Properties and cutting performance of AlTiCrN/TiSiCN bilayer coatings deposited by cathodic-arc ion plating

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Abstract

This study was intended to investigate the properties and cutting performance of AlTiCrN/TiSiCN bilayer coatings. These coatings were deposited on cemented carbide substrate by the cathodic-arc ion plating method, using AlTiCr and TiSi alloy source. The properties of these coatings were investigated by nano-indentation, transmission electron microscopy (TEM), Electron Energy-Loss Spectroscopy (EELS) and pin-on-disc test. Nano-indentation hardness of AlTiCrN and TiSiCN were 41 GPa and 51 GPa, respectively. AlTiCrN layer was columnar structure and its size was less than 50 nm. Furthermore, the TiSiCN layer appeared to have nano crystalline structure and measured about 5 nm. In particular, TiSiCN film showed good tribological behavior and its friction coefficient measured 0.18 for the bearing steel counterparts (AISI 52100). AlTiCrN/TiSiCN bilayer coated carbide endmills were also evaluated in the machining of carbon steel (AISI 1049), hardened steel (AISI D2) and gray cast iron (AISI 35). These coated endmills showed better wear resistance than comparative TiAlN coated endmills. The tribological properties of TiSiCN layer decreased adhesion; however, the cutting performance of the mono layer TiSiCN coated endmill showed high compressive residual stress, which resulted in poor cutting performance. AlTiCrN/TiSiCN bilayer coatings showed exceptional cutting performance for all types of work materials.

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Keywords: AlTiCrN/TiSiCN bilayer; Cathodic-arc; Cutting performance

1. Introduction

To increase wear resistance of cutting tools, a TiAlN film is coated on the surface of WC–Co base cemented carbide [1]. However, recently from the perspective of environmental conservation, dry machining without the use of cutting fluids has been developed and also cutting speeds have been increased to improve cutting efficiency, causing increased temperatures of cutting edge. Accordingly, materials that can replace TiAlN are required. It is widely known that TiAlN film has different properties depending on the Al composition and becomes significantly hardened and shows excellent cutting performance [2] when the Al content is about 60 at.%. Furthermore, a proposal has been made about methods of adding Cr [3] or Si [4,5] as well as methods of alternately applying different coating materials, such as TiN/AlN [6], in order to further increase hardness and heat resistance.

In the attempt of adding Cr, research shows that a slight addition of Cr to AlTiN results in excellent cutting performance in the cutting of hardened steels [7]. Recently, research on TiSiN, which has excellent hardness and heat resistance, has been conducted [8,9]. Since TiSiN has significantly high compressive residual stress and adheres poorly to a substrate, it is impossible to use only a mono layer of TiSiN for cutting tools. Furthermore, material being machined, easily adheres to the TiSiN coating surface, which causes removal or peeling of the coating and chipping of the cutting edge, resulting in a short tool life.

Thus, in this study, AlTiCrN/TiSiCN bilayer coatings were deposited which have an upper layer of TiSiCN film to which carbon is added to increase adhesion resistance of TiSiN, and microstructure, mechanical properties and cutting performance were evaluated.

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2. Experimental procedure

2.1. Deposition conditions

In this study, AlTiCrN/TiSiCN bilayer coatings were deposited by the cathodic-arc ion plating method (Kobe Steel AIP-S40) which consisted of a mono layer of TiAlN and a mono layer of TiSiCN for comparison. As a substrate for evaluating film properties, a WC–Co base cemented carbide substrate (SNGN120408) having an average surface roughness Ra of 0.01 μm or less which has been achieved by mirror polishing was used, and WC–Co base cemented carbide endmills were also tested.

First, a substrate is set in a holder in the coating chamber and the Ar ion etching (cleaning) was performed for 30 min in the 1.3 Pa Ar gas atmosphere in which the substrate temperature reached 873 K and the substrate bias voltage was −800 V. After the Ar ion etching had finished, various types of coatings were deposited under the conditions shown in Table 1.

2.2. Microstructure analysis

The cross-sectional microstructures of the AlTiCrN/TiSiCN bilayer coatings were then analyzed. Observation was made with an acceleration voltage of 300 kV by using an H-9000UHR Transmission Electron Microscope (TEM) made by Hitachi High-Tech Science Systems. With respect to the TiSiCN layer, the element distribution in the local region was measured by using the Electron Energy-Loss Spectroscopy (EELS).

