with a long crack, the difference between the ΔK_{th} values obtained by the ΔK -increasing and ΔK -decreasing tests is the highest for the F material, which is the softest material used in this study. Moreover, the value of $\Delta K_{th,\infty}$ of the F material obtained by the ΔK -decreasing tests is 1.4 times larger than that obtained by the ΔK -increasing tests.

Figure 9 shows the relationship between ΔK_{th} and R for specimens having small cracks ($\sqrt{area} = 555 \mu\text{m}$) and long cracks ($\sqrt{area} = 1850 \mu\text{m}$) with regard to the FP material in the tension-compression fatigue tests. In this figure, the values of $(1-R)/2$ are plotted on the horizontal axis, as in Fig. 5. By using Eq. (14), the values of α , for small and long cracks are estimated as 0.32 and 0.38, respectively. These values are nearly equal and higher than the value calculated using Eq. (7), which is 0.247. The difference between the values of ΔK_{th} estimated from the experimental values of α and the calculated of α ($\alpha = 0.247$) is at most 7% for small cracks and 13% for long cracks, within the range of the stress ratios tested

Fig.4 Relationship between ΔK_{th} , $\Delta K_{eff,th}$ and HV for crack growth tests at $R = -1$

Fig.5 Relationship between ΔK_{th} , $\Delta K_{eff,th}$ and stress ratio R for crack growth tests

Fig.6 Relationship between ΔK_{th} and $\sqrt{area}$ for tension-compression fatigue tests at $R = -1$

Fig.7 Fatigue limit diagram of FP material containing an artificial defect

in this study. In other words, $R = -4 - 0.3$ for small cracks and $R = -4 - 0$ for long cracks. Therefore, it is considered that the effect of the stress ratio on ΔK_{th} can be evaluated using Eq. (7) with sufficient accuracy for practical use within the range of the stress ratios tested in this study. In addition, Eq. (7) can be applied to both small and long cracks. On the other hand, the value of α obtained by the ΔK -decreasing tests (broken line in Fig. 9) is considerably larger than that obtained by the ΔK -increasing tests. It is evident that the tendency of $\Delta K_{th,\infty}$ obtained by the ΔK -decreasing tests is different from that of $\Delta K_{th,\infty}$ obtained by the ΔK -increasing tests.

4.3 Observations of crack closure in tension-compression fatigue tests

Figure 10 shows the crack closure behavior of the FP material with a long crack (notch length: $t = 1 \text{ mm}$) obtained by the unloading elastic compliance method. The specimen shown in Fig. 1(c) was tested under tension-compression loading. The fatigue test is conducted at $R = -1$ by applying a stress corresponding to the fatigue limit. In Fig. 10, t' represents the crack length obtained by adding the notch length t to the crack length c emanating from the tip of the notch. The crack closure load, P_{cl} , at $N = 1$ is relatively low, because a pre-crack was introduced under a compressive mean stress. However, the value of P_{cl} increases with the number of cycles. Simultaneously, the crack propagates to some extent and then ceases to propagate further. Therefore, the value of P_{cl} at $N = 1 \times 10^7$ is increases considerably, and the crack closure is generated in a wide range of cyclic loading. Table 3 shows the values of ΔK_{th} , $K_{cl,th}$, and $\Delta K_{eff,th}$ for the specimens with small and long cracks at $N = 1 \times 10^7$ obtained from the fatigue tests. The values of the specimens with long cracks at $R = -1$ and -1.5 are higher than those of the specimen with small cracks. However, since the values of $\Delta K_{eff,th}$ for these specimens are nearly equal, we believe that the values of $\Delta K_{eff,th}$ are not influenced by the crack length and stress ratio. The tendency of this result is the same as that of the result obtained by the crack growth tests, as shown in Figs. 4 and 5. Based on these results, the values of $\Delta K_{eff,th}$ are considered to be nearly constant, irrespective of the type of experimental method, material, and stress ratio within the range of this study. Moreover, it is considered that the values of ΔK_{th} differ under these conditions because the values of $K_{cl,th}$ also differ under the same conditions. In general, the value of $\Delta K_{eff,th}$ is considered to be constant for structural steels as well as spheroidal cast irons⁽²⁰⁾⁽²¹⁾. However, it is reported that the value of $\Delta K_{eff,th}$ decreases remarkably under the conditions of a small crack, high HV , and extremely high R ⁽²⁰⁾. Although the materials used in this study do not have a high hardness, further studies on the effect of the stress ratio, which includes extremely high R value, on ΔK_{th} are necessary.

