Effect of Si Content on SiO₂ Particle Erosion of Spherical Graphite Cast Iron

Fei-Yi Hung *, Li-Hui Chen and Truan-Sheng Lui

Department of Materials Science and Engineering, National Cheng-Kung University, Tainan 701, Taiwan, R.O. China

The effect of Si content on SiO₂ particle erosion wear of spheroidal graphite cast iron was studied. The present erosion tests were performed to provide an understanding of erosion wear resistance of spheroidal graphite (S.G.) cast iron, which is required for improving weather resistance by raising silicon content. An increased Si content promoted a decrease in the amount of the pearlite phase, thus decreasing the erosion resistance of as cast S.G. cast iron. An increased Si content hardens the ferrite phase, thereby improving the erosion resistance. The erosion rate of full pearlitic S.G. cast iron tends to increase as the Si content increases. The wear surface and subsurface morphologies which reflect the wear process, an increase in erosion wear rate could be caused either by changes in the microstructure or by the variation of silicon content which almost did not alter the impact angle of maximum erosion rate of S.G. cast iron. It should be noted that the dominant factor on the erosion resistance was the presence of the pearlite structure in the materials despite the fact that the specimens may have different silicon contents.

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

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 casting industry. Increased silicon content increases the weather resistance of S.G. cast iron. ¹ There are a few reports on erosion wear of the cast iron which indicated that it would be possible to improve erosion resistance by increasing the area fraction of the pearlite phase through heat treatment.²⁻⁴ Fewer studies, however, explored the effect of silicon content on erosion resistance of S.G. cast irons regarding the investigation of SiO₂ particle erosion.⁵,⁶ This study is a quantitative investigation to determine the relationship between erosion resistance, the factors of solid solution strengthening, microstructural changes and investigates the effect of silicon content on the differences in as-cast, ferrite matrix, and 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 wt% 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. In the current investigation, the as-cast specimens which will referred to as “A-“ hereafter, the ferrite specimens referred to as “F-“ and the pearlite specimens referred to as “P-“, were chosen as test materials.

A sandblasting type erosion tester was used, Fig. 1(a) schematically depicts the test rig. Commercial grade No. 5 SiO₂ sand (295 µm mean diameter) was selected as the erodent. As illustrated in Fig. 1(b), the SiO₂ particles are found to be of irregular of angular shape. The particles 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

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

<table>
<thead>
<tr>
<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>0.035</td>
<td>0.044</td>
<td>0.015</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>
</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>
</tr>
</tbody>
</table>

*Graduate Student, Materials Science and Engineering, National Cheng-Kung University. E-mail: hfy0716@kimo.com.tw or x7408020@email.ncku.edu.tw

Fig. 1 (a) Schematic drawing of the erosion test rig (A: compressed air flow, B: erodent supplier, C: erodent nozzle, D: specimen, E: specimen holder, P: pressure gauge, θ: impact angle); (b) SEM photo of the SiO₂ particles.
the test specimen with a specific impact angle (θ in Fig. 1(a)) chosen between 15° (oblique impact) and 90° (normal impact), the erosion direction is referred to as arrow “ED” in the following figures. In addition, using single-shot high-speed photography, the average particle velocity was estimated as 66 m s⁻¹.⁵,⁶

The mass loss caused by erosion was measured by a microbalance of 0.01 mg accuracy. The time period of each erosion test was 9 min, within which 500 g SiO₂ particles were ejected.

In addition to the experiment outlined above, a single-particle erosion test was also performed.⁵,⁶ The specimens in this test were pre-polished with No. 800 sand paper to achieve the identical initial condition and slightly pre-etched in 3% nital. An image analyzer was used for the quantitative analysis of microstructure.

Table 2 Quantitative data of the microstructure of each specimen.

<table>
<thead>
<tr>
<th>specimen</th>
<th>2.1Si</th>
<th>2.8Si</th>
<th>4.2Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite nodule count (No/mm³)</td>
<td>26</td>
<td>37</td>
<td>68</td>
</tr>
<tr>
<td>Graphite nodule size (µm)</td>
<td>50.4</td>
<td>44.2</td>
<td>28.5</td>
</tr>
<tr>
<td>Graphite area fraction</td>
<td>13.1</td>
<td>13.5</td>
<td>14.8</td>
</tr>
<tr>
<td>Grain size of ferrite (µm)</td>
<td>57</td>
<td>43</td>
<td>33</td>
</tr>
<tr>
<td>Area fraction of pearlite (as cast)</td>
<td>63.4</td>
<td>18.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 3 Optical microstructure of full annealed specimens (a) F-2.1Si, (b) F-2.8Si, (c) F-4.2Si.
Fig. 4 Optical microstructure of full pearlite specimens (a) P-2.1Si, (b) P-2.8Si, (c) P-4.2Si.

