Effect of Si Content on the Deterioration of Vibration Fracture Resistance of Ferritic SG Cast Iron under an Aqueous Environment

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Ferritic spheroidal graphite cast irons generally exhibit intergranular fracturing even if the specimens are strengthened by silicon in solid solution when tested under wet conditions. The maximum area fraction of intergranular fracture is closely related to the microstructural feature and ambient aqueous environment that caused the deterioration in vibration fracture resistance. In spite of the increasing silicon content, experimental evidence confirms the overall D-N curves can be generalized into three characteristic regions. Intergranular cracks initiated in the vicinity of the nodular graphite; the existence of nodular graphite acting as porosity should be considered as a dominant microstructural factor on the initiation of intergranular fractures. It should be noted that the intergranular cracks can be prevented, resulting in better vibration fracture resistance, when a specimen is covered with oil film. Based on experimental results, when the silicon content is increased, the vibration fracture resistance in general will be improved for all specimens whether they are tested in oil mist, air or aqueous environments. In particular, when the deflection amplitude is fixed, the vibration fracture resistance can be significantly raised for a high silicon sample (4.4Si).

(Received March 18, 2004; Accepted June 4, 2004)

Keywords: spheroidal graphite cast iron, damping capacity, resonant vibration, vibration life, aqueous ambient environment.

1. Introduction

Water-assisted deterioration of fatigue properties is likely to occur when spheroidal-graphite (SG) cast iron is exposed to an aqueous environment.1–3) Concerning the tensile properties of water-immersed SG cast irons, it has been reported that water-assisted embrittlement occurs only in the case of high strength cast irons such as ADI (austempered ductile iron). In our previous investigations on the vibrational fracture behavior of ferritic nodular graphite cast iron under aqueous conditions, vibration cracks initiating from the surface took place either from nodular graphite or sequentially along the ferritic boundary, also causing embrittlement, although microstructural refinement or damping capacity improved the vibration fracture resistance.4–6)

On the other hand, it has been recognized that increasing silicon content will improve thermal and weather-resistance of SG cast iron, the solid solution strengthening effect of Si atoms often were found to be the main controlling factor. As to the silicon affected microstructural evolution, however, why or how these metallurgical factors affected vibration fracture behavior has still not been clarified. Therefore, ferritic SG cast iron with different silicon content ranging from 2.1 mass% to 4.4 mass% were used to assess the effect of silicon as well as the environmental effect on the occurrence of intergranular embrittlement with regard to the deterioration of vibration fracture resistance.

2. Experimental Procedures

2.1 Material preparation

Ferritic spheroidal graphite cast irons were prepared by melting pig iron, silicon steel scrap and ferrosilicon in a high frequency induction furnace. Small amounts of Fe-75 mass% Si alloy and Fe-45 mass% Si-5 mass% Mg alloy were applied as inoculator and spheroidizer, respectively. Ferritizing heat treatment involved soaking at 1198 K for 3 hours prior to furnace cooling to 1023 K for another holding period of 5 hours before the final furnace cooling to room temperature. Table 1 presents the chemical compositions, where 2.1Si, 3.0Si and 4.4Si denote SG cast irons containing 2.0, 3.0 and 4.4 mass% Si, respectively. Figure 1, which shows the optical microstructures of the test materials, demonstrates that the hypoeutectic cell structure can be changed into a hypereutectic cell structure as the Si content is increased to 4.4 mass%. Table 2 presents the results of quantitative microstructural analysis of the specimens used.

### Table 1 Chemical Composition (mass%).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Mg</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1Si</td>
<td>3.37</td>
<td>2.10</td>
<td>0.062</td>
<td>0.044</td>
<td>0.008</td>
<td>0.043</td>
</tr>
<tr>
<td>3.0Si</td>
<td>3.39</td>
<td>3.01</td>
<td>0.040</td>
<td>0.053</td>
<td>0.010</td>
<td>0.035</td>
</tr>
<tr>
<td>4.4Si</td>
<td>3.32</td>
<td>4.43</td>
<td>0.059</td>
<td>0.042</td>
<td>0.007</td>
<td>0.044</td>
</tr>
</tbody>
</table>

2.2 Resonant vibration, tensile tests and damping capacity measurement

A simple cantilever beam vibration system, as shown schematically in Fig. 2(a), was used for the vibration experiment. The test specimen, rectangular with dimensions 15 mm × 100 mm × 2 mm, as shown in Fig. 2(b), was clamped on end to the vibration shaker. An acceleration sensor monitored the vibration force, and a deflection sensor measured the deflection amplitude at the end of the specimen. Vibration tests were conducted at their resonant frequencies and a fixed vibration force, with a detected acceleration of 1.7 g, where g denotes acceleration due to gravity (9.8 m/ s²). In addition, a constant deflection amplitude test (around 13.2 mm) was also performed to clarify the effect of silicon solid solution strengthening. The observed resonant frequency is obtained from the frequency leading to the largest deflection and can be examined by varying the vibration frequency continuously.

