Effect of Si in Workpiece Material on Tool Wear in Hard Turning

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The influence of Si content in steel on tool wear in turning of 0.8 mass% C hardened steels with TiAlN coated CBN cutting tools is investigated. The Si contents in the steels are varied between 0.05 and 0.6 mass%. Although these steels have similar microstructure, hardness and volume fraction of retained austenite, the width of the flank wear of the tool increases with increasing the Si content. Adhered oxides are formed on the flank face after cutting, and the amounts, compositions and crystal structures of these oxides are changed as the Si content is varied. The higher Si content results in large amounts of adhered oxides. The crystalline oxide containing a large amount of Fe is mainly formed when cutting the 0.2 mass% Si steel, while the amorphous oxide containing a large amount of Si is mainly formed when cutting the 0.6 mass% Si steel. At the interfaces between the tool coating and the adhered oxides, the Al element of the tool coating tends to diffuse more easily into the Si containing amorphous oxide than into the Fe containing crystal oxide. This indicates that the Si containing amorphous oxide, formed with the higher Si added steel, promotes diffusion wear, resulting in increased tool wear.

KEY WORDS: hardened steel; machinability; turning; cubic boron nitride; Si.

1. Introduction

Special steel parts, particularly gears and pulleys for CVT, are made from steel bars through many processes, e.g. forging, machining, and surface hardening. Many of these parts undergo a finishing process after surface hardening to improve their dimensional accuracy. Finishing processes usually involve grinding using grinding wheels. Recently, hard turning, a machining technique for hardened steel, has gained attention by making part manufacturing processes more efficient and reducing the manufacturing costs.

The tool material must preferably be three times harder or more than the workpiece material in order to stably cut the workpiece. Thus, workpieces with hardness enhanced to 700 HV or higher via carburizing and quenching or any other surface hardening method are difficult to be processed using carbide tools with hardness of about 1 500–2 000 HV.1) Meanwhile, the practical application of cubic boron nitride (CBN) sintered tools with a hardness ≥ 3 000 HV has enabled turning of hardened steels.2) In the finishing process, when grinding is replaced with turning, maintenance of grinding wheels can be omitted and equipment costs can be reduced. Some researchers have reported that hard turning can exert high compressive residual stress (about 1 000 MPa) on the surface of a processed part when the turning conditions are appropriate and that this residual stress can improve its fatigue strength.3) Furthermore, an affected layer formed on the surface of a workpiece after hard turning due to ultra-high deformation is expected to improve the characteristics of steel parts.4)

Although hard turning has the aforementioned advantages, it is not practically and widely used because it requires expensive CBN tools. Therefore, extending the tool life is important for reducing the costs. Regarding the tool life for hard turning, many reports have investigated the influence of tool materials and workpiece materials. A previous study has suggested optimum CBN content for improving the toughness and hardness of the tools for cutting bearing steel.5) Another study has revealed that ceramic binders are better than metal binders in terms of adhesive wear resistance.6) Regarding the influence of workpiece material composition on tool life, Ånmark et al.7) reported that when Ca-treated hardened steel is cut, multiple protective oxide layers of (Mn, Ca)S and (Ca, Al)(O, S) are formed on the tool, resulting in improved tool life. In addition, in the case where the work material is other than hardened steel, some researchers have reported that when cast iron is cut using a CBN tool, high Si content in the workpiece increases tool wear because Si in the workpiece reacts with Al in the tool binder, which changes the binder into SiAlON with low high-temperature strength.8,9)

As alloy contents in special steel are often adjusted to improve the mechanical characteristics, clarifying how alloying elements affect the tool wear during hard turning is important. Si can enhance the resistance to softening during tempering and thus is often added to enhance the surface
fatigue strength. In this study, we investigated the influence of Si in workpiece material on the wear of a CBN tool in the turning of 0.8 mass% C hardened steels.

