The Microstructural Effects on Tensile Properties and Erosion Wear Resistance in Upper Bainitic ADI Related to Variation in Silicon Content

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The Effects of austempering duration and silicon content on the particle erosion wear resistance of high strength upper bainitic ADI were characterized. The results showed that the amount of retained austenite dominantly affects tensile strength and variation of wear resistance. For a sample with higher silicon content, the austempering duration should be prolonged to ensure complete bainitic transformation. In addition, a tiny increase in carbide formation can certainly play an important role in debasing tensile strength and erosion wear resistance. This results in an alternation in erosion behavior. However, hardness cannot be correlated to wear resistance. Erosion-induced phase transformation of retained austenite phase will eventually produce \( \varepsilon \)-carbide, which thus promotes the erosion wear rate.

(Received February 21, 2002; Accepted May 27, 2002)

Keywords: austempered ductile iron (ADI); retained austenite; carbide; particle erosion; ductile erosive wear; brittle cracking; upper bainitic

1. Introduction

The erosion wear resistance of cast iron can be improved through austempering heat treatment.\(^1\)\(^-\)\(^4\) Austempered ductile iron (ADI) encounters particle erosion when it is used to perform functions in equipment including farming tools, blast machines, and automatic sand molding equipment.\(^1\)\(^-\)\(^4\) Though many previous research efforts have investigated the effect of silicon content and austempering duration on the micro-structural changes of ADI, and confirmed that it can be correlated to the mechanical properties of ADI,\(^2\)\(^-\)\(^5\) few studies have focused on examining the effect of Si content (up to about 4.0 mass%) on erosion wear resistance.

In general, for an increase in the silicon content of ADI at a given temperature and the austempering duration will increase the amount of retained austenite and suppresses carbide formation. Austempering conditions must be chosen very precisely, otherwise a transformation will occur in the retained austenite phase. In this investigation, the quantitative micro-structural data concentrates on the variation of retained austenite acquired to determine the relationship between micro-structural features and erosion resistance of ADI.

2. Experimental Procedure

The carbon content of each specimen was controlled at approximately 3.5 mass%, and the Si content in a range including the values 2.12 mass%, 2.82 mass% and 4.16 mass%. Table 1 shows the chemical composition, and the coding of specimens. Each sample was melted in a 100kg high frequency induction furnace. Metallic Si was then added to adjust the Si content of each specimen. The melts were cast into a Y-shaped CO2 sand mold after inoculation and spheroidization. The specimens were air cooled to room temperature. In the current investigation, all samples can be verified as a typ-

<p>| Table 1 Chemical composition of the spheroidal graphite cast irons, in mass% (designated as Si content) |
|-----------------|-----|-----|------|-----|-----|-----|---|</p>
<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>3.50</td>
<td>2.12</td>
<td>0.053</td>
<td>0.044</td>
<td>0.015</td>
<td>0.043</td>
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<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>
</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>
</tr>
</tbody>
</table>

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, \( \theta \): impact angle) (b) SEM photo of the \( \text{Al}_2\text{O}_3 \) particles.
### Table 2: Quantitative data of the microstructure vs. mechanical properties.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>2.1Si–0.5h</th>
<th>2.8Si–0.5h</th>
<th>4.2Si–0.5h</th>
<th>4.2Si–1h</th>
<th>4.2Si–2h</th>
<th>4.2Si–3h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_g$/mm²</td>
<td>26</td>
<td>37</td>
<td>68</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>$d_g$ (µm)</td>
<td>50.4</td>
<td>44.2</td>
<td>28.5</td>
<td>28.5</td>
<td>28.5</td>
<td>28.5</td>
</tr>
<tr>
<td>$A_g$ (%)</td>
<td>13.1</td>
<td>13.5</td>
<td>14.8</td>
<td>14.8</td>
<td>14.8</td>
<td>14.8</td>
</tr>
<tr>
<td>R.A. (%)</td>
<td>18.1</td>
<td>29.4</td>
<td>34.1</td>
<td>28.4</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>R.A. (%) AE</td>
<td>4.3</td>
<td>13</td>
<td>15.2</td>
<td>12.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>1053</td>
<td>1104</td>
<td>944</td>
<td>1177</td>
<td>1073</td>
<td>1043</td>
</tr>
<tr>
<td>YS (MPa)</td>
<td>761</td>
<td>790</td>
<td>712</td>
<td>884</td>
<td>685</td>
<td>667</td>
</tr>
<tr>
<td>El (%)</td>
<td>16.8</td>
<td>14.7</td>
<td>6.7</td>
<td>11.9</td>
<td>11.4</td>
<td>10.9</td>
</tr>
<tr>
<td>HRC</td>
<td>22</td>
<td>26</td>
<td>27</td>
<td>32</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>TFT (J)</td>
<td>51.7</td>
<td>52.3</td>
<td>23.8</td>
<td>46.2</td>
<td>37.4</td>
<td>34.8</td>
</tr>
</tbody>
</table>