4.4 Difference in crack growth and tension-compression fatigue tests with regard to crack closure behavior

Fig.8 Relationship between ΔK_{th} and HV for tension-compression fatigue tests at $R = -1$

Fig.9 Relationship between ΔK_{th} and R for tension-compression fatigue tests at $R = -1$

As mentioned above, the difference in the crack growth and tension-compression fatigue tests with respect to $\Delta K_{th,\infty}$ is due to the difference in the crack closure. To clarify the reason for the difference, the fracture surfaces of the specimens were observed.

Figure 11 shows the optical microscope images of the fracture surfaces of the specimens for the crack growth tests. These images show the sites around the center of the specimens, and the tips of the non-propagating cracks are denoted by dotted lines. All the fracture surfaces at the sites behind the tips of the non-propagating cracks are darkened. A comparison of the fracture surfaces of the FP, F, and P materials with $R = -1$ reveals that the lower the hardness, the darker is the fracture surface. The condition of these fracture surfaces corresponds to the values of K_{cl} . In other words, the higher the values of K_{cl} , the darker is the fracture surface. Moreover, the darkened fracture surfaces depend on R and HV . A comparison between Figs. 11 (a) and (b) reveals that the fracture surfaces darken with a decrease in the stress ratio. In contrast, such darkened surfaces were not observed in the tension-compression fatigue tests, irrespective of the crack length and stress ratio. For the FP material, the values of $K_{cl,th}$ obtained by the crack growth test, which was conducted by gradually decreasing ΔK , were approximately 1.8 and 1.3 times higher than those obtained by the tension-compression fatigue tests, which was conducted by gradually increasing ΔK . These results indicate that the darker the fracture surface, the larger is the difference in $K_{cl,th}$.

Figure 12 shows the fracture surfaces of the FP material tested at $R = -1.5$ and $R = 0.05$ and observed using an electron probe microanalyzer. Oxide was observed in the area corresponding to the darkened fracture surfaces and oxide layers, which are considered to be produced by fretting, are deposited on these surfaces. From this observation, it is considered that the crack closure is developed due to the oxide layers produced by fretting in the crack growth tests; consequently, the values of K_{cl} are larger than those in the ΔK -increasing tests, i.e., the tension-compression fatigue tests. In addition, it has been reported that graphite crushed on the fracture surface⁽²²⁾ of spheroidal cast irons induces crack closure. However, since such a surface containing crushed graphite cannot be observed on the fracture, as inferred from the carbon element distribution shown in Fig. 12, the effect of the graphite-induced crack closure is considered to be small. Furthermore, it is reported that the surface roughness on a fracture surface promotes oxide-induced crack closure caused by fretting⁽²³⁾. However, since the oxide layers are deposited on a large area of the fracture surface in the crack growth tests conducted in this study, the difference in the surface roughness cannot be evaluated quantitatively. Based on these results, the effects of HV and R on $\Delta K_{th,\infty}$ of the specimens obtained from and tension-compression fatigue tests are investigated.

Fig.10 Behavior of crack closure at fatigue limit in the specimen having a long crack for FP material (Notch depth $t = 1\text{ mm}$, Stress ratio $R = -1$)

Table3 ΔK_{th} , $K_{cl,th}$, and $\Delta K_{eff,th}$ obtained from tension-compression fatigue tests for FP material [$\text{MPa}\sqrt{\text{m}}$]

Specimen	Stress ratio	ΔK_{th}	$K_{cl,th}$	$\Delta K_{eff,th}$
Small crack ($t = 200\ \mu\text{m}$)	$R = -1$	10.01	2.15	2.86
	$R = -1.5$	10.93	1.46	2.92
Long crack ($t = 1\ \text{mm}$)	$R = -1$	14.71	4.26	3.10
	$R = -1.5$	16.16	3.42	3.04

As mentioned above, the effects of HV and R on $\Delta K_{th,\infty}$ for long cracks obtained in the ΔK -increasing tests are similar to those on ΔK_{th} for small cracks. In the case of a small crack, since the condition of small scale yielding is generally not satisfied, it is considered that crack closure is not developed and consequently the crack remains open for a wide range of loading conditions. Therefore, the values of ΔK_{th} for such a small crack are considered to be influenced by the average resistance of a material against plastic deformation as the first approximation, since the fatigue limit of smooth specimens without a crack generally has a good correlation with HV . For a long crack, the effects of oxide-induced crack closure by fretting and plastic-induced crack closure are considered, which are thought to be very small for a small crack and tend to increase as the material gets softer. However, the effects are considered to be relatively small for a long crack obtained from ΔK -increasing tests. Therefore, it is considered that the tendency of the effects of HV and R on $\Delta K_{th,\infty}$ for a long crack obtained by the ΔK -increasing tests is similar to that of the effects on ΔK_{th} for a small crack.