2.3. Mechanical properties

Hardness of the AlTiCrN layer and the TiSiCN layer of the AlTiCrN/TiSiCN bilayer coatings were individually measured by using a nano-indentation made by CSM. After the coated SNGN120408 cemented carbide substrate had been machined by means of skew mirror polishing, hardness was measured at 10 locations on the cross-section with a maximum load of 1.3 Pa. As a substrate for evaluating the TiSiCN layer, the element distribution in the local region was measured by using the Electron Energy-Loss Spectroscopy (EELS).

Table 1
Deposition conditions

<table>
<thead>
<tr>
<th>Film</th>
<th>AlTiCrN/TiSiCN bilayer</th>
<th>TiSiCN monolayer</th>
<th>TiAlN monolayer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target composition (at.%)</td>
<td>Al₆₀Ti₃₅Cr₅/Ti₈₀Si₂₀</td>
<td>Ti₈₀Si₂₀</td>
<td>Ti₆₀Al₄₀</td>
</tr>
<tr>
<td>Arc current (A)</td>
<td>150/150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Bias voltage (V)</td>
<td>−40/−200</td>
<td>−200</td>
<td>−40</td>
</tr>
<tr>
<td>Gas</td>
<td>N₂/N₂:CH₄ = 1:1</td>
<td>N₂:CH₄ = 1:1</td>
<td>N₂</td>
</tr>
<tr>
<td>Pressure (Pa)</td>
<td>2.6/2.6</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>2/1.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

2.4. Cutting performance

Cutting performance of the endmills coated by AlTiCrN/TiSiCN bilayer coatings, a mono layer of TiAlN, and a mono layer of TiSiCN were individually evaluated. Cutting performance of the endmills coated by AlTiCrN/TiSiCN bilayer coatings was measured by a RINT2400 made by Rigaku by using the Cu Kα line (λ=0.1541 nm), and stress σ was obtained by the following equation:

\[ \sigma = - \frac{E}{2(1+\nu)} \frac{\cot \theta_o - \pi}{180} \frac{E}{\sin^2 \Psi} \]

δ(2θ)/δ(sin2ψ) is a gradient of 2θ−sin2Ψ indicating a linear relationship. Furthermore, E denotes Young’s modulus, ν denotes Poisson’s ratio, θo denotes standard Bragg angle, and values of TiN were used in this study (E=429 GPa; ν=0.19).

With regard to the tribological properties, friction coefficients were measured by a pin-on-disc testing machine made by CSM, and wear modes were compared between the pin and the substrate. Evaluation conditions of the pin-on-disc test are described below.

Pin: bearing steel (AISI52100), substrate: SNGN120408 cemented carbide substrate (mono layer of TiAlN and mono layer of TiSiCN), revolution: 500 rpm, load: 2 N, radius: 1 mm, 2 min at room air temperature.

3. Results

3.1. Microstructure analysis

Fig. 1 shows the structures of the AlTiCrN layer and the TiSiCN layer viewed using a TEM. The AlTiCrN layer has excellent crystalline properties and has a microscopic columnar structure of 50 nm or less. On the other hand, in the TiSiCN layer, crystalline structures of 5 nm or less are dispersed in the adjacent amorphous layer. Table 3 shows the element ratio with regard to crystalline structure B-1 and amorphous structure B-2 measured by the EELS. The crystalline structure B-1 mainly

Table 2
Cutting conditions

<table>
<thead>
<tr>
<th>Work material</th>
<th>Tool shape (endmill)</th>
<th>Speed (m/min)</th>
<th>Feed rate (mm/tooth)</th>
<th>Axial depth of cut (mm)</th>
<th>Cutting length (m)</th>
<th>Condition</th>
<th>Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1049 (HB185)</td>
<td>Dia6 mm, 4 teeth</td>
<td>200</td>
<td>0.15</td>
<td>10</td>
<td>50</td>
<td>Down cut</td>
<td>Air blow</td>
</tr>
<tr>
<td>AISI D2 (HRC61)</td>
<td>Dia10 mm, 6 teeth</td>
<td>150</td>
<td>0.06</td>
<td>1.2</td>
<td>30</td>
<td>Down cut</td>
<td>Air blow</td>
</tr>
<tr>
<td>AISI 35 (HB220)</td>
<td>Dia6 mm, 4 teeth</td>
<td>180</td>
<td>0.18</td>
<td>0.6</td>
<td>180</td>
<td>Down cut</td>
<td>WET</td>
</tr>
</tbody>
</table>