(N$_g$/mm²: graphite nodule count, $d_g$ (µm): graphite nodule size, $A_g$ (%): graphite area fraction, R.A. (%) B.E.: the content of retained austenite before erosion, R.A. (%) A.E.: the content of retained austenite after erosion, UTS: ultimate tensile strength (MPa), Y.S.: yield strength (MPa), El (%): elongation, HRC: rockwell hardness, TFT: tensile-fracture toughness)

Fig. 2 Optical microstructure of specimens: (a) 2.1Si–0.5h, (b) 2.8Si–0.5h, (c) 4.2Si–0.5h, (d) 4.2Si–1h, (e) 4.2Si–2h, (f) 4.2Si–3h.
Fig. 3  (a) The tensile-fracture toughness of the specimen (4.2 mass% Si-ADI) with different austempering duration (h) vs. tensile strength and retained austenite (%), (b) The tensile-fracture toughness of the specimen with different silicon content (mass%) vs. tensile strength.

Fig. 4  X-ray diffraction patterns as austempering before erosion.

Fig. 5  Erosion rate data of the specimen: (a) 4.2Si–ADI, (b) 2.1Si–0.5h, 2.8Si–0.5h and 4.2Si–1h.
ically ‘upper bainitic matrix’, which will be referred by the coding names shown in Table 2.

The ADI samples were held at a constant temperature of 930°C (1203 K) for 1 h. Then, the samples were rapidly soaked in a salt bath under a constant austempering temperature of 420°C (693 K). The four different austempering durations of the ADI samples were 0.5 h, 1 h, 2 h, and 3 h, finally the ADI samples were water cooled to room temperature. The code corresponding to each sample is listed in Table 2. To examine the effect of silicon content, an austempering duration of 0.5 h was selected and applied to 2.1Si and 2.8Si specimens.

A sandblasting type erosion tester was used. Figure 1(a) shows a schematic of the test rig. Commercial grade No. 5 Al₂O₃ sand (275 µm mean diameter) was selected as the erodent. As illustrated in Fig. 1(b), Al₂O₃ particles possess both angular and irregular shapes. They were ejected by a compressed air flow of 3 kg·cm⁻² pressure (0.29 MPa), the flow capacity of the erosion particles was 1 g s⁻¹, impacting the test specimen with a specific impact angle (which is θ in Fig. 1(a)) in a range between 15° (oblique impact) and 90° (normal impact). This was referred to as the erosion direction, shown as an arrow “ED” in the following figures. In addition, using single-shot high-speed photography, the average particle velocity was estimated as 73 m s⁻¹.

The mass loss caused during the erosion test was measured using a microbalance of 0.01 mg accuracy. The time period of each erosion test was 9 min, within which 500 g Al₂O₃ particles were ejected, the erosion rate curves to be summarized afterwards.

For understanding, 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 mass of about 1 g solid particles. The surface features of the single-particle erosion were examined with SEM. An image analyzer was used for quantitative analysis of mor-

Fig. 6 Wear surface morphologies: (a) 4.2Si–1h–30° impact, (b) 4.2Si–3h–30° impact (ED: erosion direction).