Fig. 5 Effect of silicon content and erosion impact angle on erosion rate of as-cast graphite cast iron.

Fig. 6 Wear surface morphologies: (a) A-2.8Si-30° impact, (b) A-2.8Si-90° impact. (ED: erosion direction)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>A-2.1Si</th>
<th>A-2.8Si</th>
<th>A-4.2Si</th>
<th>F-2.1Si</th>
<th>F-2.8Si</th>
<th>F-4.2Si</th>
<th>P-2.1Si</th>
<th>P-2.8Si</th>
<th>P-4.2Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS (MPa)</td>
<td>564</td>
<td>543</td>
<td>621</td>
<td>432</td>
<td>485</td>
<td>627</td>
<td>879</td>
<td>933</td>
<td>967</td>
</tr>
<tr>
<td>Y.S. (MPa)</td>
<td>403</td>
<td>423</td>
<td>518</td>
<td>296</td>
<td>345</td>
<td>526</td>
<td>629</td>
<td>736</td>
<td>752</td>
</tr>
<tr>
<td>EI (%)</td>
<td>12.4</td>
<td>15.7</td>
<td>16.3</td>
<td>22.1</td>
<td>20.4</td>
<td>15.7</td>
<td>6.3</td>
<td>5.8</td>
<td>5.4</td>
</tr>
<tr>
<td>HRb</td>
<td>83</td>
<td>80</td>
<td>94</td>
<td>61</td>
<td>79</td>
<td>92</td>
<td>HRc : 23</td>
<td>HRc : 24</td>
<td>HRc : 27</td>
</tr>
</tbody>
</table>
3. Results

3.1 Effect of Si content on microstructure and tensile properties of erosion test specimens

The optical microstructures of the three cast specimens are shown in Fig. 2 and the metallurgical data listed in Table 2. From the information listed on the table it is clear that A–2.1Si specimen possesses a higher area fraction of pearlite than the A–2.8Si specimen, it can also be seen that the as-cast A–4.2 Si specimen, as shown in Fig. 2(c), is almost full with ferrite matrix. Heat treated full ferrite and full pearlite samples are shown in Fig. 3 and Fig. 4, respectively.

Table 3 shows the tensile test results of each sample under a constant strain rate of $3.3 \times 10^{-3}$ s$^{-1}$ that ensure the mechanical properties of the samples prior to the erosion test.

3.2 Effect of Si content on erosion rate of as-cast specimens

Figure 5 plots the effect of Si content on the erosion rate under an average particle velocity of 66 m s$^{-1}$. From a comparison between the as-cast specimens it seems increases in the erosion rate is directly proportional to increases in the Si content. Figure 5 also reveals that the impact angle of maximum erosion rate is commonly at $\sim 30^\circ$ for the three materials. As compared to A–4.2Si specimen under the same erosion test condition, A–2.1Si specimen proved to be more erosion resistant, especially under lower angle impacts.

A typical example of wear surface morphologies as those illustrated in Figs. 6(a) and (b) reveal ductile wear mechanisms such as grooving, lip formation and cratering. Around these location, the A–2.1Si specimen shows less cave-in evidence than the A–4.2Si and A–2.8Si specimens.

Figures 7(a) and (b) illustrate the subsurface features of as-cast specimens eroded under 30$^\circ$ and 90$^\circ$ impact. As depicted, flow of the materials along erosion direction can be distinguished from the beading of near-surface. In addition to the matrix deformation, it was found that nodule graphite also significantly deformed after impact. The wear subsurface also shown in Fig. 7(b) under 90$^\circ$ normal impact indicated that there is marked evidence of plastic deformation of graphite nodules and its surrounding ferrite phase (F). Compare to A–2.8Si specimen with an identical erosion test condition, A–2.1Si specimen seems to be more erosion resistant.

