Effect of Si and Al Additions to Steel on Machinability in Gear Cutting

Toshiharu AISO1)* and Takashi MATSUMURA2)

1) Steel Research Laboratories, Nippon Steel Corporation, 20-1 Shintomi, Futtsu City, Chiba, 293-8511 Japan.
2) Department of Mechanical Engineering, Tokyo Denki University, 5 Senjyu Asahi-cho, Adachi-ku, Tokyo, 120-8551 Japan.

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The influence of Si and Al additions to 0.55 mass% C steel on machinability is discussed in cutting with a fly tool of TiAlN coated high speed steel, as performed in gear cutting. Three model steels are prepared with controlling nearly the same hardness to study the effects of the alloying elements: one reference steel with C as the only alloying element (Base steel), and two steels alloyed also with 1 mass% Si or Al. The cutting tests are performed to obtain the cutting forces, observe the cutting chips and analyze the damage on the rake faces of the tools. The orthogonal cutting data in the cutting force simulation are identified to minimize the discrepancies between the measured and the simulated forces for the tested steels. When cutting the Base steel, few adhered materials form and the coated thin layer is worn mainly by abrasion. When cutting the Si alloyed steel, the coating surface is covered by adhered layers containing Si–O, Fe2SiO4 and FeO, which contribute to the lowest friction and protect the coated thin layer from wear. When cutting the Al alloyed steel, an Al2O3 layer forms on the coating. The Al2O3 layer induces high friction, large cutting forces and cutting heat, resulting in the rapid substrate softening and coating fracture.

KEY WORDS: gear; cutting; fly tool; machinability; steel; silicon; aluminium; simulation.

1. Introduction

Steels for machine structural use are used to manufacture many of gears in automobiles, as well as construction and industrial machinery, through processes such as hot forging, machining, carburizing and quenching. The demands for carbon dioxide emission reduction and energy conservation have recently increased to protect the global environment. In terms of carburizing, the shorter processing time and the process change to the induction hardening would give contributions to the protection.1) Such process changes require a higher carbon content than approximately 0.2 mass% (hereinafter denoted as %), at which the steel such as JIS-SCM420 for the gear parts conventionally contains. However, the increase in carbon content generally deteriorates machinability with high material hardness, and hence, results in higher costs in machining of gears. Therefore, the cutting processes of high carbon steels should be studied to improve the machinability in terms of the environment.

The authors previously investigated the effect of carbon content on the machinability in gear cutting of steels at carbon contents of 0.2–0.6%, in which the similar microstructures and nearly the same hardness were controlled by adjusting the tempering temperature after quenching.2) In cutting of these steels, the cutting resistance and cutting temperature increase with the carbon content. Local deformation occurs on the rake face of the tool due to thermal softening in the substrate of high speed steel (HSS) and crack initiation and propagation occur rapidly in the coated thin layer, while adhesive wear is significantly promoted on the flank face. The addition of S or Pb has been widely applied to reduce tool damage. However, these additives are limited in uses due to their negative effects on the mechanical properties and environment, respectively. Thus, other approaches are expected to improve machinability.

In the standard cutting conditions for steels, the contact interface between the tool and the chip undergoes high pressures at high temperatures due to high strain rates in the shear zone, where the normal stress achieves 500–1 600 MPa and the maximum temperature exceeds 1 000°C.3) When cutting steels containing Si and Al, their oxides or nitrides form in the tool/chip interface to affect machinability. The addition of Si improves lubrication with the Fe–Si–O scale generation on the chip surface,4) suppresses the notch wear due to the formation of Si oxides acting as a protective layer on the tool surface,5) and promotes the diffusion wear of tool coating components by the formed Si oxides.6) The Al addition forms Al-based oxides on the tool surface accompanied...
with MnS suppressing tool damage,\textsuperscript{7) }promotes the adhesive wear,\textsuperscript{5) }and generates an AlN thin film on the tool surface as a protective layer.\textsuperscript{8) }According to the prior studies, the effects of Si or Al on machinability depend on the work material hardness, the tool type, the cutting manner, the cutting conditions, \textit{etc.} Therefore, machinability of carbon steel containing Si or Al should be studied systematically to clarify these effects based on the target process.