Fig. 7 Wear subsurface observation: (a) 2.8Si–0.5h–30° impact, (b) 4.2Si–1h–30° impact, (c) 4.2Si–3h–30° impact (ED: erosion direction).
Fig. 8 Wear surface morphologies vs. subsurface observation: (a) 2.8Si–0.5h–90° impact, (b) 4.2Si–1h–90° impact, (c) 4.2Si–2h–60° impact (d) 4.2Si–3h–90° impact (ED: erosion direction).

Fig. 9 Transmission electron micrograph and SADP from 4.2Si–3h specimen: (a) BF image, (b) DF image.
The phase constitution of ADI was checked by X-ray diffraction (Cu Kα) and TEM. Before or after erosion, the amount of retained austenite can also be determined by X-ray diffraction. The erosion rate datum was the average of the results from at least three tests performed during this experiment.

3. Results

3.1 Microstructural features and tensile properties before erosion test

The optical microstructures and quantitative data of all specimens used in this study are as shown in Fig. 2 and Table 2. Increasing silicon content not only increased the graphite nodule counts but also increased the fractional volume of graphite. Figure 2 also showed the micro-structural changes on the austempered matrix of increasing silicon content. The effect of silicon content on tensile yield strength and also tensile-fracture toughness data was obtained from the integral area of the tensile stress-strain curve as indicated in Table 2. The table also shows the significant influence of the amount of retained austenite, and that the best conditions for better mechanical properties should be carefully selected. However, for the highest tensile strength obtainable by controlling the austempering duration as shown in Fig. 3, the critical conditions can be defined qualitatively as stage I and stage II region. In addition, the best condition for 4.2Si sample was a 1 h duration, while that of both the 2.8Si and 2.1Si samples was approximately 0.5 h (Fig. 3(b)). The tensile-fracture toughness is also affected by silicon content and austempering duration as illustrated in Fig. 3.

The typical X-ray diffraction patterns as shown in Fig. 4 are commonly used to verify the amount of retained austenite, but the carbide peaks cannot be observed. The retained austenite amount and the tensile test results of each sample are listed in Table 2, which refers to many previous reports to specify the mechanical properties of the samples used in this study prior to the erosion tests.\textsuperscript{(7–9)} In addition, the hardness data tended to increase alongside increasing silicon content or with longer austempering durations.

3.2 Erosion rate

The Erosion wear curves for the 4.2Si mass\% upper bainitic ADI specimens with four different austempering durations as a function of erosion impact angle were plotted in Fig. 5(a). It can be seen that specimen 4.2Si–1h generally possesses better erosion resistance than other 4.2Si samples. Figure 5(a) also indicated a tendency for the impact angle of maximum erosion resistance to be shifted to a higher impact angle side as the austempering duration reached 3 h. Particularly, the a double peak wear curve can be recognized from 4.2Si–2h and 4.2Si–3h samples. The first peak commonly appears at the oblique impact angle of 30°, and the second peak appears with an impact angle of approximately 60°. In addition, the erosion wear rate tended to increase alongside austempering duration where the impact angle ranged between 15° and 75°.

Since the erosion rate data as represented in Fig. 5(a) reveals that 4.2Si–1h sample possesses the best erosion resistance among the three other high-silicon upper bainitic ADI specimens, this sample was used in subsequent comparisons with 2.1Si–0.5h and 2.8Si–0.5h specimen those have been treated as stage II ADI. The three wear curves were shown in Fig. 5(b), decreasing the silicon content lead to debasing the wear resistance in the oblique impact range. Though 2.8Si–0.5h is generally more erosion resistant than other specimens, the erosion wear resistance of high silicon 4.2Si–1h specimen is still similar to that of 2.8Si–0.5h specimen. However, the effect of silicon content on erosion wear resistance as recognized is dependant on the micro-structural features of the bainitic matrix, the possible reason for this will be discussed later. On the other hand, based on the hardness data as shown in Table 2, the ADI specimens with higher hardness certainly did not also demonstrate better erosion wear resistance.