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Three ambient environmental conditions were applied; air, an aqueous and an oil environment were introduced by spraying water and oil mist (using a drop device) on the surface of the specimens during vibration testing, denoted as Air Aq and Oil, respectively. The mechanical properties of the samples were examined by tensile testing, with an initial strain rate of $6.67 \times 10^{-4} \text{s}^{-1}$, for verification.

Damping capacity is a material’s ability to measure the dissipated strain energy during a vibration test. The logarithmic-decrement value ($\delta$), derived from the deflection-amplitude decay of a specimen under a free vibration test, is one method to measure damping capacity. In this study, the specimen was placed under a resonant vibration condition with a fixed push force of 0.8 g, and then the shaker was stopped abruptly after 5 seconds of vibration. Thus, the decay of the deflection amplitude could be measured. The logarithmic-decrement value can be expressed as follows.

$$\delta = \frac{1}{n} \ln \left( \frac{A_i}{A_{i+n}} \right)$$

where $A_i$ and $A_{i+n}$ are the deflection amplitude of the $i$th and $(i+n)$th cycles after the load was removed, as shown in Fig. 2(c).

3. Results

3.1 Relation between silicon content and logarithmic-decrement value with respect to initial deflection amplitude

Based on our previous report, the vibration life ($L_v$) is affected primarily by crack propagation resistance and initial deflection amplitude ($D_I$). The former is directly proportional to its yield strength ($Y_S$), and this can be correlated with silicon content and recognized as a positive effect. It can be expressed as $L_v \propto Y_S$. But the latter is controlled by damping capacity, which is inversely proportional to deflection amplitude. Both factors are closely related to silicon content, therefore, we can consider the maximum deflection amplitude ($D_{max}$) as a factor of deflection effect. To clarify the relation between $Y_S$ and $\delta$ with respect to $D_{max}$, the data points are shown in Table 2.

3.2 Relation between silicon content, initial deflection amplitude, and logarithmic-decrement value with respect to vibration life

From Fig. 3, it is clear that the overall D-N curves are strongly ambient environmentally dependent and can be generalized into three characteristic regions. The feature can

![Image](https://example.com/image1.png)

Fig. 1 Typical optical microstructure of electrochemical etching samples: (a) 2.1Si (b) 3.0Si (c) 4.4Si.

![Image](https://example.com/image2.png)

Fig. 2 (a) Vibration apparatus (b) dimensions of test specimens (c) measurement of logarithmic decrement $\delta$. 

![Image](https://example.com/image3.png)
be described from the beginning as follows: Region I, with increasing deflection amplitude, Region II, with a constant deflection amplitude and Region III with descending deflection amplitude. Based on our previous investigations\textsuperscript{7,8)} and observed evidence as shown in Fig. 3(a), strain-hardening results in an ascending deflection in the early stage of the D-N curve (Region I). The deformation is mainly localized in the vicinity of graphite nodules due to the stress concentration effect under cyclic loading on the surface (Fig. 4(a)). Region II, the constant deflection amplitude, can be attributed to the strain hardening effect in competition with crack generation and linking, is shown in Fig. 4(b). Region III, with a descending trend, resulting from the actual vibration frequency deviating from the resonant frequency, can be attributed to the rapid inward propagation of major cracks.

Therefore, the quantitative data for vibration fracture resistance can reasonably be defined as the total number of vibration cycles within the interval of Region I and II.

On the other hand, the specimens tested in ambient oil mist conditions commonly exhibited a significant improvement in vibration fracture resistance compared to the specimens tested under identical air and ambient water mist environments. This implies that the ambient environmental factor plays an important role in the deterioration of fracture resistance, and this can be correlated with the silicon content of SG cast iron.