This study discusses cutting process of high carbon steel with the addition of Si or Al in gear cutting. Model steels of 0.55\%C with different Si and Al compositions were prepared for the cutting tests, where hardness of the steels were controlled to be nearly the same in heat treatments. In order to perform the same manner as hobbing, the cutting tests were conducted using a fly tool in the same operation as that of our previous study.\textsuperscript{2) }The cutting force simulations based on energy analysis method\textsuperscript{9,10) }were applied to analyze the shear deformation in the workpiece material and the friction characteristics on the tool surface. Surface analyses were conducted for the tool face to observe the adhered material after cutting.

\section{Experimental Procedures}
\subsection{Workpiece Material}
Three types of steels were employed as shown in Table 1. The Base steel contained only 0.55\% carbon as an alloying element. In the Si and Al alloyed steels, nominally 1\% Si or Al was also added, respectively. These were melted in a vacuum melting furnace and cast into 180 kg ingots. The ingots, then, were forged into round bars with a diameter of 70 mm. The steel bars were homogenized by holding at 1253 K for 120 min and air-cooling to room temperature. Subsequently, they were normalized by holding at 1203 K for 30 min and air-cooling to room temperature. Next, heat treatments were conducted to form nearly the same microstructure and hardness in the conditions of Table 1. The austenitizing and annealing temperatures were controlled to reduce the differences in the austenite grain size and hardness, respectively. In order to suppress the formation of coarse ferrite grains and achieve sufficient hardness, oil-quench was conducted in an accelerated cooling treatment for the Base steel and the Al alloyed steel. Workpiece specimens were cut into block shapes of 50 \times 35 \times 70 mm from the heat-treated round bars.

The hardness of all steels manufactured in the abovementioned process was 201 \pm 5 HV, as shown in Table 1. The microstructures of all steels are mainly composed of fine pearlite though the Base steel might contain the tempered martensite and the Si and Al alloyed steels contain slight amounts of ferrite, as shown in Fig. 1.

\subsection{Cutting Test}
Interrupted cutting tests were conducted using a fly tool on a machining center shown in Fig. 2 under the cutting conditions of Table 2. The cutting conditions were determined referring to the literature\textsuperscript{11,12) }in dry gear cutting. The

Table 1. Chemical composition (mass\%), Vickers hardness (HV) and heat treatment of the work materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Al</th>
<th>Mn</th>
<th>S</th>
<th>Hardness</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.55</td>
<td>0.003</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>196</td>
<td>1123 K/30 min - Oil quench \rightarrow 763 K/300 min</td>
</tr>
<tr>
<td>Si</td>
<td>0.55</td>
<td>0.992</td>
<td>0.003</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>197</td>
<td>1223 K/30 min - Air cooling \rightarrow 873 K/300 min</td>
</tr>
<tr>
<td>Al</td>
<td>0.55</td>
<td>0.003</td>
<td>1.010</td>
<td>0.001</td>
<td>0.001</td>
<td>206</td>
<td>1223 K/30 min - Oil quench \rightarrow 843 K/300 min</td>
</tr>
</tbody>
</table>

Table 2. Cutting conditions.

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed</td>
<td>120 m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.65 mm/rev</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>4.5 mm</td>
</tr>
<tr>
<td>Shift length</td>
<td>2.413 mm</td>
</tr>
<tr>
<td>Lubrication</td>
<td>Air (dry)</td>
</tr>
<tr>
<td>Cutting method</td>
<td>Down cut milling</td>
</tr>
<tr>
<td>Outside diameter</td>
<td>90 mm</td>
</tr>
<tr>
<td>Rake angle</td>
<td>0°</td>
</tr>
<tr>
<td>Module</td>
<td>3</td>
</tr>
<tr>
<td>Pressure angle</td>
<td>20°</td>
</tr>
<tr>
<td>Material</td>
<td>TiAlN coated HSS</td>
</tr>
</tbody>
</table>

Fig. 1. Microstructure of the work materials.