2. Experimental Procedures

2.1. Workpiece Material

The chemical compositions of four tested steel workpieces are shown in Table 1. The basic composition of the four workpiece materials was that of JIS Cr–Mo steel, a common alloy steel for machine structural use. While the amount of C was 0.8 mass% (hereinafter referred to as “%”) for all four materials assuming a carburized layer, the amounts of Si were varied for individual materials to 0.05%, 0.2%, 0.3%, and 0.6%. Each material with different Si content was first casted in a vacuum melting furnace to produce a steel ingot of 50 kg and was then forged at a heating temperature of 1 198 K for 3.6 ks, the round bar was reduced in diameter to 35 mm via machining. Next, the machined round bar was heated at 1 203 K for 3.6 ks and retained at 1 103 K for 1.8 ks, followed by oil quenching, as shown in Fig. 1. This heat treatment was conducted in a carburizing atmosphere with the carbon potential (CP) at 0.8% to prevent the round bar from being decarbonized. Then, the round bar was heated at 453 K for 7.2 ks for tempering. Subsequently, it was cut and the resulting round bar had a diameter of 40 mm. After being normalized at 1 198 K for 3.6 ks, the round bar was reduced in diameter to 35 mm via machining. Next, the machined round bar was heated at 1 203 K for 3.6 ks and retained at 1 103 K for 1.8 ks, followed by oil quenching, as shown in Fig. 1. This heat treatment was conducted in a carburizing atmosphere with the carbon potential (CP) at 0.8% to prevent the round bar from being decarbonized. Then, the round bar was heated at 453 K for 7.2 ks for tempering. Subsequently, it was cut and the resulting round bar had a diameter of 30 mm and a length of 300 mm. The four workpiece materials prepared herein were used for the cutting tests. Further, the plane parallel to the longitudinal direction of each round bar with 30 mm in diameter underwent observation of the microstructure using an optical microscope, Vickers hardness testing, and measurement of the retained austenite volume fraction using X-ray diffraction. In the cutting tests, the area on the outer periphery, depth not exceeding 2 mm from the surface of the round bar, where the microstructure and hardness were confirmed to be uniform, was repeatedly cut, as shown in Section 2.2.

2.2. Cutting Test and Analysis Method

In the cutting tests, the workpiece materials underwent longitudinal turning using a numerically controlled (NC) lathe. As a cutting tool, a commercially available coated CBN tool (4NC-CNAG120412LS-BNC200, Sumitomo Electric Hardmetal Corp.) was used. Water-soluble cutting fluid was used to conduct the wet cutting tests with conventional flood cooling. The chemical composition of the PVD coating and binder of the tool was TiAlN. The thickness of the coating was approximately 2 μm. Assuming the finishing process of the carburized parts, the depth of cut was 0.1 mm and the feed rate was 0.3 mm/rev. These cutting conditions were within the ranges recommended by the tool manufacturer. The cutting speed was set to 200 m/min, which was slightly higher than the value recommended by the tool manufacturer for accelerating the wear of the tool in order to make it easier to observe the differences between the four steel materials. The tool was moved in the longitudinal direction of round bars from a cutting start position with a predetermined depth of cut. Once the tool reached near the edge of the round bar, the tool was separated from the round bar to start cutting again from the cutting start position in the same manner. This process was repeated for 300 s in total in a test. The cutting force for 5 s from the cutting start was measured using a dynamometer to obtain the average value. The chips produced during the first 5 s of cutting were also collected to observe the shape and microstructure using a digital camera and microscope. The cross-sections of the chips were prepared through embedding and polishing. Each test was conducted once, since previous work7) with similar cutting tests shows the standard deviation in the test is expected to be small. The depth of cut of 0.1 mm was small against the nose radius of the tool of 1.2 mm. This would cause the tool to wear on the end cutting edge side at the corner radius, as shown in Fig. 2. This study evaluated the flank wear, which is particularly important as it would affect the surface integrity of the finished parts. After cutting for 300 s, a region of the tool flank in the square shown in Fig. 2(a) was observed using a microscope from a direction that was almost face to face with the region (direction with arrow A in Fig. 2(a)) and the maximum wear width was determined as the flank wear width. When a material adhered at the boundary between a worn area and unworn area was observed, the upper end of the adhered material was regarded as the boundary. This will be discussed later using Fig. 8. The crater wear is important as it may deteriorate the strength of the cutting edge or cause the cutting edge recession. However, the crater wear occurs at the chamfer, as shown in Fig. 2(b), which may lower the accuracy of the measurement of tool wear. For this reason, the crater wear was not evaluated in this study. The elemental analysis on the tool flank after cutting was performed using scanning electron microscopy–energy dispersive X-ray spectrometry (SEM–EDS) with an acceleration voltage of 15 kV. A cross-section perpendicular to the worn surface on the flank was created using focused ion beam (FIB). The sample stage in the SEM was tilted by 52° to observe the cross section. Before processing using FIB, Pt vapor deposition was conducted to protect the surface of the samples. A thin film specimen was sampled from each adhered material on the tool using FIB to be analyzed with scanning transmission electron microscopy–energy dispersive X-ray spectrometry (STEM–EDS) at an acceleration voltage of 200 kV. The crystal structures of the adhered materials were analyzed.