Figure 3 show the D-N curves of the specimens tested with various ambient environmental conditions for specimen 2.1Si vs. 3.0Si (similar $D_A$ value) and 2.1Si vs. 4.4Si (different $D_A$ value), respectively. The vibration life of 3.0Si specimens is better than 2.1Si specimens when the deflection amplitude is similar. But, as shown in Fig. 3(b), the high silicon specimen (4.4Si) cannot acquire further improvement due to higher deflection amplitude. In order to clarify the effect of the damping capacity factor caused by silicon solid solution strengthening, a fixed constant deflection amplitude test was
performed, as shown in Fig. 5. It is clear that the vibration life of 4.4Si specimens is profoundly longer than 2.1Si specimens. To gain a better understanding of the predominant factors of vibration life, it is reasonable to take $\text{YS}$ and $\delta/C14$ into consideration at the same time when tested in a fixed push force. Since $D_{\text{max}}$ is inversely proportional to the logarithmic-decrement value ($\delta$), it can be recognized as a negative effect, and can be expressed as $L_x \propto 1/(1/\delta)$. That is $L_x \propto \delta$. Combining both of the above-mentioned terms, finally we get the relation $L_x \propto \text{YS} \times \delta$. Figure 6 shows the vibration life increased at the beginning then decreased as $\text{YS} \times \delta$ increased. On the other hand, for constant deflection amplitude tests, since they have isolated the effect of damping capacity, it is reasonable to only take $\text{YS}$ into consideration. Figure 7 shows the vibration life increased as $\text{YS}$ increased. This implies that if we can eliminate the effect of damping capacity, then the solid solution strengthening of silicon will lead to better vibration fracture resistance for all specimens regardless of whether they are tested in an oil mist, air or aqueous environments.

Moreover, to quantitatively assess how the silicon solid solution strengthening affects the vibration life, since there is very little intergranular fracture evidence when tested in an oil environment, it is reasonable to define the degradation rates (D.R.), and calculate as follows:

$$\text{D.R.} = \frac{(1 - L_{\text{air}}, L_{\text{aq}}/L_{\text{oil}})}{100\%}$$

where $L_{\text{air}}$, $L_{\text{aq}}$ and $L_{\text{oil}}$ are the vibration lives of the specimens when tested in air, aqueous, and oil environments, respectively. For the specimens tested with fixed push force, Fig. 8 reveals that the ones tested in an aqueous environment are more serious intergranular fracture than those tested in the air, regardless of whether they were tested with fixed push force or constant deflection amplitude. Figure 8(a) shows that the degradation rates kept constant at the beginning then improved as $\text{YS} \times \delta$ increased for the specimens tested with fixed push force. Figure 8(b) shows the degradation rates generally can be improved as $\text{YS}$ increased for the specimens tested with constant deflection amplitude.

### 3.3 Effect of silicon content on the initiation of intergranular fracture under ambient aqueous environment

As mentioned above and marked by arrow A indicated in Fig. 4(a), it is clear that the cracks initiated in the vicinity of graphite nodules due to the stress concentration effect regardless of whether the specimens were strengthened by silicon solid solution when tested under wet conditions. Moreover, the typical fractography of each specimen, tested with fixed push force and constant deflection amplitude, was examined. Figures 9 and 10 show that many intergranular cracks can be observed in the vicinity of graphite nodules. However, the cracks initiated from the surface of the test
piece. It should be noted that the penetration area fraction of intergranular cracks was significantly intensified when the specimens were tested in an aqueous ambient environment regardless of whether they were tested with fixed push force or constant deflection amplitude.

4. Discussion

Concerning the vibrational application, it is clear that a significant deterioration of vibration fracture resistance commonly occurs in ferritic SG cast iron containing different silicon contents when tested in an aqueous environment.
Based on our earlier investigations, the resonant vibration samples, resembling the reverse bending fatigue test, suffer from alternate bending stress. It can be deduced that the alternate tensile-compressive stresses should be correlated to the existence of nodular graphite which actually plays an important role in causing deterioration in vibration fracture resistance.

As for the specimen tested in the simple cantilever beam vibrating system, Fig. 3 shows the deflection increases as the number of vibration cycles increases in the initial stage. According to our previous examination, this should be associated with increasing work hardening.

Furthermore, in order to verify the effect of silicon solid solution strengthening, a constant deflection amplitude test was also performed. From Fig. 5, it is clear that the vibration life increased as the silicon content increased. It is reasonable to suggest that if we eliminated the effect of damping capacity, then the solution strengthening of silicon will improve the vibration fracture resistance for all specimens regardless of whether they are tested in an oil mist, air or aqueous environment. On the other hand, if we cannot isolate the effect of damping capacity, it still can be decreased through mechanical design by placing a cushion or high damping alloy at certain places. Then the solution strengthening of silicon can also acquire the actual application.