Fig. 2. (a) Appearance of a fly tool and (b) test setup. (Online version in color.)
tool material in Fig. 2(a) was a HSS coated with TiAlN on the rake and flank faces by physical vapor deposition, which is generally used in hobbing. The coating thickness and its roughness were approximately 5 μm and Ra 0.2 μm, respectively. The workpiece specimen was cut in tool rotation with a feed motion in the direction designated in Fig. 2(b). Subsequently, the pick feeds were repeated in the Z-direction with the same operations. In order to consider the workpiece shape finished in the previous pick feed, the workpiece was finished in the preliminary cutting in a feed using the same type of tool before the cutting tests. The cooling air was supplied near the cutting edge for the chip control. A same type of tool before the cutting tests. The cooling air was finished in the preliminary cutting in a feed using the same type of tool before the cutting tests. The cooling air was supplied near the cutting edge for the chip control. A same type of tool before the cutting tests.

2.3. Observation and Analysis of Chip and Tool

The chip shape and color were observed with an optical microscope. Additionally, the central cross-sections of the chips were observed after embedding the chips in the resin and polishing. Vickers hardness tests, then, were conducted to measure and average the hardness at 5 positions at the center of the chip thickness at an indentation load of 1.96 N.

The tool surfaces were observed and analyzed using optical microscopy, scanning electron microscopy (SEM), energy dispersion X-ray spectroscopy (EDS), and Auger electron spectroscopy (AES). The electron beam acceleration voltage in the SEM–EDS analysis was either 10 or 20 kV. The tool specimens were also embedded in the resin and polished to observe in the cross-sections containing the chip flow directions using an optical microscope. In addition, the tool surfaces were sputtered with a focused ion beam (FIB) to observe the cross-sections after the deposition of protective Pt films on the surfaces. Subsequently, the cross-sections were observed through SEM at a tilt angle of 52°. Furthermore, a thin film sample was cut out from the tool surface using an FIB and observed with transmission electron microscopy (TEM) at an acceleration voltage of 200 kV.

3. Results

3.1. Cutting Force

An energy analysis method for milling (10) was applied to analyze the changes in the cutting forces during a rotation of the fly tools. In this analysis, the cutting edge is divided into small discrete segments to define the changing edge geometry. The cutting process of the segmented edge inclined against the cutting direction is regarded as oblique cutting. Therefore, the three-dimensional chip flow is interpreted as a piling up of the orthogonal cuttings in the planes containing the cutting velocities and chip flow velocities. The orthogonal cutting model is determined by the orthogonal cutting data that associates the shear angle, shear stress on the shear plane, and friction angle with the cutting velocity, cutting thickness, and tool rake angle. Then, the cutting energies are calculated at given chip flow angles. Because the cutting energy depends on the chip flow angle, the chip flow angle is determined to minimize the cutting energy.

The cutting force, then, is acquired in the chip flow model. In the fly cutting, the cutting force is analyzed with the cutting thickness changing with the rotation angle of the cutting edge. This analytical model predicts the cutting force for the three-dimensional edge geometry and the cutting conditions using the orthogonal cutting data.

Because the hardness of the work material and the tool material of this study was nearly the same as that of our previous study, the following orthogonal cutting data are referred to literature (3) in the analysis:

\[ \phi = \exp(0.034392V + 1.885.966t_1 + A_{03}) \]
\[ \tau_s = \exp(0.016495V + 12.05192t_1 + A_{13}) \]
\[ \beta = \exp(-0.02056V - 1.788.55t_1 + A_{23}) \]

where \( \phi, \tau_s, \) and \( \beta \) are the shear angle, shear stress on the shear plane, and friction angle in the orthogonal cutting, respectively. \( V \) and \( t_1 \) are the cutting velocity and uncut chip thickness, respectively. The general formula of the orthogonal cutting data (10) involves the term for rake angle of the tool. Since the rake angle is 0° as shown in Table 2, the term for the rake angle effect is removed from Eq. (1).

The workpiece and tool materials are characterized by the coefficients in Eq. (1), and the effects of the cutting conditions on the cutting model are controlled by the coefficients of the terms \( V \) and \( t_1 \). Here, the coefficients of the terms \( V \) and \( t_1 \) in our previous study (2) were used in the analysis, while the constant terms \( A_{ij} \) (\( i = 0.1,2 \)) were determined to minimize the discrepancies between the predicted and measured cutting forces. Table 3 shows the identified coefficients \( A_{ij} \) (\( i = 0,1,2 \)) of the work materials for the cutting distance. Note that only the parameters in a cutting distance of 0.07 m are shown for the Al alloyed steel because the coating damage occurred early on the rake face.