Table 3
Element ratios of the AlTiCrN layer

<table>
<thead>
<tr>
<th>Element</th>
<th>B-1</th>
<th>B-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>42%</td>
<td>45%</td>
</tr>
<tr>
<td>Ti</td>
<td>27%</td>
<td>30%</td>
</tr>
<tr>
<td>Cr</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>N</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Si</td>
<td>5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Fig. 1 shows the structures of the AlTiCrN layer and the TiSiCN layer viewed using a TEM. The AlTiCrN layer has excellent crystalline properties and has a microscopic columnar structure of 50 nm or less. On the other hand, in the TiSiCN layer, crystalline structures of 5 nm or less are dispersed in the adjacent amorphous layer. Table 3 shows the element ratio with regard to crystalline structure B-1 and amorphous structure B-2 measured by the EELS. The crystalline structure B-1 mainly
consists of TiCN. On the other hand, since the content of Ti is reduced and Si is increased, the amorphous layer mainly consists of Si–C–N.

### 3.2. Mechanical properties

Results of measured nano-indentation hardness of AlTiCrN/TiSiCN bilayer coatings and a mono layer of TiAlN, are individually shown in Fig. 2. The hardness of the conventional TiAlN film is 36.9 GPa, while the hardness of the AlTiCrN layer is 40.7 GPa and the hardness of the TiSiCN layer is 51.1 GPa. This indicates a significant increase in hardness. Additionally, it was found that variations of hardness with regard to the AlTiCrN layer and the TiSiCN layer are significantly small when compared to the variations of hardness of the conventional TiAlN film.

Results of residual stress measured by the XRD indicate that the AlTiCrN film is $-2.8$ GPa and the TiSiCN film is $-5.3$ GPa. Specifically, it was found that the TiSiCN film has compressive residual stress of $-5.3$ GPa which is significantly high.

Fig. 3 shows tribological properties of a mono layer of TiAlN, a mono layer of TiSiN and a mono layer of TiSiCN. With regard to the mono layer of TiSiN, Ti80–Si20 at.% was used as a target material and the film was deposited under the same conditions as that of the mono layer of TiAlN. The friction coefficient of TiSiCN is $\mu = 0.18$ which is relatively small when compared to the values of TiAlN ($\mu = 0.51$) and TiSiN ($\mu = 0.55$). Inspection of the TiSiCN film, showed small wear of the pin (TiSiCN: 0.04 mm, TiAlN: 0.12 mm) and small wear depth of the disk (TiSiCN: 0.06 mm, TiAlN: 0.24 mm), which indicates good tribological properties.

### 3.3. Cutting performance

Fig. 4 shows the SEM micrograph of a damaged cutting edge after cutting carbon steel (AISI1049). Since the mono layer of TiSiCN film starts to exfoliate in the early stage at the cutting edge and wears quickly, evaluation was cancelled at this point when the cut length became 30 m. In comparison with a mono layer of TiAlN, AlTiCrN/TiSiCN bilayer coatings showed good wear resistance comparatively. Fig. 5 shows the SEM micrograph of a damaged cutting edge after cutting hardened steel (AISI D2). The mono layer of TiSiCN film exfoliated and the cemented carbide substrate was exposed resulting in very poor adhesion. Furthermore, in comparison with the width of wear for a conventional mono layer of TiAlN which was 84 $\mu$m, the width of wear for AlTiCrN/TiSiCN bilayer coatings was only 39 $\mu$m.

### Table 3

Relative composition of TiSiCN layer by EELS analysis in at.%

<table>
<thead>
<tr>
<th></th>
<th>Ti</th>
<th>Si</th>
<th>C</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>47</td>
<td>3</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>B-2</td>
<td>25</td>
<td>7</td>
<td>43</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 2. Nano-indentation hardness.
indicating a significant increase in wear resistance. Fig. 6 shows
the SEM micrograph of a damaged cutting edge after cutting
gray cast iron (AISI 35). In the case of gray cast iron, adhesion
occurred between the conventional TiAlN film and the work
material, and delamination of the film was also recognized;
however, there was almost no adhesion on the AlTiCrN/TiSiCN
bilayer coatings indicating good damage morphology.