Table 1. Chemical composition of the workpiece materials (mass%).

|    | C  | Si  | Mn  | P  | S  | Cr | Mo |
|----|----|-----|-----|----|----|----|----|
| 0.0Si | 0.81 | 0.05 | 0.79 | 0.013 | 0.010 | 1.20 | 0.20 |
| 0.2Si | 0.82 | 0.20 | 0.79 | 0.015 | 0.011 | 1.18 | 0.19 |
| 0.3Si | 0.83 | 0.29 | 0.79 | 0.013 | 0.010 | 1.20 | 0.20 |
| 0.6Si | 0.82 | 0.57 | 0.81 | 0.011 | 0.010 | 1.20 | 0.20 |

Fig. 1. Heat treatment pattern for the workpiece materials. The hardening is conducted under the carburizing atmosphere with a carbon potential (CP) of 0.8.
using selected area electron diffraction.

3. Results

3.1. Characteristics of the Workpiece Materials, Chip Shapes and Cutting Forces

All of the four workpiece materials had tempered martensite structures containing retained austenite, as shown in Fig. 3. The Vickers hardness was 712–734 HV. The retained austenite volume fractions were 22.5–23.4 vol.%. Thus, the added amounts of Si had little influence on the microstructure, hardness, and retained austenite volume fraction.

The chips were in continuous shapes with almost no curl as shown in Fig. 4, showing only small differences between

Fig. 2. (a) Overview of a cutting tool and (b) typical tool wear patterns. (Online version in color.)

Fig. 3. Microstructure, hardness and retained austenite contents of the workpiece materials.

Fig. 4. Chips collected during first 5 s cutting tests.
the four steel materials. In Fig. 5, each chip appears as saw teeth with cyclic sharp projections and depressions on the free surface side. A white layer was formed on the tool-chip contact surface. The thickness, spacing between the saw teeth and appearances of the formed white layers from the four steel materials were similar. The tangential component, radial component and longitudinal component of the average cutting force during first 5 s of cutting were almost at the same level between the four steels, as shown in Fig. 6.

3.2. Wear and Surface Appearance of the Tool Flanks

As shown in Fig. 7, as the Si content increases, the flank wear increases. This is due to the higher tendency of adhesion and consequently higher flank wear. The SEM images in Fig. 8 show two different types of adhered materials indicated by arrows showing I and II.
wear becomes larger. As shown in Fig. 8, the coating was worn and the base material CBN was exposed at the end of the cutting edge with any four steel materials. In addition, two types of adhered materials (lighter and darker contrasts) were observed. They are marked as “I” and “II,” respectively, in Fig. 8. Adhered material I was located around the center of the wear width, and its amount tended to increase as the Si content increased. Adhered material II was mainly observed at the lower end of the contact region between the tool and the workpiece material. Adhered material I was hardly seen for the 0.05Si steel. For the other steels, as the Si content increased, the amount and area of the adhered material increased.

3.3. Adhered Materials on the Tool Flanks

3.3.1. Adhered Materials on the Tool Flank when Cutting the 0.2Si Steel

Mainly O and Fe were detected in the adhered materials of the 0.2Si steel, as shown in the EDS maps of the tool flank in Fig. 9. In the enlarged image of the adhered materials and EDS point analysis result shown in Fig. 10, the detected EDS peaks of Ti, Al, and N were from the TiAlN coating. O, Fe, Si, Mn, and Cr were detected in the adhered material I. The atomic ratio of metal elements obtained using semi-quantitative analysis was Fe:Si:Mn:Cr = 70:6:11:13, implying that adhered material I mainly contains Fe oxides. O, Fe, Si, Mn, and Cr were also detected in adhered material II, but the atomic ratio of metal elements was Fe:Si:Mn:Cr =

![Fig. 9. SEM image and EDS maps of the flank face after cutting the 0.2Si steel for 300 s. The black rectangle is magnified in Fig. 10. (Online version in color.)](image)