In contrast, with regard to the crack growth tests, the values of $\Delta K_{th,\infty}$ were measured by gradually decreasing ΔK . Therefore, the crack closure was generated before reaching $\Delta K_{th,\infty}$. Figure 13 shows the changes in K_{cl} in the ΔK -increasing and ΔK -decreasing tests. The change in K_{cl} in the ΔK -decreasing test indicates that the crack closure K_{cl} did not decrease, although ΔK gradually decreased. Instead, the value of K_{cl} increased due to the formation of an oxide layer by fretting. The effect of the oxide layer on the crack closure is large, and the value of $K_{cl,th}$ in the ΔK -decreasing tests is sometimes 1.8 times higher than that in the ΔK -increasing tests, as mentioned above. Thus, since the effect of the oxide-induced crack closure on ΔK_{th} in the ΔK -decreasing tests is larger than that in the ΔK -increasing tests, it is believed that the tendency of the effects of HV and R on ΔK_{th} in the ΔK -decreasing tests is different from that of the effects in the ΔK -increasing tests.

In general, the tendency of $\Delta K_{th,\infty}$ in the ΔK -decreasing tests to decrease as the material becomes harder is attributed to the fact that fretting is generated more easily as the material becomes softer, although fretting, which could be the main cause of the development of crack closure, is not necessarily dependent on only HV . With regard to the effect of R on $\Delta K_{th,\infty}$, since fracture surfaces are often in contact with each other over a wide range of loading conditions, the lower the stress ratio, the easier it is to generate fretting. Therefore, it is considered that $\Delta K_{th,\infty}$ at a low R value increases remarkably and its tendency is different from that in the ΔK -increasing tests.

Fig.11 Photomicrographs of fracture surfaces on specimens for crack growth tests

Fig.12 EPMA analysis around the crack front at ΔK_{th} on FP material for crack growth tests

Fig.13 Crack closure behavior of FP material for ΔK -increasing tests and ΔK -decreasing tests at $R = -1$

Based on these results, the application of prediction equations using $\Delta K_{th,\infty}$ and α obtained by the ΔK -decreasing tests results in the overestimation of the fatigue strength of shot-blasted ductile cast irons with cast surfaces, which contain large defects and residual stress. Therefore, the fatigue limit evaluation of these materials should employ $\Delta K_{th,\infty}$ and α obtained by the ΔK -increasing tests, as shown in this study. For the range of stress ratios tested in this study, Eq. (7) can be used, to predict the fatigue limit of not only the shot-blasted ferrite-pearlitic ductile cast irons having a small crack but also of those having a long crack with sufficient accuracy for practical use.

5. Conclusion

In this study, the threshold stress intensity factors, ΔK_{th} s, for specimens with small and long cracks were estimated by tension-compression fatigue tests, which were conducted by gradually increasing ΔK , and crack growth tests, which were conducted by gradually decreasing ΔK . Further, the effects of hardness (HV) and stress ratio (R) on ΔK_{th} were investigated from the viewpoint of crack closure behavior. The following results were obtained:

- (1) The effects of HV and R on ΔK_{th} for specimens with a small crack can be successfully evaluated by applying the $\sqrt{area}$ parameter model.
- (2) With respect to the effect of HV and R on the threshold stress intensity factor range of specimens with a long crack, $\Delta K_{th,\infty}$, the tendency of $\Delta K_{th,\infty}$ in the ΔK -decreasing tests is clearly different from that of $\Delta K_{th,\infty}$ in the ΔK -increasing tests.
- (3) The values of $\Delta K_{th,\infty}$ obtained by the ΔK -increasing tests increase as the material becomes harder, and the effect of R on $\Delta K_{th,\infty}$ obtained by the ΔK -increasing tests is similar to that on ΔK_{th} of specimens with a small crack.
- (4) The difference in the ΔK -decreasing and ΔK -increasing tests with respect to $\Delta K_{th,\infty}$ depends on the difference in their crack closure. Further, the crack closure of the specimens obtained under the ΔK -decreasing tests develops remarkably due to an oxide layer on the fracture surface produced by fretting.

