**Effect of Morphology and Si Content on SiO₂ Particle Erosion of Full Pearlitic Spheroidal Graphite Cast Iron**

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The effect of morphology and Si content on SiO₂ particle erosion wear of full pearlitic spheroidal graphite cast iron was studied. Experimental data shows the specimen possesses more area fraction of cementite for an identical silicon content, that contribute to improve erosion resistance. However, the specimen possesses larger interlamellar spacing (\( \lambda \)) at increased Si content, even if the matrix hardness is higher that still degrade the erosion resistance. The 2.1Si-air(930°C) specimens not only possess finer \( \lambda \) value and larger cementite fraction but also with better ductility, which could improve erosion resistance.

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**Keywords**: erosion wear, erosion, SiO₂ particle, spheroidal graphite cast iron

### 1. Introduction

The cast iron encounters particle erosion when it is used in many facilities such as farming tool, delivery pipe or automatic sand molding equipment in the casting industry. In order to increase the weather resistance of spheroidal graphite cast iron (S. G. cast iron), increased silicon content is easier to operate.¹ There are a few reports on erosion wear of the cast iron suggesting that by increasing the area fraction of the pearlite phase through heat treatment an improvement of erosion resistance may be achieved,²⁻⁴ however there were very few studies that examined the effect of silicon content on erosion resistance of full pearlitic S. G. cast irons regarding the investigation of SiO₂ particle erosion.⁴,⁵ A quantitative investigation is required to determine the relationship between erosion resistance, factors of the solid solution strengthening, and cementite lamellae change. This study investigated the effect of silicon content on pearlite matrix S. G. cast irons using Si content in the range of 2.1 mass%–4.2 mass% Si.

### 2. Experimental Procedure

The C content of each specimen was controlled at about 3.5 mass% and the Si content in the range of 2.12 mass%, 2.82 mass% and 4.16 mass%. Table 1 shows the chemical composition and coding of specimens. Specimens were melted in a 100 kg high frequency induction furnace and metallic Si was added to adjust the Si content in the specimens. The molten specimens were respectively cast into Y-shaped CO₂ sand molds after inoculation and spheroidization and air cooled to room temperature. In the current investigation, the pearlite specimens referred to as “\( x \times x \) Si”, were chosen as test materials. The pearlite spheroidal graphite cast iron were held at a constant temperature of 930°C for 1 hour, and forced air cool to room temperature. The 2.1 Si specimens partially were 870°C oil quenched or 870°C forced air cooled to room temperature.

A sandblasting type erosion tester was used, commercial grade No. 5 SiO₂ sand (295 µm mean diameter) was selected as the erodent. Schematically depicts the test rig and the SiO₂ particles as illustrated in the paper (JIM to published (Vol. 42, No. 12): “Effect of Si Content on SiO₂ Particle Erosion of Spheroidal Graphite Cast Iron”-No. MRA2001374). They were ejected by a compressed air flow of 3 kg cm⁻² (0.29 MPa) pressure, the flow capacity of the erosion particles was 1 g s⁻¹, impacting the test specimen with a specific impact angle chosen between 15° (oblique impact) and 90° (normal impact), those are study refer to the erosion direction as an arrow “ED” in the following figures. In addition, using single-shot high-speed photography, the average particle velocity was estimated as 66 m s⁻¹.

The weight loss caused by erosion was measured by a microbalance of 0.01 mg accuracy. Before weighing, the specimens were ultrasonically cleaned in acetone. The time period of each erosion test was 9 min, within which 500 g SiO₂ particles were ejected. Each erosion rate datum was the average of at least three test results.

The wear surface and subsurface morphologies were observed by taking secondary electron images in a scanning electron microscope (SEM). For subsurface observation, the worn specimens were carefully sectioned along the surface normal direction. The crack number of materials erosion subsurface were measured with impact angle 45° after test, that scanning length designated as 400 µm in near-subsurface.