Figure 3 shows an example of the cutting force simulations compared to the measured cutting force. The dynamic force components induced by the vibration in the cutting test system were superimposed on X and Y components in the measured cutting force. When the dynamic force components are neglected, the force model is validated with the identified orthogonal cutting data in agreement of the simulations with the measurements. Figure 4 shows the maximum force components from the measured cutting

<table>
<thead>
<tr>
<th>Cutting distance [m]</th>
<th>( A_{i0} )</th>
<th>( A_{i1} )</th>
<th>( A_{i2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.07</td>
<td>-0.91</td>
<td>20.244</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>-0.933</td>
<td>20.231</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>-1.048</td>
<td>20.207</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>-1.098</td>
<td>20.1945</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>-1.082</td>
<td>20.235</td>
</tr>
<tr>
<td>Si</td>
<td>0.07</td>
<td>-0.91</td>
<td>20.182</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>-0.788</td>
<td>20.203</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>-0.788</td>
<td>20.238</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>-0.788</td>
<td>20.227</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>-0.788</td>
<td>20.226</td>
</tr>
<tr>
<td>Al</td>
<td>0.07</td>
<td>-1.27</td>
<td>20.172</td>
</tr>
</tbody>
</table>

Table 3. Identified coefficients \( A_{ij} \) (\( i = 0,1,2 \)) in the orthogonal cutting data in the simulation.
forces, where the cutting forces associated with the uncut chip thickness are assumed to change along the center of the vibration amplitude. Compared with all the cutting force components with the Base steel, those with the Si alloyed steel are smaller, while those with the Al alloyed steel are larger. The \( F_x \), \( F_y \), and \( F_z \) of the Si alloyed steel decrease by 10.8\%, 31.2\%, and 33.9\%, respectively, at the cutting distance where the remarkable difference from the Base steel is measured. The \( F_x \), \( F_y \), and \( F_z \) of the Al alloyed steel increase by 12.8\%, 35.6\%, and 30.6\%, respectively, compared with those of the Base steel at a cutting distance of 0.07 m.

The shear strain \( \gamma \) and friction coefficient \( \mu \) are given by the following equations at a rake angle \( \alpha \):

\[
\gamma = \frac{\cos \alpha}{\sin \phi \cos (\phi - \alpha)} \quad \cdots \cdots \cdots \cdots \cdots \cdots (2)
\]

\[
\mu = \tan \beta \quad \cdots \cdots \cdots \cdots \cdots \cdots (3)
\]

\( \phi \) and \( \beta \) are the parameters in the orthogonal cutting model determined by the cutting force analysis. Figure 5 shows \( \tau_s \), \( \gamma \), and \( \mu \) at the center of the top cutting edge (designated later in Fig. 8) in the maximum uncut chip thickness. The shear stress on the shear plane is not significantly affected by the additions of Si and Al, as well as indicates little change for the cutting distances. The shear strain is slightly larger for the Al alloyed steel, while almost no difference is observed between the Base steel and the Si alloyed steel at any cutting distances. On the other hand, the friction coefficient with the Base steel increases from 0.31 to 0.39 up to a cutting distance of 2.8 m and then achieves a constant coefficient. The friction coefficient with the Si alloyed steel is 0.31, nearly same as that with the Base steel in the beginning of cut, decreases to 0.25 up to a cutting distance of 0.7 m and becomes constant. The friction coefficient with the Al alloyed steel is 0.46 larger than those with the Base steel and the Si alloyed steel in the beginning of cut.

### 3.2. Chip Formation

Figure 6 compares the tempered colors of chips formed in cutting of work materials. A brown color appears in the chips of the Base steel and the Si alloyed steel. Because the chip of the Al alloyed steel exhibits almost uniform blue, the higher temperature of the chip is estimated than those of the other steels, which correlates with the larger cutting resistance of the Al alloyed steel, as shown in Fig. 4.

The microstructures of the cross-section in the chips are shown in Fig. 7, where hardness is also designated in the pictures. Plastic flows are observed along the shear direction from the upper right to the lower left in the pictures of
chips. No significant difference is observed in terms of the cross-sectional hardness. Little difference is confirmed in the chip thicknesses for the Base steel and the Si alloyed steel, while the chip of the Al alloyed steel is thick a little. It is well known that the shear stress on the shear plane increases with the hardness of the chip. The shear stresses on the shear planes are nearly the same, as shown in Fig. 5(a). In general, the primary shear strain increases with the chip thickness. The shear strain of the Al alloyed steel becomes higher than those of the other steels, as shown in Fig. 5(b).