Figures 8(a) and (b) illustrate the subsurface feature of the A–4.2Si specimen eroded under 30$^\circ$ and 90$^\circ$ impact, Fig. 8(a) indicates a scratched grooves and cave-in evidence around graphite nodule. Figure 8(b) indicate that the deformation manner of graphite nodule (A–4.2Si) is larger than A–2.8Si as shown in Fig. 7(b). In this ductile erosion process, it was found that the pearlite phase not only reinforce the matrix but also suppresses the wear loss by cave-in breaking.

Fig. 7 Subsurface observation: (a) A–2.1Si–30$^\circ$ impact, (b) A–2.8Si–90$^\circ$ impact. (ED: erosion direction)

Fig. 8 Subsurface features of A–4.2Si specimen: (a) 30$^\circ$ impact, (b) 90$^\circ$ impact. (ED: erosion direction)
3.3 Effect of Si content on the erosion rate of ferritic spheroidal graphite cast iron

Figure 9 shows the effect of Si content on the erosion rate and suggests that the specimen with higher silicon content possesses higher erosion resistance. Figure 9 also reveals that the impact angle of maximum erosion rate is commonly at \( \sim 30^\circ \) for the full annealed ferritic spheroidal graphite cast iron even with different Si contents. A typical example of wear surface morphologies as shown in Fig. 10(a) reveals cutting scratches (grooving) but little evidence of lip formations were observed under oblique impact. The specimens with a higher silicon content are mainly also worn by brittle fracture when eroded under large-angle impact (Fig. 10(b)).

Figure 11(a) illustrates a typical subsurface feature of ferritic S.G. cast iron eroded under 30° impact. As depicted, some cracks can be observed in the ferrite matrix as the materials flow along the direction of erosion. Figure 11(b) shows the 90° normal impact wear subsurface of F-2.8Si where the graphite nodule near the subsurface was markedly deformed and many cracks were also found as shown by the arrow.

3.4 Effect of Si content on the erosion of pearlitic S.G. cast iron

Figure 12 shows the effect of Si content on the erosion rate of full pearlitic spheroidal graphite cast iron. It should be noted that the P-2.1Si specimen is more erosion resistant than the other P-2.8Si and P-4.2Si specimens under different impact angles. Figure 12 also reveals that the impact angle of maximum erosion is \( \sim 30^\circ \) for the P-2.1Si and P-2.8 Si, this angle slightly shifts to large angle side (about \( \sim 40^\circ \)) for P-4.2Si specimen.

The wear surfaces of P-2.1Si and P-2.8Si are similar as can be seen in Figs. 13(a) and (b). The lip formation (shown by the arrow) can be recognized under 30° oblique impact (Fig. 13(a)). A large number of erosion cave-in pits were found...
under 90° normal impact in Fig. 13(b). Figure 13(c) shows where the wear surface feature of P–4.2Si was under 30° impact the occurrence of lip formations significantly less than P–2.1Si as may evident in Fig. 13(a). Figure 13(d) shows the wear surface of P–4.2Si under 90° normal impact. Many cracks were found in the region shown by the arrow while cracks were much less distinct in P–2.1Si (Fig. 13(b)).

Figure 14(a) shows the wear subsurface of P–2.1Si under a 30° oblique impact. Grooves on the material were found and no marked erosion cracks existed on the boundary between subsurface. Figure 14(b) shows the wear subsurface of P–2.1Si under 90° normal impact where concave deformations were found on the wear surface. Figure 14(c) shows the wear subsurface of P–4.1Si under a 40° oblique impact, the deformation of graphite nodule (shown by arrow g) and bulge appearances were observed in the pearlite matrix (shown by arrow pit). Figure 14(d) shows the 90° normal impact wear subsurface of P–4.1Si where concave appearances after erosion (shown by arrow pit) can be easily seen.

4. Discussion

The results of the experiments outlined above suggests that the silicon content and the area fraction of pearlite could both alter the erosion behavior on S.G. cast iron. Whereas the area fraction of pearlite was increased to promote the erosion resistance, an increased Si content promoted a decrease in the pearlite phase, and debased the erosion resistance of as-cast S.G. cast iron. A schematic diagram as shown in Fig. 15 helps to describe a typical erosion process, and that the pearlite lamella structure is more erosion resistant than other phases. To investigate the wear behavior, Fig. 16 shows the surface morphologies after single-particle erosion test, where 1 g of SiO₂ particles was used in the impacted to examine the wear

![Graph showing effect of silicon content and erosion impact angle on erosion rate of full pearlitic spheroidal graphite cast iron.](image)

Fig. 12  Effect of silicon content and erosion impact angle on erosion rate of full pearlitic spheroidal graphite cast iron.