From Fig. 8, it is clear that the degradation rate can be
improved if the silicon content is increased, especially when tested with constant deflection amplitude. It is reasonable to suggest that silicon strengthening is active even in the 4.4Si specimen ($D_2 = 16.1 \text{ mm}$) which suffered from much more induced push force than the 2.1Si specimens ($D_2 = 13.2 \text{ mm}$) when tested with a fixed push force. Moreover, from our previous results, the cracks tended to nucleate from and propagate toward the prior-eutectic cell-wall regions where a fair amount of MgO inclusions embedded in-between the nodular graphite.\(^5,9\) Figure 1, also reveals that the silicon content will affect the microstructural feature, and although the MgO inclusion clustered\(^{10,11} \text{ region}\) is an inevitable route for vibration crack propagation, little influence can be recognized in this study. However, more detailed investigation is needed.

As for the fracture behavior of ferritic SG cast irons during vibration testing, it must be pointed out that many surface cracks generally exhibit intergranular cracks which initiated from the ferrite rim of nodular graphite regardless of whether the specimens were tested in air or an aqueous environment. The intergranular fracture formed around the nodular graphite as a rim shape, however also occurred in the vicinity of nodular graphite as shown in Fig. 11. According to previous investigations,\(^{12} \text{ the effect}\) of the plastic strain rate and stress concentration at the tip of a notch will encourage a cleavage fracture to occur. Moreover, the SG cast iron exposed to an aqueous environment shows a larger area fraction of intergranular fracture. A generally accepted opinion is that the wet environmental effect on fatigue crack propagation should be considered closely related to hydrogen-induced cracking.\(^{13,14} \text{ For} \text{ SG cast iron, graphite nodules acting as porosity will lead to the stress concentration in the vicinity of graphite nodules during the elastic deformation stage.}^{15,16} \text{ Concerning the hydrogen resolving from water molecules contained in the air or aqueous environments, the effect of stress concentration around nodular graphite can be assumed to be responsible for the initiation of intergranular fracture.}^{17} \text{ In addition, the preferential absorption of atomic hydrogen along metalloid-segregated grain boundaries, and subsequent intergranular cracking were related to the deterioration of vibration fracture resistance.}

With regard to the vibration fracture process, cyclic loading with an alternate tensile-compressive stress will promote the diffusion of interstitial atoms.\(^{15} \text{ From previous investigations,}^{18,19} \text{ particularly for ferritic spheroidal graphite cast iron, Si showed negative segregation at the old austenite shells associated with spheroidal graphite. Furthermore, silicon solution in matrix will decrease the strength of the ferritic grain boundary.}^{19} \text{ The graphite nodules are believed to play an important role in promoting the hydrogen-induced fracture effect on grain boundary decohesion.}^{17} \text{ In the case of the degradation rate, a most likely possibility for the effect of silicon content of SG cast iron is through the governing fracture behavior.}

5. Conclusions

(1) The vibration fracture resistance of ferritic SG cast iron is reduced through contact with water molecules regardless of silicon solid solution strengthening. Samples, tested in an aqueous environment, exhibit a larger inward extended intergranular fracture area fraction than those tested in other conditions. In particular, the specimens tested in an oil mist environment exhibited very few intergranular fractures.

(2) It is reasonable to suggest that the reaction between water molecules, containing hydrogen, and ferritic SG cast iron is responsible for the deterioration of vibration fracture resistance. In particular, the cracking behavior of ferritic SG cast iron is probably correlated to the existence of nodular graphite, which is the stress concentration site during testing and results in the induced intergranular cracks in the earlier stages of vibration.

(3) The solid solution strengthening of silicon will decrease the damping capacity when tested with fixed gravity. Solid solution strengthening of silicon will enhance the vibration fracture resistance for the specimens with higher silicon content regardless of whether they were tested in an oil mist, air or aqueous environment, when the vibration test was conducted under constant initial deflection amplitude. The degradation rate can be improved, as $YS \times \delta$ and $YS$ increases for a fixed gravity push force and constant deflection amplitude, respectively.

Acknowledgments

The authors would like to thank the National Science Council of the R.O.C. (Taiwan) for financial support of this research under Contract No. NSC 92-2216-E-006-040-.

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