![Fig. 10. (a) Backscattered electron image and (b) EDS spectra of the adhered materials on the flank face after cutting the 0.2Si steel for 300 s. The region of (a) is marked with the rectangle in Fig. 9. The EDS spectra are obtained at the positions indicated by the white crosses at I and II in (a). The white line between X and X’ indicates the position of the cross-section in Fig. 11. The ratios of atomic concentrations of Fe, Si, Mn and Cr are shown in (b).](image)
4:61:31:4 in which the Si content was higher. This indicates that adhered material II mainly comprised Si oxides. Hereinafter, an oxide mainly comprising Fe will be referred to as an Fe-containing oxide, while that mainly comprising Si will be referred to as an Si-containing oxide.

The observed cross-section of the tool flank in Fig. 11 shows that the coating is continuously thinning from the lower end of the worn surface (side X’ in the figure) toward the cutting edge (side X in the figure). The wear width is approximately 50 μm, which is consistent with the value in Fig. 7. On the coating, adhered material II was observed in region A at the lower end of the worn surface, while adhered material I was seen in region B around the center of the wear width. The thicknesses of adhered materials I and II were approximately 0.43 and 0.20 μm, respectively. Region C is near the boundary between a region in which the coating was thinned due to wear and another region in which CBN was exposed due to the wear of the coating. Even at such a boundary, the coating and base material were in complete contact and the surface of the coating was smooth.

Figure 12 shows a STEM image and EDS maps of the interfacial region between adhered material I and the coating corresponding to region B in Fig. 11. Adhered material I comprised two layers, which indicates that the side coming into contact with the tool is an oxide layer containing Fe, Si, Mn, and Cr, whereas the surface side is a metal layer of Fe. The electron beam diffraction pattern obtained from the area containing the two layers in the adhered material within a diameter of approximately 200 nm exhibited the shape of a ring. This shows that adhered material I has a fine grain structure. The interface between adhered material I and the coating was clear and smooth.

3.3.2. Adhered Materials on the Tool Flank when Cutting the 0.6Si Steel

Si, Mn, Cr, O and Fe were clearly detected in the adhered material of the 0.6Si steel, as shown in the EDS maps of the tool flank in Fig. 13. In the point analysis of the adhered material as shown in Fig. 14, O, Fe, Si, Mn and Cr were detected in both adhered materials I and II. The ratio of the metal elements of adhered material II was Fe:Si:Mn:Cr = 5:58:34:3, indicating that the adhered material is a Si-containing oxide, as is the case with the 0.2Si steel in Fig. 10. On the contrary, the atomic ratio of the

![Fig. 11. SEM images of a FIB cross-section of the flank face after cutting the 0.2Si steel for 300 s. The cross-section was obtained at the position of the white line between X and X’ in Fig. 10. An overview image is shown in the upper part and the areas within the black rectangles A, B and C are magnified in the lower images.](image1)

![Fig. 12. STEM bright field image and EDS maps of a cross-section through the adhered material formed after cutting the 0.2Si steel at the position corresponding to the area B in Fig. 11. Selected area diffraction pattern in the inset was obtained from an area about 200 nm in diameter in the adhered material. (Online version in color.)](image2)
Fig. 13. SEM image and EDS maps of the flank face after cutting the 0.6Si steel for 300 s. The black rectangle is magnified in Fig. 14. (Online version in color.)

Fig. 14. (a) Backscattered electron image and (b) EDS spectra of the adhered materials on the flank face after cutting the 0.6Si steel for 300 s. The region of (a) is marked with the rectangle in Fig. 13. The EDS spectra are obtained at the positions indicated by the white crosses at I and II in (a). The white line between Y and Y’ indicates the position of the cross-section in Fig. 15. The ratios of atomic concentrations of Fe, Si, Mn and Cr are shown in (b).

metal elements of adhered material I was Fe:Si:Mn:Cr = 26:40:24:10 in which the Si concentration was higher, showing a composition significantly different from that with the 0.2Si steel, as shown in Fig. 10.