4. Discussion

Normally, a TiAlN film deposited by the cathodic-arc ion
plating method has a columnar structure of 100 nm or more, while
an AlTiCrN layer has a microscopic columnar structure of 50 nm
or less (Fig. 1). On the other hand, the TiSiCN layer is configured
in such that the crystalline structure mainly consisting of TiCN of
5 nm or less are surrounded by the amorphous layer mainly
consisting of Si–C–N. It is considered that grain boundary slip is
suppressed due to the nano composite of the microscopic crys-
talline structure and the amorphous structure, which results in a
significantly high degree of hardness.

As the result of the miniaturization of the crystalline struc-
ture, as seen as a microscopic columnar structure in AlTiCrN
and a nano composite structure in TiSiCN, hardness becomes
greater and the variation of hardness significantly decreases in
comparison with coarse-grained TiAlN.

Although TiSiCN is significantly hard, it has poor adhesion
to a substrate due to its high compressive residual stress. Tests
conducted cutting carbon steel and hardened steel, in the case of
a mono layer of TiSiCN, the coating is initially exfoliated
thereby increasing wear, while in the case of AlTiCrN/TiSiCN
bilayer coatings, delamination is suppressed showing good
wear resistance (Figs. 4 and 5). It is considered that high
compressive residual stress (−5.3 GPa) of the TiSiCN layer seems to be decreased by the AlTiCrN layer (−2.8 GPa). When using TiSiCN for a cutting tool, a stress relieving layer, such as AlTiCrN, is necessary to ensure adhesion of the coating.

A material having a high lubricity factor is desirable for the coating of cutting tools. This is advantageous because it prevents exfoliation of the coating due to preventing adhesion to the work material as well as preventing abnormal damage to a cutting edge, and also decreases the cutting edge temperature. As shown in Fig. 3, comparison of nitride, such as TiAIN and TiSiN, TiSiCN displayed excellent tribological properties. This is because carbon is contained in the coating as a form of TiSiCN. In the case of work materials, such as gray cast iron and low carbon steel, which are highly adhesive, providing a lubricative TiSiCN film on the surface will significantly increase adhesion resistance. When machining of a significantly harder material, such as hardened steel, it is possible to prevent the coating from oxidative wear so that the cutting edge temperature will not increase.

As stated above, AlTiCrN/TiSiCN bilayer coatings showed excellent cutting performance for all types of work materials from significantly hard materials, such as hardened steel, to adhesive materials such as gray cast iron and low-carbon steel.

5. Conclusion

In this study, AlTiCrN/TiSiCN bilayer coatings were deposited by the cathodic-arc ion plating method, and investigation of the mechanical properties, analysis of the microstructure and evaluation of the cutting performance were carried out. Results are as follows.

1. The hardness of AlTiCrN layer (40.7 GPa) and TiSiCN layer (51.1 GPa) is higher than conventional TiAIN (36.9 GPa).
2. AlTiCrN layer is a microscopic columnar structure of 50 nm or less. TiSiCN layer is nano composite structure in which a microscopic crystalline structure consisting of TiCN of 5 nm or less and amorphous layer mainly consisting of Si–C–N.
3. In comparison with nitride coatings such as TiAIN or TiSiN, TiSiCN showed excellent tribological properties.

<table>
<thead>
<tr>
<th></th>
<th>A 100μm</th>
<th>B 30μm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AlTiCrN/TiSiCN</strong> bilayer</td>
<td><img src="image" alt="AlTiCrN/TiSiCN" /></td>
<td><img src="image" alt="AlTiCrN/TiSiCN" /></td>
</tr>
<tr>
<td><strong>TiAIN monolayer</strong></td>
<td><img src="image" alt="TiAIN monolayer" /></td>
<td><img src="image" alt="TiAIN monolayer" /></td>
</tr>
</tbody>
</table>

Fig. 6. SEM image of the flank wear (AISI D2).

Fig. 6. SEM image of the cutting edge (AISI 35).
(4) Since adhesion to a substrate of TiSiCN monolayer is low, a stress relieving layer such as AlTiCrN is necessary.
(5) AlTiCrN/TiSiCN bilayer coated carbide endmills shows excellent cutting performance for various types of work materials.

References