3.3. Adhesion and Tool Damage on Rake Face of Tool

3.3.1. Tool Appearance and Cross-section

Since the top and side cutting edges removed the work material simultaneously in fly cutting, the chips flowed on the rake face at an inclination angle with respect to the top cutting edge, as indicated by the arrow in Fig. 8. In cuttings of the Base steel and the Si alloyed steel, no significant damage occurs on the rake faces up to a cutting distance of 0.07 m. Regions with black colored scratches are observed around 0.28 m, and subsequently, they expand as the cutting distance increases. By contrast, in cutting of the Al alloyed steel, a region containing white colored scratches appears at 0.07 m, and a prominent adhered lump, as indicated by the white arrow in the figure, forms at 0.28 m. Figure 9 compares the cross-sections of the tools etched in nital. No damages occur in the coated layer and substrate for the Base steel, while cracks and delamination are observed in the coated layer on the rake face side and a white etching layer is formed on the substrate for the Al alloyed steel.

3.3.2. Adhesion and Tool Damage When Cutting the Base Steel

In the EDS maps after cutting the Base steel shown in Fig. 10, tool coating components Ti and Al are detected on the overall rake face with few adhered materials. Figure 11(a) shows the magnified area in the white rectangles in Fig. 10. The streaky grooves induced by abrasive particles are observed in the chip flow direction, as indicated by the white arrows. It is proved that the tool wear occurs in the regions with black colored scratches of Fig. 8(a). In Fig. 11(a), the adhered materials appear in the direction perpen-

![Fig. 6. Representative chips. The contact surfaces with the tool are observed. The lines A and B indicate the parts of the chip formed by top cutting edge and side cutting edge, respectively.](image)

![Fig. 7. Optical microscope images and hardness of the cross-section of the chips. The hardness measurement was performed around the center position in the chip thickness using a load of 1.96 N.](image)

![Fig. 8. Optical microscope images of the rake faces of the tools after cutting (a) the Base steel, (b) the Si alloyed steel and (c) the Al alloyed steel with different cutting distances. The white dashed lines indicate the positions corresponding to the cross-sections in Fig. 9. An adhered lump in the image of (c) is shown by the arrow.](image)
Fig. 10. An SEM image and EDS maps of the rake face after 4.9 m cutting of the Base steel. The electron beam acceleration voltage was 20 kV. The area in the rectangle is magnified in Fig. 11(a). (Online version in color.)

Fig. 11. (a) SEM images on the rake face after 4.9 m cutting of the Base steel. An image, corresponding to the white rectangle in Fig. 10, is shown to the left and the area in the black rectangle is magnified in the image to the right. In the magnified image, some grooves are indicated by white arrows. (b) An SEM image of a FIB cross-section made on the position shown by the line between A and B in the image of (a). (c) An EDS spectrum obtained from the Fe–O layer. The electron beam acceleration voltage was 10 kV.

Fig. 12. An SEM image and EDS maps of the rake face after 4.9 m cutting of the Si alloyed steel. The electron beam acceleration voltage was 20 kV. The area in the rectangle is magnified in Fig. 13(a). (Online version in color.)
3.3.3. Adhesion and Tool Damage When Cutting the Si Alloyed Steel

In the EDS maps after cutting the Si alloyed steel shown in Fig. 12, Si, Fe, and O are detected in the black colored scratch.
regions of Fig. 8(b) on the rake face, which is associated with the formation of an Fe–Si–O layer. As shown in Fig. 13(a), the magnified area designated by white rectangles in Fig. 12, the Fe–Si–O adhered layer widely covers on the rake face as uniform and smooth film. The wear mark is not observed, in contrast to the Base steel in Fig. 11(a). According to observation of cross-section in Fig. 13(b), the smooth and continuous Fe–Si–O layer covers on the rough surface of TiAlN coating in an approximately 3.3 μm thick. Figure 13(c) shows that the adhered layer contains a large amount of Si. In Fig. 14(a) of the cross-section of the layer observed with TEM, the Si and Fe oxides are shown in white and black contrasts in the BF (bright field) image, respectively. These oxides are alternately stacked in thicknesses of several hundreds of nanometers. According to electron diffraction patterns in Fig. 14(b), the Si oxide is composed mainly of amorphous Si–O. The Fe oxide, then, contains a significant amount of Fe2SiO4 from the surface to the center in the layer and comprises a mixture of Fe2SiO4 and FeO near the coating layer.