The observed cross-section of the tool flank in Fig. 15 shows that the coating is continuously thinning away from the lower end of the worn surface (side Y’ in the figure) toward the cutting edge (side Y in the figure), as is the case with the 0.2Si steel in Fig. 11. The wear width was approximately 58 μm, and it almost accords with the value shown in Fig. 7 as well. Mainly adhered material II of approximately 1.0 μm thick was observed in region A at the lower end of the worn surface. This adhered material was seen on the coating or on adhered material I. In region B, around the center of the wear width, adhered material I continuously covered the coating. The thickness was approximately 0.96 μm, which was approximately twice that with the 0.2Si steel in Fig. 11. Region C is near the boundary at which the coating has worn out. At the boundary, the coating and base material were in complete contact and the coating surface was smooth, as is the case with the 0.2Si steel shown in Fig. 11.

Figure 16 shows a STEM image and EDS maps of a position corresponding to region B shown in Fig. 15. They show that adhered material I comprises two layers. The layer on the tool side is a Si-containing oxide, including Mn and Cr,
Fig. 15. SEM images of a FIB cross-section of the flank face after cutting the 0.6Si steel for 300 s. The cross-section was obtained at the position of the white line between Y and Y’ in Fig. 14. An overview image is shown in the upper part and the areas within the black rectangles A, B and C are magnified in the lower images.

Fig. 16. STEM bright field image and EDS maps of a cross-section through the adhered material formed after cutting the 0.6Si steel at the position corresponding to the area B in Fig. 15. Selected area diffraction pattern in the inset was obtained from an area about 200 nm in diameter in the adhered material. (Online version in color.)

while the layer on the surface side is an Fe-containing oxide mainly comprising O and Fe. The diffraction obtained at a selected area aperture from the adhered material on the tool side with a diameter of approximately 200 nm resulted in a halo pattern, proving that the adhered material was amorphous. The interface between the tool and adhered material I was clear and smooth.

4. Discussion

These experimental results show that the addition of Si to workpiece materials increases tool flank wear when cutting hardened steel. As shown in Fig. 3, the Si content barely affected the microstructure and hardness of the workpiece material. In addition, as evident from Figs. 4 and 5, the appearance and cross-sectional shape of chips barely varied between the steel types. Furthermore, as seen from Fig. 6, the cutting forces barely changed due to the addition of Si. These results indicate that the chip formation behavior in the primary shear zone during cutting is possibly almost the same, regardless of the four steel compositions. Meanwhile, as shown in Fig. 8, the behavior of adhesion of the workpiece materials considerably varies depending on the amount of Si added, which affects the flank wear.

The adhered materials observed in this experiment were mainly two types of oxides as shown as I and II in Fig. 8. As the Si content of the workpiece material increased, the amount of both adhered materials tended to increase. To understand this behavior, the supply of oxygen to the tool flank during cutting and the cutting temperature must be considered. Trent and Wright[11] reported that an oxide is formed outside the position A in Fig. 17 due to oxygen supplied from the air. Here, position A is lower end of the contact area between the tool and the workpiece material.
The tool is in contact with the workpiece material in the area between lower end A and cutting edge O in Fig. 17. Thus, the amount of oxygen that enters the vicinity of lower end A is considerably small and the entering amount of oxygen becomes smaller as it nears cutting edge O. Ueda et al. found that using a two-color thermometer the tool flank temperature reaches approximately 1 173 K when hardened steel with a hardness similar to that in our experiment is cut. Some cutting procedures and cutting conditions differed between our experiment and that of Ueda et al. The largest difference is that Ueda et al. conducted the experiment in a dry process, while our experiment was conducted in a wet process. Tanaka et al. reported that using a cutting fluid decreases the flank temperature by approximately 70–130 K. Based on these reports, the flank temperature in our experiment may have reached at least approximately 1 073 K.

As explained above, the lower end of the contact area between the tool and workpiece material is under high temperature with low oxygen. As a result, Si and other alloying elements that tend to oxidize more easily than Fe were selectively oxidized, regardless of the small added amounts in the workpiece material. Thus, oxides with the composition as shown in Figs. 10(b) (II) and 14(b) (II) were formed. Aiso et al. reported that in a sliding contact test between a tool and steel material simulating cutting, easily oxidized alloying elements in the steel are enriched in adhered materials. These results support the aforementioned interpretation in this study. For the elements contained in the oxides observed in our experiment, Si, Mn, Cr, and Fe are easily oxidized in this order. The concentration of the elements in adhered material II follows this sequence, as shown in Figs. 10(b) and 14(b), showing the significant effect of easily oxidized elements in the steel on the formation of the adhered material II. For this reason, adhered material II was hardly formed for the 0.05Si steel with a small added amount of Si. As the added amount of Si increased, the amount and area of the formed adhered material II increased.