In addition to the experiment reported above, a single-particle erosion test was also performed. The specimens in this test were pre-polished with No. 800-grit SiC paper to achieve an identical initial condition and slightly pre-etched in 3% nital. They were eroded by a total of about 1 g of SiO₂ particles. The surface locations of single-particle erosion were then examined with SEM. For quantitative analysis

### Table 1 Chemical composition of the spheroidal graphite cast irons, in mass% (designated as Si content).

<table>
<thead>
<tr>
<th></th>
<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>3.50</td>
<td>2.12</td>
<td>0.053</td>
<td>0.044</td>
<td>0.015</td>
<td>0.043</td>
<td>Bal.</td>
</tr>
<tr>
<td>2.8Si</td>
<td>3.45</td>
<td>2.82</td>
<td>0.061</td>
<td>0.032</td>
<td>0.019</td>
<td>0.041</td>
<td>Bal.</td>
</tr>
<tr>
<td>4.2Si</td>
<td>3.52</td>
<td>4.16</td>
<td>0.048</td>
<td>0.037</td>
<td>0.014</td>
<td>0.046</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

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Fig. 1 Optical microstructure of full pearlite specimens (a) 2.1Si-oil(870°C), (b) 2.1Si-air(870°C), (c) 2.1Si-air (930°C), (d) 2.8Si-air (930°C) (e) 4.2Si-air (930°C), (f) 2.1Si-air(870°C).

Table 2 Quantitative data of the microstructure vs. mechanical properties.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ng/mm²</th>
<th>dg (µm)</th>
<th>Ag(%)</th>
<th>λ (µm)</th>
<th>UTS</th>
<th>Y.S.</th>
<th>El(%)</th>
<th>HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1Si-oil (870°C)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.19</td>
<td>776</td>
<td>713</td>
<td>2.3</td>
<td>40</td>
</tr>
<tr>
<td>2.1Si-air (870°C)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.20</td>
<td>755</td>
<td>647</td>
<td>6.1</td>
<td>36</td>
</tr>
<tr>
<td>2.1Si-air (930°C)</td>
<td>26</td>
<td>50.4</td>
<td>13.1</td>
<td>0.25</td>
<td>879</td>
<td>629</td>
<td>6.3</td>
<td>23</td>
</tr>
<tr>
<td>2.8Si-air (930°C)</td>
<td>37</td>
<td>44.2</td>
<td>13.5</td>
<td>0.28</td>
<td>933</td>
<td>736</td>
<td>5.8</td>
<td>24</td>
</tr>
<tr>
<td>4.2Si-air(930°C)</td>
<td>68</td>
<td>28.5</td>
<td>14.8</td>
<td>0.35</td>
<td>967</td>
<td>752</td>
<td>5.4</td>
<td>27</td>
</tr>
</tbody>
</table>

(Ng/mm²: graphite nodule count, dg (µm): graphite nodule size, Ag (%): graphite area fraction, λ (µm): interlamellar spacing, UTS: ultimate tensile strength (MPa), Y. S.: yield strength (MPa), El(%): elongation, HRC: rockwell hardness.)

The microstructures were studied using both optical and scanning electron microscopy. The phase constitution of the specimens was checked by the X-ray diffraction (Cu Kα). The chemical characterisation of the samples was performed by the XPS. The X-ray photoelectron spectra were obtained with a magnesium anode (Mg Kα = 1253.6 eV).

3. Results

3.1 The microstructure and tensile properties of specimens

The optical microstructures of the five pearlite specimens are shown in Fig. 1, it can be seen that the 4.2Si-air(930°C) specimen possess larger lamellae than other specimens. A typical example of morphology is illustrated in Fig. 1(f) while the metallurgical data and mechanical properties are list in Table 2. The average spheroidal graphite nodule count and graphite area fraction tend to increase as increased Si content. On the contrary, the average grain size of nodule graphite tend to decrease as increased Si content.

Table 2 also reveals the tensile test results of each sample under a constant strain rate of $3.3 \times 10^{-3} \text{ s}^{-1}$ that can ensure the mechanical properties of the samples prior to the erosion...
test. Both tensile deformation resistance and hardness tend to increase as increased silicon content in the air quenched fully pearlite samples.

### 3.2 The effect of pearlite morphology on erosion rate

In order to investigate the effect of $\lambda$ value of pearlitic structure on erosion wear resistance, a comparison was made between the erosion rate data for the sample with an identical silicon content (Fig. 2). It was found that the erosion rate of 2.1Si-air(930°C) specimen is significantly lower than 2.1Si-oil(870°C) specimen and 2.1Si-air(870°C) specimen while the impact angle $\geq 30^\circ$. Figure 2 reveals that the impact angle of maximum erosion was approximately $30^\circ$ for the 930°C air cooled specimen, this angle slightly shifts to larger angle side (about $45^\circ$) for 870°C air cooled and oil quenched specimens.$^{5,6}$

The wear morphologies of 2.1Si-oil(870°C) and 2.1Si-air(870°C) are similar after erosion test as shown in Figs. 3(a) and (b) that mainly revealed cutting scratches while little evidence of lip formation was observed. Concave deformation and many erosion cracks were found on the near-surface (Fig. 3(b)). On the other hand, many erosion cracks also can be observed on wear surface after $90^\circ$ normal impact for 2.1Si-oil(870°C) specimen in Fig. 3(c). The erosion behavior should be considered that strongly influenced by brittle cracking. The erosion test of 2.1Si-air(930°C) specimen was compared with that under the same test condition, mainly grooves on the material were found and no marked erosion cracks existed.