3.3.4. Adhesion and Tool Damage When Cutting the Al Alloyed Steel

Fe is detected in a wide range on the rake face after cutting the Al alloyed steel, as shown by the EDS maps in Fig. 15. The region containing white colored scratches shown in Fig. 8(c) corresponds to the adhered Fe of the workpiece material. The area indicated by the white arrow in Fig. 15 contains a significant amount of adhered Fe in a form of a lump surrounded by O. The left and right sides of Fig. 16(a) show the regions where the adhered Fe and O are observed, respectively. The magnified image of Fig. 16(a) and the AES maps of Fig. 16(b) show the regions containing O. The bright contrast area designated by “B” is the Fe-rich area, while the dark contrast area of “D” is the Al-rich area. Al is not from the TiAlN coating because Ti is not detected in this area. According to TEM study of the cross-section of this area in Fig. 17(a), the TiAlN coating is covered by the Al-rich oxide layer in the maximum thickness of approximately 500 nm. The Fe-rich layer adheres on the upper and front of the Al-rich layer in nearly the same thickness. Based on the electron diffraction patterns of Fig. 17(b), the Al-rich layer is mainly composed of Al2O3 (α), while the Fe-rich layer contains α-Fe of the workpiece material.

Figure 18 shows the cross-section of the rake face, where sample is cut along H–I in Fig. 16(a). Cracks, fracture and delamination are observed in approximately 5 μm thick coating layer though remarkable wear does not occur. The rough surface induced by the above deterioration, in turn, promotes the adhesion of Fe of the workpiece material.
4. Discussion

In the experiment, the machinability is improved by the addition of 1% Si but deteriorated by the addition of 1% Al. The Si addition reduces the cutting force with no tool wear progress, while the Al addition makes the cutting force increase and induces damage in the tool coating. According to Fig. 5, the shear stress on the shear plane and the shear strain do not significantly change when hardness and microstructures are nearly the same in the testing steels. By contrast, the friction coefficient between the rake face and chip depends on the steels. Then, the cutting force and tool damage change with adhesion behavior on the rake face by means of addition of Si or Al, which is correlated with the friction coefficient.

Because the interface between the tool and chip generally undergoes high stresses at high temperatures, some of the constituent elements in the workpiece material often adhere to the rake face and form a deposited layer. According to Figs. 10 to 17, typical oxides form in cuttings of each steel. In the interrupted cutting test, where cutting and non-cutting are repeated during a tool rotation, a small amount of oxygen penetrates into the interface from atmosphere and causes oxidation. Being oxidized easily compared to Fe, Si and Al are selectively oxidized and enriched in the adhered layers with poor oxygen supply. Such the oxidized adhesive layers were also confirmed in actual hobbing.\textsuperscript{13} In addition, some studies reported similar adhered materials, which were associated with the friction coefficient and tool damage, in sliding tests simulating the interface of the interrupted cutting of the model steels.\textsuperscript{14–16} Here, it was reported that Al of the coating components was selectively oxidized by heat generation on the rake face in cutting with TiAlN coated tools.\textsuperscript{17} However, this study clarifies that an Al\textsubscript{2}O\textsubscript{3} adhered layer forms only in cutting of the Al alloyed steel. Therefore, formation of Al\textsubscript{2}O\textsubscript{3} layer mainly depends on the selective oxidation of solute Al in steel rather than Al in the coating components.