3.3 Surface and subsurface morphologies after erosion test

A typical wear surface as shown in Fig. 6 displays that grooving is a common wear mechanism under oblique impact (30°). For the above-mentioned 4.2Si–1h specimen, large lips often were retained in the front of the grooves (see Fig. 6(a)). Whereas for 4.2Si–2h and 4.2Si–3h, some cracks could be observed (see Fig. 6(b)). However, for 4.2Si–1hr specimen the numerous lips retained presented on the grooves after the erosion test should be correlated with better wear resistance under oblique impact (30°). Moreover, Figure 2 shows the effect of silicon content on microstructure features was significant, but the difference between the wear features in 2.1Si–0.5h, 2.8Si–0.5h and 4.2Si–1h specimens was small.

To examine the erosion effect of silicon content, Figs. 7(a) and (b) illustrate the subsurface features of 2.8Si–0.5h and 4.2Si–1h specimens eroded under 30° impact. Grooves were found to occur on both the wear surface and subsurface, but no marked erosion induced cracks could be observed in the vicinity of subsurface. On the other hand, Fig. 7(c) illustrates another wear feature examined on the subsurface of 4.2Si–3h specimen eroded under 30° impact. In this longer austem-
pering duration ADI sample, a number of erosion cracks can significantly be observed on subsurface. In addition, the wear subsurface of 2.8Si–0.5h and 4.2Si–1h specimens is shown in Figs. 8(a) and (b), erosion cracks can not be observed, even if the specimen are eroded under 90° normal impact. It implies that the amount of retained austenite on erosion resistance might play an important role in effecting the above-mentioned erosion induced cracking behavior.

It should be noted that the observation results on the prolonged duration 4.2Si–2h sample eroded at 60°, an angle corresponding to the second peak of erosion curve (see Fig. 5). The Wear subsurface of this specimen as shown in Fig. 8(c) reveals very little evidence of lip formation. However, it has been worn by brittle fracture mode and a number of cracks induced by the erosion process can be observed. Furthermore, Fig. 8(d) shows more significant erosion induced cracks after erosion under normal impact.

Based on the TEM analysis of 4.2Si–3h specimen as represented in Fig. 9, this evidence can be used to confirm that carbides precipitating along the boundaries of lath-like ferrite grains result in a deterioration of wear resistance. In addition, X-ray diffraction patterns of the specimen before the erosion test are illustrated in Fig. 4, the specimens have almost no significant carbide peaks to be discerned, whereas an identical specimen after performed an erosion test clearly represented ε-carbide peaks as indicated in Fig. 10. In the ADI (2.8Si–0.5h and 4.2Si–1h) after the erosion test, the retained austenite could be transformed to ε-carbide and α. TEM data revealed that there was no sign of martensite in the matrix of Stage II ADI after the erosion test (see Fig. 11). Based on Fig. 10 and Fig. 11, it implies that both the retained austenite and a small portion of bainitic ferrite phase are in unstable
phase and might have possibility to transform into \(\varepsilon\)-carbide phase after erosion impact.

4. Discussion

The effect of silicon content on the mechanical properties has been clarified in many previous reports on ADI\(^\text{10,11}\). The effects of increased silicon content include suppressing carbide formation and stabilizing the retained austenite phase by a rise in the level of the carbon concentration of ADI. It also causes significant variation of the critical condition for completely bainitic reaction during austempering. Based on aforementioned experimental results as shown in Table 2 and Fig. 5(a), this critical austempering duration from Stage I to Stage II austempering region shifts to a longer duration alongside increasing silicon content.