Figure 4 reveals the effect of morphology changes on the number of cracks after $45^\circ$ impact. Note that an increased cooling rate will harden the matrix and increased the average cracks number. More evidence as indicated in Fig. 5, from the XPS peaks spectra of the 2.1Si-air(870°C) and 2.1Si-air(930°C) samples, reveals that carbon and iron concentration of the cementite lamellae is different. Whereas the pearlitic morphology changes reflects the cooling condition, the amount of cementite phase can also be determined by X-ray diffraction, as shown in Fig. 6. The 2.1Si-air(930°C) specimens not only possess finer $\lambda$ value but also larger cementite fraction than other specimen, therefore, it posses better wear resistance.

### 3.3 The effect of silicon content on erosion rate

Figure 7 shows the effect of Si content on the erosion rate of full pearlitic spheroidal graphite cast iron. It should be noted that the 2.1Si-air(930°C) specimen is more erosion resistant than the other specimens (2.8Si-air(930°C) and 4.2Si-air(930°C)) under all different impact angles, Fig. 7 also reveals that the impact angle of maximum erosion is commonly around $\sim 30^\circ$.

It should be noted that while morphologies of 2.1Si-air(930°C) and 2.8Si-air(930°C) possesses similar characteristics, the wear morphologies of 2.1Si-air(930°C) as shown in Figs. 8(a) and (b) were found to have more lip formation (shown by the arrow) on the wear surface of 2.1Si-air(930°C) under $30^\circ$ oblique impact (Fig. 8(a)). Furthermore, when compared to the wear surface feature of 2.1Si-air(930°C) under $30^\circ$ impact, it was found that the an increased area fraction of lip formation is evident when comparing with 4.2Si-air(930°C). The typical wear surface of 4.2Si-air(930°C) under $90^\circ$ normal impacted in Fig. 8(c) that also shows the deformation of graphite nodule, and many cracks were found in the region shown by the arrow while cracks were not easily found in 2.1Si-air(930°C) specimen.

Figure 9 reveals the specimen with higher silicon content...
are mainly also worn by brittle fracture when eroded under 45° impact. However, the severity of brittle erosion cracking tends to increase as increased silicon content with air cooled specimen while the impact angle >45°. Figure 10(a) shows the XPS spectra of the 4.2Si-air(930°C) sample. Compare to Fig. 5, the carbon concentration tent to increase as the Si content increased, therefore 4.2Si-air(930°C) specimen has higher hardness (see Table 2). The amount of cementite phase can be determined by X-ray diffraction, as shown in Fig. 10(b), the 2.1Si-air(930°C) specimens not only possess finer λ value but also larger cementite fraction than the 4.2Si-air(930°C) sample.

4. Discussion

Figure 11 shows the surface morphologies after single-particle erosion test, that is only impacted about 1 g of SiO₂ particles to examine the wear surface. A typical example of 2.1Si-air(930°C) after 30° single-particle erosion is shown in Fig. 11(a). The lip formation on the wear surface are larger when compared to those of 2.8Si-air(930°C) (Fig. 11(b)) and 4.2Si-air(930°C) (Fig. 11(c)). Here, 4.2Si-air(930°C) (Fig. 11(c)) was also used as a typical example to describe the characteristics of the wear surface after 40° impact, little lip formation can be observed in the eroded grooves, and the number of lips are markedly fewer than 2.1Si-air(930°C) (Fig. 11(a)), that is denoting a marked difference between 4.2Si-
Fig. 8 Wear surface morphologies vs. subsurface observation: (a) 2.1Si-air(930°C)-30° impact, (b) 2.1Si-air(930°C)-30° impact, (c) 4.2Si-air(930°C)-90° impact. (ED: erosion direction).

Fig. 9 The hardness of the specimen with different Si content vs. average crack number of the specimen that has eroded under 45° impact.