Figure 10(b) shows that the concentration of Fe in adhered material I with the 0.2Si steel is high. Thus, the adhered material I is possibly the workpiece material itself that adhered to the tool during cutting and was oxidized when the tool was exposed to air. As explained in Section 2.2, in our experiment the tool was moved in the longitudinal direction at a predetermined depth to cut the steel. When the tool reached near the end of the round bar of the workpiece material, the tool was separated from the workpiece material. Cutting was initiated again from the cutting start position, and this process was repeated. During these processes, when the tool is separated from the workpiece material, the adhered material on the tool surface is exposed to air and oxidized. This is supported by the fact that Fe and O existed on the tool side, whereas Fe existed on the surface side, as shown in Fig. 12. For the 0.6Si steel, adhered material I contains Si, Mn and Cr in relatively large concentrations in addition to Fe, as shown in Fig. 14(b). This is because as shown in Fig. 16, adhered material I comprises two layers of an Si-containing oxide and Fe-containing oxide, while the results in Fig. 14(b) are the averages of both oxide compositions. In other words, the Si-containing oxide was first formed on the tool and then the Fe-containing oxide, which was oxidized workpiece material itself, adhered on top of the Si-containing oxide. The mechanism of the increase in the amount of adhered material I with the increase in the added amount of Si is likely as follows: With higher Si concentration in the steel, the area in which an Si-containing oxide adheres spreads wider to cover the flank wear region around the lower end of the contact area between the tool and the workpiece. This Si-containing oxide promotes the adhesion of the Fe-containing oxide. Heinrichs et al. reported that the unevenness of the tool surface or the chemical affinity between the tool and workpiece material significantly affects the adhesion of the workpiece material on the tool. In our study, the chemical affinity between the Si-containing oxide and Fe-containing oxide is likely to have a major influence on the formation of the two-layered adhered material I because of the facts that both oxides were formed originally through oxidation reaction of the workpiece material itself and that the interface between the oxides seems continuous in Fig. 16.

As shown in Figs. 11 and 15, the coating has continuously worn. However, no detachment or cracking of the coating is observed. This means that normal wear, such as abrasive wear, adhesive wear, and diffusion wear, constitutes the main mechanism for all steels. In our study, the oxygen contents in all steels did not exceed 0.002% and Al, a strong deoxidation element, was sufficiently added to all steels at approximately 0.03%. Therefore, the amount and size of hard inclusion in steels barely vary due to differences in the Si content of the workpiece material. Consequently, the abrasive wear loss should remain unchanged by adding Si. In addition, at the boundary between a region where CBN is exposed and another region where the remaining coating shown in region C in Figs. 11 and 15 exists, the coating is continuously thinning due to wear, while any piece of the coating taken away with adhered material was not observed. Therefore, believing that the addition of Si caused the adhesive wear to vary significantly is difficult. Consequently, the addition of Si caused differences in the diffusion wear behavior to vary.

By focusing on adhered material I located near the center of the wear width, we conducted STEM–EDS linear analysis of the interface between the adhered material and tool for each of the 0.2Si steel and 0.6Si steel, as shown in Fig. 18. For both steels, the composition on one side of the inter-

![Fig. 17. Schematic illustration of a cutting process showing oxygen supply from the atmosphere to a flank face. The cutting edge and the end of the contact zone between the tool and the workpiece are indicated by positions O and A, respectively.](image-url)
face differs significantly from that on the other side. The components of the coating are barely found in the adhered material. This is likely because the diffusion layer between the adhered material and tool was extremely thin for a linear analysis step of 20 nm, which made it difficult to detect elements near the interface. To resolve this issue, the tool used in the cutting test was heat-treated before the interface was analyzed. The following heat treatment conditions were set: the heat treatment temperature at 1 173 K assuming the flank temperature during cutting in hard turning and the heating time for 7.2 ks for sufficient diffusion. For the 0.2Si steel shown in Fig. 19(a) of the result with the heat-treated sample, it is indicated that the cutting interface is mainly the tool and Fe-containing oxide, with no coating components found in the Fe-containing oxide. On the contrary, for the 0.6Si steel in Fig. 19(b), it is shown that the cutting interface is mainly the tool and Si-containing oxide, with Al of a component of the tool coating found in the Si-containing oxide. These results indicate that Al, a coating component, diffuses more easily into Si-containing oxides.

