Tool Wear and Wear Mechanism of Carbide Tool in Cutting Al–Si Alloy Diecastings1

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Tool wear and wear mechanism of carbide cutting tool in turning Al–Si alloy diecastings were investigated. Decreasing amount of coarse primary silicon was effective for reducing cutting resistance and cutting tool wear. New hyper-eutectic Al–Si system alloy which doesn’t contain coarser silicon particles provided good turning machinability equivalent to conventional eutectic Al–Si system alloy. In case of increasing feed rate from 0.05 mm/rev to 0.10 mm/rev, cutting tool wear of conventional hyper-eutectic Al–Si system alloy increased. On the other hand, that of eutectic Al–Si system alloy decreased, and that of new hyper-eutectic Al–Si system alloy didn’t changed. Built-up edge and aluminum deposit on the flank wear land were observed in all aluminum alloys. [doi:10.2320/matertrans.M2021805]

1. Introduction

In sliding of hyper-eutectic Al–Si system alloy parts in automotive engines and transmissions, the larger the mean diameter and area ratio of primary silicon particles in the aluminum alloy, the more the transition from severe wear to mild wear occurs easily.1) As a result, the wear amount of aluminum alloys that contains coarser silicon particles was reduced in many cases.

But, in the mating material whose matrix is softer than silicon particles in aluminum alloys, such as plastics reinforced by fibers or hard particles, the bigger the mean diameter and area ratio of primary silicon particles in aluminum alloy, the larger the wear amount of mating material is in some cases. Authors presumed that coarser silicon particles provides bad hostility to mating materials, based on wear test results, evaluation results of automotive parts, and past studies. So, we developed a new hyper-eutectic Al–Si system alloy in which crystallization of silicon more than 20 µm was suppressed.2)

In a previous study,3) authors investigated wear resistance, hostility to mating material, and wear mechanism in sliding between Al–Si system alloy and Carbon Fiber Reinforced Plastics (abbreviated to be only CFRP, hereafter). And we reported that the new hyper-eutectic aluminum alloy which didn’t contain coarser silicon particles provided better wear resistance and less hostility to CFRP, compared to existing aluminum alloys.

It is assumed that the control of primary silicon size is also effective for extending tool life in cutting hyper-eutectic Al–Si system alloys.

Yamada and Tanaka investigated the influence of the particle size and number of primary silicon particles on the machinability of hyper-eutectic Al–Si alloys, and reported that primary silicon refining was effective in reducing tool wear.4) Komazaki and others reported that coarse primary silicon particles prevented from producing built-up edge on cutting edges, and severe abrasive wear of tool occurred due to direct contact between tool edge and broken primary silicon particles.5)

In this study, cutting tests of the new hyper-eutectic Al–Si system alloy and other Al–Si system alloys were conducted, and the influence of primary silicon particle size on tool wear and wear mechanism of carbide tool was investigated.

2. Experimental

2.1 Experimental materials

Chemical composition of experimental alloys is shown in Table 1.

15.6Si is the existing hyper-eutectic Al–Si system alloy.6,7) 13.5Si is the new hyper-eutectic Al–Si system alloy which was developed for reducing coarse primary silicon particles with the diameter of 20 µm or more in 15.6Si. D12 is the eutectic Al–Si system alloy ADC12.

Figure 1 shows ring-on-disk type wear test results of the aluminum alloys and CFRP, reported in the previous study.3) Wear test conditions (contact pressure: 1.4 MPa, sliding speed: 15.7 m/s, sliding distance: 22,000 km) were selected based on the sliding condition of a certain automotive part. Wear depth of D12 was large, compared with other alloys. Wear depth of CFRP sliding against 15.6Si was large, compared with other alloys. On the other hand, Wear depth of 13.5Si was smaller than that of 15.6Si, and wear depth of CFRP sliding against 13.5Si was small, compared with other alloys.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cu (mass%)</th>
<th>Si (mass%)</th>
<th>Mg (mass%)</th>
<th>Fe (mass%)</th>
<th>Mn (mass%)</th>
<th>Cr (mass%)</th>
<th>Ti (mass%)</th>
<th>P (mass%)</th>
<th>Al (mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.6Si</td>
<td>3.4</td>
<td>15.6</td>
<td>0.81</td>
<td>0.74</td>
<td>0.51</td>
<td>0.21</td>
<td>0.10</td>
<td>0.009</td>
<td>Bal.</td>
</tr>
<tr>
<td>13.5Si</td>
<td>3.5</td>
<td>15.3</td>
<td>0.82</td>
<td>0.81</td>
<td>1.24</td>
<td>0.27</td>
<td>0.09</td>
<td>0.006</td>
<td>Bal.</td>
</tr>
<tr>
<td>D12</td>
<td>2.6</td>
<td>11.2</td>
<td>0.26</td>
<td>0.74</td>
<td>0.22</td>
<td>—</td>
<td>0.04</td>
<td>—</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