Fig. 10 (a) XPS spectra of 4.2Si-air (930°C) specimen, (b) X-ray diffraction.

air(930°C) and 2.1Si-air(930°C). Lip formation of 2.1Si-air(930°C) can be considered as one of the evidence for better erosion wear resistance (Fig. 7).

On the other hand, it may be observed that the presence of a large number of pits on the wear surface after single-particle erosion under 90° impact in all specimens is a common and not irregular phenomenon. Both of the 2.1Si-air(930°C) and 2.8Si-air(930°C) did not reveal an overtly brittle appearance, especially 2.1Si-air(930°C) specimen where almost no erosion cracks were visible. Typical examples of 4.2Si-air(930°C) after 90° single-particle erosion were shown in Fig. 11(d), the phenomena of brittle cracking and material
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Fig. 11 Single-particle wear surface morphologies: (a) 2.1Si-air (930°C)-30° impact, (b) 2.8Si-air (930°C)-30° impact, (c) 4.2Si-air (930°C)-40° impact, (d) 4.2Si-air (930°C)-90° impact. (ED: erosion direction).

breaking are more frequently observed, that corresponding to lower erosion wear resistance. It can be seen that there is significant difference on Fig. 8(c), more cracks were comparatively larger on the 4.2Si-air(930°C) specimen. The specimen possesses larger interlamellar spacing (λ) as the result of an increased Si content, though the matrix hardness is higher that still debase the erosion resistance.

The improvement of matrix toughness,⁵,⁷ which will reflect the erosion wear resistance is easily recorded through a hardness test. It could be useful for the quantitative understanding and prediction of erosion wear resistance of pearlitic S. G. cast iron, if the relationship can be quantitatively correlated with the hardness data. The relationship between erosion rate under 45° impact and the matrix hardness as shown in Fig. 12(a), erosion resistance tends to increase as the hardness decreases even in specimens possessing different Si contents as a result of the variation of morphology. It should be noted that when the materials eroded under a ductile behavior, owing to the 2.1Si-air(930°C) specimen not only possess finer λ vaule and larger cementite fraction, but also with better ductility (Table 2), there are important factors for the observed improvement of erosion resistance. Schematic representation of morphology changes corresponding to heat treatment condition of pearlitic microstructure virtually can be described by Figs. 12(b)–(d).

Compare to the 2.1Si-air(930°C) specimen under a same erosion test condition, even if the 2.1Si-oil(870°C) and 2.1Si-air(870°C) posses finer interlamellar spacing (λ), and the matrix hardness of 2.1Si-oil(870°C) and 2.1Si-air(870°C) are higher (see Table 2), that corresponding to a lower erosion wear resistance than 2.1Si-air(930°C) specimen, especially under larger angle impact. The effect of silicon content on the erosion characteristic as shown in Fig. 12(a), the resistance to plastic metal flow can be considered that governs the material removal rate. Figure 8(a) indicate a larger number of lips formed in the pearlitic S. G. cast iron (2.1Si-air(930°C)), and the number of lips decreased as the Si content increased (Fig. 11(c)). On the other hand, the wear surfaces after large-angle erosion indicate more cracks existed in 4.2Si-air(930°C) (as indicated in Figs. 8(c) and 11(d)) while these cracks were not evident on the wear surfaces of 2.1Si-air(930°C) and 2.8Si-air(930°C). In comparing 4.2Si-air(930°C) and 2.1Si-air(930°C), it was observed that more erosion cracks occurred in 4.2Si-air(930°C) under normal impact (as in Fig. 11(d)),
Fig. 12 (a) The hardness of the specimen vs. erosion rate of the specimen that has eroded under 45° impact. Schematic representation of morphology changes of pearlite: (b) 2.1Si-air(870°C), (c) 2.1Si-air(930°C), (d) 4.2Si-air(930°C). ER: Erosion rate (g g$^{-1}$).

which also can be correlated with the deterioration of erosion resistance.

5. Conclusions

(1) The erosion resistance of the sample with more area fraction and finer interspacing of lamellae cementite phase will be improved, however 930°C-air cooled specimen posses better erosion wear resistance that resulted from better toughness than other 2.1Si specimen.

(2) Decreasing silicon content of full pearlitic spheroidal graphite cast iron lead to reduce the interlamellar spacing ($\lambda$), and increased the area fraction of cementite phase that contribute to improve erosion resistance.

(3) Increased silicon content of full pearlitic spheroidal graphite cast iron lead to raise up the matrix hardness and erosion crack numbers, that can be correlated with the deterioration of erosion resistance.

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