Ikeda and Satoh found that when a TiAlN coating is oxidized, Al atoms in TiAlN are selectively oxidized to form Al oxides on the outermost layer and Ti–Al oxides, Ti oxides, or their oxynitrides under the outermost layer. They have also reported that same type of selective oxidation of Al occurs in actual cutting due to the heat generated during cutting. In addition, Al is more easily oxidized than Si, and Al tends to form an oxide more easily than a nitride. Based on these, in this experiment, Al might be thermodynamically more stable after forming an oxide in the adhered material than existing as Al in the coating. For example, Al may form an oxide through a process in which a chemical compound with an intermediate composition, as described above, is formed or a process in which a nitride is dissolved. In addition, as shown in Figs. 12 and 16, the Fe-containing oxide for the 0.2Si steel had a fine grain structure, while the Si-containing oxide for the 0.6Si steel was amorphous. The atomic arrangement of amorphous does not possess long-range order; thus, not all atoms are contiguously arranged in the same manner, forming irregular spacing. For instance, when comparing α-Fe with an Fe-based amorphous alloy, the diffusion coefficient in the amorphous alloy is larger by $10^5$–$10^7$. This implies that the diffusion coefficient of Al may have been higher in the Si-containing oxides than in the Fe-containing oxides due to differences in the crystal structures of the oxides. Therefore, it is considered that once a Si-containing oxide adhered, Al in the coating diffused to the adhered material to be oxidized through the processes described above. The coating was worn when the Al component was transported away together with the adhered material of Si-containing oxide during cutting.

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![Fig. 18.](image1)

**Fig. 18.** EDS line profiles obtained at the interface between the tool and adhered material formed when cutting (a) the 0.2Si and (b) 0.6Si steels. The vertical axes are ratios of atomic concentrations of Fe, Si, Al, Ti, Mn and Cr. The analyzed positions of (a) and (b) correspond to the regions in Figs. 12 and 16, respectively.

![Fig. 19.](image2)

**Fig. 19.** EDS line profiles obtained at the interface between the tool and adhered material formed when cutting (a) the 0.2Si and (b) 0.6Si steels, after the samples were heat-treated at 1 173 K for 7.2 ks. The vertical axes are ratios of atomic concentrations of Fe, Si, Al, Ti, Mn and Cr. The analyzed positions of (a) and (b) correspond to the regions in Figs. 12 and 16, respectively.
It is reported that when soft steel with a hardness of approximately 200 HV is cut, flank wear is mainly caused due to abrasive wear. Meanwhile, Enomoto and Kato showed that the flank temperature in hard turning where workpiece materials have high hardness became higher by approximately 180 K than that in turning of soft material. As the hardness of the workpiece materials used in our study was ≥700 HV, the flank temperature became high, increasing the diffusion wear. The addition of Si increases the tool wear during hard turning because the formation of Si-containing oxides on the tool promotes the diffusion wear.

5. Conclusions

Hardened steels with different added amounts of Si (0.05–0.6%), having a hardness ≥700 HV, were turned using a TiAlN-coated CBN tool to investigate the influence of Si in the steel on the tool wear. The main conclusions are summarized as follows:

(1) Although the microstructure, hardness and retained austenite volume fractions barely changed by differences in the added amounts of Si and the differences in the shapes of chips and cutting forces were small, the tool flank wear width increased as the added amount of Si was increased.

(2) As the added amount of Si increased, the amount of material adhered on the tool flank increased. Additionally, its composition was found to have changed. At the center of the flank wear width, crystalline Fe oxides mainly adhered on the tool when 0.2% Si steel was cut, while amorphous Si oxides mainly adhered on the tool when 0.6% Si steel was cut.

(3) The tool used to cut each steel material was heat-treated, and next the interface between the adhered material and tool was analyzed. For the 0.2% Si steel, no component of the tool coating was found in the adhered material. On the contrary, for the 0.6% Si steel, Al of a coating component was found in the adhered material. It is considered that after a Si oxide adhered on the tool, Al in the tool coating diffused to the adhered material and oxidized. The coating component Al was transported away together with the adhered material during cutting, promoting the wear. The tool wear increased with an increase in the Si content in the steel due to this acceleration of diffusion wear. This effect likely became obvious during hard turning where the cutting temperature was high with high hardness of the workpiece material.

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