A slight amount of Fe-O on the rake face in cutting of the Base steel has little influence on the friction coefficient. By contrast, in cutting of the Si and Al alloyed steels, the oxidized adhesive layers form in wide areas; shearing occurs in the interfacial regions between the adhered layers and chips, and the shear strength gives a contribution to change in the friction coefficient. Because a smooth surface of the adhered material is confirmed in cutting of the Si alloyed steel, as shown in Fig. 13, the shear strength is expected to be relatively lower than those for the other steels and the friction coefficient reduces. As shown in Fig. 5(c), the friction coefficients with the Base steel and the Si alloyed steel are nearly the same at the cutting distance of 0.07 m, and the friction coefficient with the Si alloyed steel decreases.
after formation of the adhered layer containing black colored scratches shown in Fig. 8(b). In the case of the Al alloyed steel, Fe of workpiece material adheres with formation of Al2O3, as shown in Figs. 16 and 17. According to Fig. 17, Al2O3 first forms on the TiAlN coating surface, and subsequently, Fe adheres to the top and front areas of the Al2O3 layer having a rough surface. The shearing and separation, then, repeat in the interface with adhesion and fracture of Fe on the chip surface due to high shear strength of the Al2O3 layer. According to work done by Umino et al., the eutectic temperature or melting point of the oxides at the interface between the rake face and chip affects the lubrication characteristics. Because the eutectic temperature of the oxides (Si–O, Fe2SiO4, FeO) in cutting of the Si alloyed steel is 1453 K, the oxides are softened to reduce the shear strength by the heat generation on the rake face. On the other hand, the melting point of Al2O3 in cutting of the Al alloyed steel is 2323 K. The oxide layer remains relatively hard with a high shear strength even at elevated temperature.

Grooves caused by abrasive hard inclusions in the steel are observed on the rake face in cutting of the Base steel, as shown in Fig. 11(a), while no wear mark is observed in cutting of the Si alloyed steel due to the Fe–Si–O layer covering the rake face and acting as a protective film that suppressed wear, as shown in Fig. 13(b). In the case of the Al alloyed steel, fracture and delamination of the coated thin layer occur, as shown in Fig. 18, though no wear is observed in each fragment. Furthermore, a white etching layer exists in the tool substrate under the cracked and delaminated areas in each fragment. Furthermore, a white etching layer exists on the rake face in cutting of the Base steel, but little wear is observed in cutting of the Si alloyed steel. With the Si alloyed steel, the oxidized adhesive layer continuously covers the rake face surface and acts as a protective film suppressing wear. In cutting of the Al alloyed steel, crack generation, propagation and delamination occur in the coated thin layer due to softening of the tool substrate with phase transformation in cutting, as the Al alloyed steel exhibits high cutting resistance and temperature.

5. Conclusions

Cutting tests with a fly tool were conducted to discuss the effect of Si and Al additions on the machinability in gear cutting. In order to exclude the effects of hardness, microstructure, and other alloying elements, this study prepared three types of model steels so that hardness of approximately 201 HV and mainly fine pearlite microstructure were nearly the same through the control of heat treatment conditions: Fe–0.55%C (Base steel), Fe–0.55%C–1%Si (Si alloyed steel), and Fe–0.55%C–1%Al (Al alloyed steel). First, the effects of Si and Al additions on the shear stress on the shear plane, shear strain, and friction coefficient were characterized in analytical cutting force model based on minimum cutting energy. Next, the tool damage was associated with the adhesion behavior on the rake face. The results are summarized as follows:

(1) Cutting force

Si addition reduces the cutting force, while Al addition increases the cutting force. The difference is mainly caused by the friction coefficient on the rake face. Few adhered materials exist on the rake face when cutting the Base steel. The oxidized adhesive layer containing Si–O, Fe2SiO4, and FeO forms when cutting the Si alloyed steel, while the oxidized adhesive layer mainly composed of Al2O3 forms when cutting the Al alloyed steel. The changes in the friction coefficient depend on the shear strength of the oxidized layers in cutting. The Si–O, Fe2SiO4, and FeO, which have relatively low eutectic temperature, are softened to become low shear strength due to the heat generation on the rake face. By contrast, the Al2O3 with a high melting point remains relatively hard with a high shear strength.

(2) Tool damage

Abrasive wear is confirmed on the tool surface in cutting of the Base steel, but little wear is observed in cutting of the Si alloyed steel. With the Si alloyed steel, the oxidized adhesive layer continuously covers the rake face surface and acts as a protective film suppressing wear. In cutting of the Al alloyed steel, crack generation, propagation and delamination occur in the coated thin layer due to softening of the tool substrate with phase transformation in cutting, as the Al alloyed steel exhibits high cutting resistance and temperature.

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