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2.2 Specimens

Cup-shaped die castings of aluminum alloy were provided for cutting test. The size is 90 mm in outer diameter, 80 mm in inner diameter, 50 mm in length, and 10 mm in thickness of bottom part. Cast surface with a thickness of 1.0 mm was removed for eliminating the influence of primary silicon-free zone. And, plate-shaped die castings were provided for investigating mechanical properties and physical properties. The size is 180 mm × 150 mm × 12 mm. Casting temperature of 15.6Si was 997 K, and that of 13.5Si and D12 was 973 K.

2.3 Cutting test

In this cutting test, the modified test machine of the lathe (SHOUN KOUSAKUYO’s type ST5) was used. Appearance of test machine is shown in Fig. 2. Carbide cutting tool is K10 (MITSUBISHI MATERIAL’s type TPGN160304) with the geometry of (front rake angle: 0°, side rake angle: 5°, front clearance angle: 11°, side clearance angle: 6°, front cutting edge angle: 60°, side cutting edge angle: 0°, nose radius: 24 mm). Table 2 shows cutting conditions. Tool materials and cutting conditions were selected based on mass production cutting conditions for automotive parts made of hyper eutectic Al–Si system alloys.

Cutting resistance was measured with piezoelectric 3-component cutting dynamometer (Nippon KISTLER’s type 9121). Flank wear of tools was measured after removing built-up edge on cutting edge with aqueous sodium hydroxide solution.

3. Experimental Results and Discussions

3.1 Microstructure and properties of Al–Si system alloys

Figure 3 shows optical micrographs of the Al–Si system alloys and photographs of 13.5Si and 15.6Si after image processing. White particles in images are primary silicon particles. The particle size distribution of primary silicon particles is shown in Table 3. The number of primary silicon particles with the diameter of 14 µm or more in 13.5Si is smaller than that in 15.6Si. And the number of primary silicon particles with the diameter no more than 14 µm in 13.5Si is larger than that in 15.6Si. Authors showed Fig. 3 and Table 3 in the previous study and reprinted them for showing the properties of experimental materials in this paper.

Table 4 shows the mean diameter and area ratio of primary silicon particles, mechanical properties, and physical properties of the experimental alloys.

Some studies reported that elongation and hardness of aluminum alloys affected on tool wear, as rich ductility of matrix reduced direct collision of hard particles with cutting edge. However, hardness and elongation of 13.5Si and those of 15.6Si are almost same values. Accordingly, it is assumed that the primary silicon particles distribution affects on the tool wear strongly.

3.2 Result of cutting test

3.2.1 Chip morphologies

Figure 4 shows morphologies of chips in cutting at feed rate 0.05 mm/rev. Chips of D12 are coil shape. On the other hand, Chips of 13.5Si, 15.6Si are fan shape. It is assumed that primary silicon particles acted as a nucleus of chip breaking for formation of fan-shaped chips, as reported by Kamiya and others.
3.2.2 Cutting resistance

Figure 5 shows cutting resistance at cutting distance 0.25 km in cutting at feed rate 0.05 mm/rev. Cutting resistance made bigger in the order of 13.5Si, D12, 15.6Si. And the thrust force of 15.6Si showed the maximum value. Thrust force is affected by (1) Friction between flank face of tool and cutting surface, (2) Friction between cutting face of tool and chips, (3) Shearing deformation energy of aluminum alloy. In this experiment, (1)'s friction force is seemed to affect on the thrust force strongly. On cutting surface, it is assumed that protrusion amount of primary silicon particle and the diameter of detached silicon particle are higher with a diameter of particle, as reported previous studies.1,3) Therefore, it is assumed higher contact probability of primary

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~4</td>
</tr>
<tr>
<td>15.6Si</td>
<td>1022</td>
</tr>
<tr>
<td>13.5Si</td>
<td>1104</td>
</tr>
</tbody>
</table>

Table 3 Primary silicon particle size distribution.3)

Table 4 Properties of Al-Si system alloys.