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References

- (1) Yamabe, J., et al., Evaluation of Fatigue Strength of Ductile Cast Iron Composed Ferrite and Pearlite Structures with As-cast surface (Effect of Surface Roughness and Microstructure Transition Layers on Fatigue Strength), *Trans. J. Soc. Mech. Eng. A*, Vol. 71, No. 702 (2005), pp. 262–270.
- (2) Yamabe, J., et al., Evaluation of Fatigue Strength of Ductile Cast Iron Composed Ferrite and Pearlite Structures with casting surface (Effect of Surface Roughness, Microstructure

- Transition Layers and Defects on Fatigue Strength), *Trans. J. Soc. Mech. Eng. A*, Vol. 71, No. 701 (2005), pp. 116–123.
- (3) Murakami, Y., Endo, M., A Geometrical Parameter for the Quantitative Estimation of the Effects of Small Defects on Fatigue Strength of Metals, *Trans. J. Soc. Mech. Eng. A*, Vol. 49, No. 438 (1983), pp. 127–136.
- (4) Murakami, Y., Endo, M., Effect of Hardness and Crack Geometry on ΔK_{th} of small cracks, *J. Soc. Mater. Sci., Jpn.*, Vol. 35, No. 395 (1986), pp. 911–917.
- (5) Murakami, Y., *Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions* (2002), Elsevier.
- (6) Miyazaki, T., et al., Quantitative Evaluation of Fatigue Limit of a Metal with a Arbitrary Crack under a Stress Controlled Condition, *Trans. J. Soc. Mech. Eng. A*, Vol. 68, No. 673 (2002), pp. 1352–1359.
- (7) Kondo, Y., et al., The effect of material hardness and mean stress on the fatigue limit of steels containing small defects, *Fatigue Fract. Engng. Mater. Struct.*, Vol. 26 (2003), pp. 675–682.
- (8) Kawakami, Y., et al., Study on Fatigue Strength of SCM440 Steel under High Mean Stress, *Trans. J. Soc. Mech. Eng. A*, Vol. 69, No. 678 (2003), pp. 396–403.
- (9) Japan Welding Society, WES2805 (1997).
- (10) Nakai, Y., et al., Stress Ratio Effect on Fatigue Crack Growth Threshold in Steels, *J. Soc. Mater. Sci., Jpn.*, Vol. 33, No. 371 (1984), pp. 1045–1051.
- (11) Klesnil, M. and Lukas, P., Effect of stress cycle asymmetry of fatigue crack growth, *Mat. Sci. Eng.*, Vol. 9 (1972), pp. 231–240.
- (12) Horikawa, T., et al, Y., Effect of Stress Ratio on Fatigue Strength of Micro Pulse Induction Hardness Steel with Very Thin Case-Hardened Depth, *J. Soc. Mater. Sci., Jpn.*, Vol. 46, No. 11 (1997), pp. 1242–1247.
- (13) Zhang, L., et al., Effect of Stress Ratio on Fatigue Threshold of Cracked Components, *Trans. J. Soc. Mech. Eng. A*, Vol. 64, No. 621 (1998), pp. 1221–1228.
- (14) ASTM standard E 647–95a (1995).
- (15) Kikukawa, M., et al., Study on Test Method of Fatigue Crack Growth Threshold, *J. Soc. Mater. Sci., Jpn.*, Vol. 30, No. 330 (1981), pp. 276–282.
- (16) Toyosada, M. and Niwa, T., *Prediction of fatigue life for steel structures* (2001), pp. 92, Kyouritu Syuppan Co. LTD.
- (17) Murakami, Y., editor-in-chief, *Stress Intensity Factors Handbook*, Vol. 1 (1987), Pregamon Press.
- (18) Ogawa, T., et al., Fatigue Crack Growth of Spheroidal–Graphite Cast Irons with Different Microstructures, *Trans. J. Soc. Mech. Eng. A*, Vol. 58, No. 554 (1992), pp. 1772–1778.
- (19) Ogawa, T., et al., Fatigue Crack Propagation Characteristics of Spheroidal Graphite Cast Irons with Various Dual Phase Matrix Microstructures, *Trans. J. Soc. Mech. Eng. A*, Vol. 56, No. 523 (1990), pp. 482–487.
- (20) Kondo, Y., et al., Large Reduction in the $(\Delta K_{eff})_{th}$ of Short Crack at Extremely High Stress Ratio, *J. Soc. Mater. Sci., Jpn.*, Vol. 53, No. 6 (2004), pp. 661–666.
- (21) Tanaka K., Mechanics Approach to Small Fatigue Crack Propagation, *Trans. J. Soc. Mech. Eng. A*, Vol. 54, No. 497 (1985), pp. 1–7.
- (22) Ogawa, T., et al., Threshold Characteristics and Crack Closure of Fatigue Crack Growth of Spheroidal Graphite Cast Iron FCD450 (in Japanese), *Trans. J. Soc. Mech. Eng. A*, Vol. 51, No. 467 (1984), pp. 1660–1667.
- (23) Sugiyama, Y., et al., Difference in Fatigue Crack Propagation Behavior at Stage II between Spheroidal Graphite Cast Iron and High Strength Steel, *J. Soc. Mater. Sci., Jpn.*, Vol. 37, No. 418 (1987), pp. 776–782.