In general, the improvement of tensile-fracture toughness and hardness data\(^\text{5,7,8}\) will be reflected in erosion wear resistance. If the relationship can be linearly correlated, it could be useful for a quantitative understanding and evaluation of erosion wear resistance of ADI. Therefore, the relationship between austempering duration and tensile-fracture toughness of high silicon sample as shown in Fig. 12 was examined. It is obvious that 4.2Si–1h specimen possesses not only better tensile-fracture toughness but also erosion resistance. Figure 12 also depict a relationship between tensile-fracture toughness and erosion resistance data cause by prolonging the austempering duration up to 3h. The tendency for prolonging the austempering duration in Stage II region to increase the erosion rate can be recognized. Especially in the data set obtained from 75\(^\circ\) impacts, linear relations between erosion wear resistance and tensile-fracture toughness can be easily recognized. On the other hand, according to the hardness data as shown in Table 2, it should be noted that the improvement of wear resistance can not be correlated with an increases in hardness due to significant carbide precipitation caused by prolonging austempering duration (Fig. 9). Based on Fig. 4, Table 2, Fig. 10 and Fig. 11, the fraction of retained austenite tends to decrease after an erosion test. Erosion-induced phase transformation of retained austenite phase has determined that it will eventually transform into \(\varepsilon\)-carbide, and thus promote the erosion wear rate. It also implies the amount of retained austenite actually plays an important role in wear resistance.

On the other hand, for high angle impact conditions, more cracks can be observed existing in the vicinity of the wear surface. Typical evidence can be found in 4.2Si–1h and 4.2Si–3h specimens (as indicated in Figs. 8(c) and (d)), while the cracks were not evident on 2.1Si–0.5h and 2.8Si–0.5h specimens. By comparing 4.2Si–1h and 4.2Si–2h, more erosion cracks occurred in 4.2Si–2h under an impact of 75\(^\circ\), therefore this should be considered a factor causing the deterioration of erosion resistance. A schematic diagram as shown in Fig. 13 helps to describe the effect of erosion induced cracking, which can also be correlated with the appearance of the second peak on the erosion curve of Stage II ADI\(^\text{9,12}\).

For understanding, Fig. 14 shows the surface morphologies after a single-particle erosion test, a typical example of 4.2Si–3h after 30\(^\circ\) single-particle erosion shows smaller lips on the wear surface (Fig. 14(b)) compared to those of 2.8Si–0.5h and 4.2Si–1h (Fig. 6(a)). Moreover, 4.2Si–3h (Fig. 14(d)) can be also used as another typical example describing the characteristics of the wear surface (after performed 60\(^\circ\) impact), few lip formations can be observed in their eroded grooves, and hence the number of lips are markedly decreased compared to the 4.2Si–1h sample, which denotes a significant deterioration of erosion wear resistance of 4.2Si–3h sample. However, lip formation features can be found on 2.8Si–0.5h and 4.2Si–1h samples, which can be considered as partial evidence for better erosion wear resistance. Finally, the 4.2Si–3h sample after single-particle 90\(^\circ\) erosion also shows brittle cracking.
features as shown in Fig. 14(e).

5. Conclusions

(1) The amount of retained austenite dominantly affects tensile strength and wear resistance even in samples with different silicon content. However, optimal austempering duration is needed for weather resistant high silicon ADI.

(2) A linear relationship between tensile fracture toughness and erosion wear resistance is easily recognized under 75° erosion impact. This relationship can be correlated with the retained austenite amount of Stage II ADI, however the hardness data cannot be applied for evaluation of erosion wear resistance.

(3) Erosion-induced phase transformation of retained austenite phase can be determined to be an eventual transformation into \(\varepsilon\)-carbide, which hence causes the deterioration of erosion wear resistance.

(4) Lip formation feature can be recognized as partial evidence for better erosion wear resistance under oblique impact. On the other hand, the variation of cracks produced by erosion is closely related to the wear resistance under larger angle impact. A second peak tends to appear on the wear curve alongside decreasing tensile-fracture toughness and retained
The microstructural effects on tensile properties and erosion wear resistance

Acknowledgments

The authors are grateful to the Chinese National Science Council for its financial support (Contract: NSC 90-2216-E-006-068).

REFERENCES

9) F. Y. Hung, L. H. Chen and T. S. Lui: accepted for publication in Wear (April 2002).