<table>
<thead>
<tr>
<th></th>
<th>D12</th>
<th>13.5Si</th>
<th>15.6Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (MPa)</td>
<td>330</td>
<td>305</td>
<td>320</td>
</tr>
<tr>
<td>0.2% Proof strength (MPa)</td>
<td>177</td>
<td>245</td>
<td>247</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>5.1</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Hardness (HRB)</td>
<td>69</td>
<td>81</td>
<td>78</td>
</tr>
<tr>
<td>Fatigue strength (MPa)</td>
<td>120</td>
<td>200</td>
<td>131</td>
</tr>
<tr>
<td>Thermal expansion coefficient (×10^-6/K)</td>
<td>21.0</td>
<td>19.4</td>
<td>19.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean diameter (μm)</th>
<th>Area ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary silicon</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mean diameter (μm)</td>
<td>6.0</td>
<td>6.6</td>
</tr>
<tr>
<td>Area ratio (%)</td>
<td>8.1</td>
<td>12.1</td>
</tr>
</tbody>
</table>

3.2.2 Cutting resistance

Figure 5 shows cutting resistance at cutting distance 0.25 km in cutting at feed rate 0.05 mm/rev. Cutting resistance made bigger in the order of 13.5Si, D12, 15.6Si. And the thrust force of 15.6Si showed the maximum value. Thrust force is affected by (1) Friction between flank face of tool and cutting surface, (2) Friction between cutting face of tool and chips, (3) Shearing deformation energy of aluminum alloy. In this experiment, (1)'s friction force is seemed to affect on the thrust force strongly. On cutting surface, it is assumed that protrusion amount of primary silicon particle and the diameter of detached silicon particle are higher with a diameter of particle, as reported previous studies.1,3) Therefore, it is assumed higher contact probability of primary
silicon particles with the tool increased friction force in 15.6Si, illustrated in Fig. 6. The friction force between flank face and cutting surface of D12 was low. But, the thrust force in cutting D12 was higher than that in cutting 13.5Si. The reason is assumed that the friction force between the cutting face and chips of D12 was higher.

3.2.3 Wear of tool

Figure 7 shows the relationship between cutting distance and flank wear amount of tools in cutting at feed rate 0.05 mm/rev. Wear curve of 13.5Si was similar to that of D12. Wear amount increased linearly and there was no difference between severe wear amount and mild wear amount. To the contrary, the initial wear amount and total wear amount of 15.6Si were large, compared to 13.5Si, D12. But in the case of 15.6Si, the transition from severe wear to mild wear occurred and mild wear amount of 15.6Si was equivalent to those of 13.5Si and D12. Nearly same results were obtained in the test at feed rate 0.10 mm/rev.

It was reported that tool wear amount in an initial stage was proportional to the size and number of primary silicon particles, as primary silicon particles in aluminum alloy and detached silicon particles attacked flank face of tool directly.\(^4\) It was found that 13.5 Si, in which coarser silicon particles were reduced, made tool life extend, equivalent to eutectic Al–Si alloys.

Severe-mild wear transition in sliding parts\(^4\) means a transition from primary wear at high wear rate to stable wear at moderate wear rate through running-in process. In many cases, this transition is occurred by decrease of surface roughness or formation of adequate clearance for lubrication.\(^12-14\) However, in this study, it is assumed that the wear speed of 15.6Si decreased, as direct contact between aluminum alloy and tool were suppressed by built-up edge and aluminum deposit on the cutting edge.

Wear conditions of cutting edge after cutting of 8.0 km are shown in Fig. 8 and Fig. 9. Figure 8 shows SEM images of cutting edge before removing built-up edge with aqueous sodium hydroxide solution, and Fig. 9 shows those after removing built-up edge. Komazaki and others conducted cutting tests of ADC14 containing 17.0%Si and reported as follows; In the ADC14 containing many primary silicon particles with the diameter of 20 µm or more, those silicon particles prevented formation of built-up edges. On the other hand, built-up edges were formed on the ADC14 containing small quantity of primary silicon particles with the diameter of 20 µm or more.

In this experiment, built-up edges were observed on all samples. And wide abrasive wear trucks as reported in some studies\(^10,11\) were not observed.