![Wear surface morphologies: (a) P–2.1Si–30° impact, (b) P–2.1Si–90° impact, (c) P–4.2Si–30° impact, (d) P–4.2Si–90° impact. (ED: erosion direction).](image)

Fig. 13  Wear surface morphologies: (a) P–2.1Si–30° impact, (b) P–2.1Si–90° impact, (c) P–4.2Si–30° impact, (d) P–4.2Si–90° impact. (ED: erosion direction)
the reason for the better erosion wear resistance (Fig. 12).

Figure 16(d) shows the single particle erosion wear surface after a 40° impact of P-4.2Si, the lips were markedly fewer than P-2.1Si (Fig. 16(c)), denoting a marked difference between P-4.2Si and P-2.1Si. On the other hand, many pits commonly can be found on the wear surface after single-particle erosion under 90° impact in all specimens. The pits on F-2.1Si are larger in size, as shown by the arrow in Fig. 16(e), that corresponding to lower erosion wear resistance.

A general comparison on the effect of silicon content on erosion wear resistance of S.G. cast iron is shown in Fig. 17 that shows the P-2.1 possesses the best wear resistance, and also demonstrates the microstructure change of pearlite phase with different silicon content is a dominant cause for the observed decrease of erosion wear resistance.

Examination of the ductile full annealed specimens that indicated more erosion cracks than the as-cast specimens with partially pearlite phase under an identical large-angle impact. It can be seen that there is significant difference between Fig. 7(b) and Fig. 11(b), as the number of cracks were lessened considerable due to the specimen’s possession of partially pearlite phase in A-2.8Si, that accounts for better erosion resistance than full annealed specimens.

It is easier to find erosion cracks and metal flow in the vicinity of surface under oblique impact. A comparison made in Figs. 8 and 11(b) confirms that the erosion cracks can be suppressed by increasing silicon content of ferritic S.G. cast
iron. Figure 16(e) also shows the pit that indicated that the deformation resistance of F-2.1Si is lower than accounted for the specimens with lower erosion wear resistance.

The effect of silicon content on the erosion characteristic should also be examined. When eroded under oblique impact, the resistance to plastic metal flow can be considered to govern the material removal rate. Figure 13(a) indicates that a larger number of lips formed in the pearlitic S.G. cast iron (P-2.1Si), the number of lips decreased as the Si content increased (as indicated in Fig. 13(c)). Similar results were also found on the wear subsurface of P-4.2Si (lips formation were easily found in P-2.1Si as shown in Fig. 14(a)).

On the other hand, the wear surfaces after large-angle erosion indicate that more cracks existed in P-4.2Si (as in Fig. 13(d)) while these cracks were not evident on the wear surfaces of P-2.1Si and P-2.8Si. Comparing P-4.2Si and P-2.1Si, comparatively more erosion cracks occurred in P-4.2Si under normal impact (as in Fig. 13(d)), which can be correlated with the deterioration of erosion resistance. The impact of maximum erosion rate of the pearlite specimen with higher silicon content shift to 40° (Fig. 12), which implies the effect of silicon content on pearlite structure, given such results, it is clear that further examinations would be called for in this area.

5. Conclusions

(1) In the as-cast spheroidal graphite cast iron, increas-
ing silicon content leads to reducing area fraction of pearlite phase that causes the deterioration of erosion wear resistance. Partially existent pearlite phase promoted the lip formation under oblique impact, and therefore larger area fraction of pearlite phase leads to better erosion resistance.

(2) In the full annealed ferritic spheroidal graphite cast iron, the effect of solid solution strengthening tends to increase as the Si content increases. Such increases in the Si content hardens the matrix and debase the material removal rate, thus enhanced better erosion wear resistance.

(3) Increasing silicon content in pearlitic S.G. cast iron (P–4.2Si) will still result in the S.G. cast iron possessing a superior erosion wear resistance than full annealed ferritic S.G. cast iron (F–4.2Si). The large existence of pearlite phase was the dominant factor for improving the erosion wear resistance.

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