In Fig. 8 thin aluminum deposition occurred on the flank wear land which is shown in Fig. 9. Hirono and others reported that similar deposition occurred on the wear part in cutting hyper-eutectic Al–Si alloys, when flank wear amount exceeded a certain value, and that aluminum deposition increased with the increase of the flank wear amount.\(^15\) In 15.6Si, as early flank wear amount was large, tool wear rate was decreased by aluminum deposition on the flank wear land. Conversely, in 13.5Si and D12, tool wear rate increased.

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Fig. 6 Schematic illustration of friction between tool and material.

Fig. 7 Relationship between cutting distance and flank wear.

Fig. 8 Tips of cutting tool after cutting. (feed rate 0.05 mm/rev)
linearly. The reason is assumed that early wear rate was as small as the wear rate after aluminum deposition.

3.2.4 Influence of feed rate on tool wear amount

It is reported that increasing feed rate raises cutting temperature, and tool wear amount is increased by softening of tool material. On the other hand, Yan and Wong reported that increasing feed rate reduced tool wear amount at feed rate 0.025~0.10 mm/rev.16) This feed rate was used in many experiments4,5,10,15,16) and is used in mass production.

Therefore, in this study, the influence of feed rate on tool wear amount in cutting the experimental alloys was investigated.

Figure 10 shows the relationship between feed rate and flank wear amount. The cutting test at feed rate 0.025 mm/rev was conducted on D12 and 13.5Si only. When feed rate increased from 0.05 mm/rev to 0.10 mm/rev, increase or decrease of wear amount differed depending on alloys. The tool wear amount in cutting 15.6Si increased, that in cutting D12 decreased, and that in cutting 13.5Si didn’t change so much. Increasing feed rate makes feed force and cutting temperature increase. Therefore, matrix of aluminum alloy near the edge of tool is easily softened. In that case, the finer silicon particles, the more those particles are embedded in the matrix or dropped from matrix by feed force easily. For that reason, the friction force between silicon particles and flank face, and tool wear amount decreases. On the other hand, in the case of coarser silicon particles, it is assumed that tool wear amount increases with feed rate, as detached particles get caught in between flank face and aluminum alloy.

Figure 11 shows SEM images of wear condition on tool edge. Crater wear occurred in cutting D12, because long coil-shaped chips easily collided with cutting face. Crater wear in cutting 13.5Si, 15.6Si didn’t occur, because small fan-shaped chips collided with cutting face rarely.

3.2.5 Surface roughness of finished materials

Figure 12 shows surface roughness of finished surfaces in cutting 13.5Si, D12. In hyper-eutectic Al–Si alloys, detached primary silicon particles roughen surface.17) Yamada and Tanaka reported that surface roughness of finished materials were proportional to the size and numbers of primary silicon particles.18) In this experiment, surface roughness of 13.5Si was larger than that of D12. But difference of surface roughness between both alloys was small, compared to previous studies, and surface roughness of 13.5Si was satisfied with required value of automotive parts.

4. Conclusion

Tool wear and wear mechanism of carbide cutting tool in cutting Al–Si alloy diecastings were investigated. The following conclusions were drawn.

(1) Refining of primary silicon in hyper-eutectic Al–Si system alloys was effective for reducing cutting
resistance and tool wear amount. New hyper-eutectic Al–Si system alloy, in which crystallization of primary silicon more than 14 µm was suppressed, provided good cutting ability equivalent to conventional eutectic Al–Si system alloy.

(2) Built-up edge and aluminum deposit on flank wear land of tool were observed in cutting both hyper-eutectic Al–Si alloys and eutectic Al–Si system alloy.

(3) Tool wear curve in cutting the existing hyper-eutectic Al–Si system alloy showed the severe-mild wear transition. It is assumed that tool wear amount of this alloy was high in an initial stage, as primary silicon particles in aluminum alloy attacked flank face of tool directly, and that built-up edge and aluminum deposition on the flank wear land occurred this transition.

(4) In cutting the eutectic Al–Si system alloy and the new hyper-eutectic Al–Si system alloy, tool wear rate increased linearly. The reason is assumed that early wear rate was the same as wear rate after aluminum deposition.

(5) In the case of increasing feed rate from 0.05 mm/rev to 0.10 mm/rev, tool wear amount of the existing hyper-eutectic Al–Si system alloy increased. On the other hand, that of the eutectic Al–Si system alloy decreased, and that of the new hyper-eutectic Al–Si system alloy didn’t changed.

REFERENCES

2) JP4341438.