A Comparative Study of TiAlN and CrAlN Coatings Deposited on Sialon Ceramic Cutting Inserts by Physical Vapor Deposition

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Abstract. TiAlN and CrAlN coatings were prepared by physical vapor deposition (PVD) on Sialon ceramic cutting tools. The results illustrated that the surface morphology of TiAlN coating was smoother than that of CrAlN coating. The thickness of TiAlN coating was about 1 µm, which was thicker than that of CrAlN coating (about 0.5 µm). However, the hardness of TiAlN coating was lower (30.1 GPa) than that of CrAlN coating (37.5 GPa). Also the elastic modulus of TiAlN coating (346.9 GPa) was also lower than that of CrAlN coating (430.7 GPa), indicating that the stiffness of CrAlN coating was better than that of TiAlN coating. According to scratch tests, the adhesion force of TiAlN and CrAlN coatings were 31 N and 45 N, respectively, which revealed that the CrAlN coating exhibited better adhesion than the TiAlN coating. Cutting performance of the TiAlN coated and CrAlN coated Sialon ceramic cutting inserts were investigated by turning nickel-based alloys under dry conditions. For comparison, uncoated Sialon ceramic cutting inserts were also used for turning tests under the same conditions. The results indicated that the cutting performance of the inserts was considerably improved by the TiAlN and CrAlN coatings on the surfaces. The dominant failure mechanisms of the CrAlN coated inserts were abrasive and adhesive wear, whereas adhesive wear and spalling were the main failure mechanisms of the TiAlN coated inserts. The service life of TiAlN and CrAlN coated inserts were much longer than that of the uncoated inserts, indicating that the two coatings could effectively protect the inserts from wear.

Introduction

Because of the excellent properties, such as fracture toughness, high hardness and modulus, Sialon ceramic cutting inserts are usually for machining the high-temperature alloys in dry and high speed conditions [1-5]. But, oxidation, chemical dissolution and frictional wear of the cutting inserts will be happened during the turning process due to the high temperatures encountered [6]. On the surface of the inserts, a wear resistant and hard coating is prepared to protect the inserts from physical and chemical abrasion [7-9].

Nitride-based hard compounds were more frequently chosen as protect coating materials to improve the tool life [7, 10-12]. Owing to excellent oxidation resistance as well as good chemical stability, mechanical and tribological properties, the researches are particularly attracted by TiAlN and CrAlN materials [11, 13-18].

Recently, chemical vapor deposition (CVD) is mainly used to prepare the coatings on Sialon ceramic surfaces [19-21], while reports on preparing coatings by PVD technique are really rare for Sialon ceramics. However, for silicon nitride hard coatings deposited by CVD and PVD, that have been more investigated [9, 22-24].

Liu et al. [9] have investigated silicon nitride cutting inserts with MoS2 coatings, which is prepared by PVD technique. And the inserts wear life was prolonged obviously by the coatings. The structures and properties of nitride hard coatings on nitride tool ceramics were studied by Dobrzański team [22, 23], they revealed that tool life with the hard coatings was limited by low coating/substrate adhesion. Peng and his co-work [24] have prepared a hard TiN coating on the silicon nitride ceramic and proved the tool life for several times for turning hard CrWMn steel.
In this paper, TiAlN and CrAlN coatings were prepared on Sialon ceramic cutting inserts by the PVD technique. The coated Sialon ceramic cutting inserts were applied on turning tests with nickel-based alloys. The cutting performance and wear mechanism of the coated inserts were studied to compare the properties of the two coatings.

**Experimental Details**

**Characterization of the Substrates**

Sialon ceramic cutting inserts were chosen as substrates, made by Ceram Tec (named SL606, Suzhou, China). The phase composition of the inserts was characterized by an X-ray diffractometer (D8 Advance, BRUKER, Germany) with Cu Kα radiation. Data were digitally recorded in a continuous scan in the range of angle (2θ) from 20° to 50°C with scanning rate of 0.08°·s⁻¹. The density of the inserts was determined by Archimedes’ method. The morphologies of Sialon ceramic cutting insert surfaces, which were polished and etched by plasma for several seconds, were observed by scanning electron microscopy (SEM, Quanta 400, FEI, Netherlands).

**Preparation of TiAlN and CrAlN Coatings**

The TiAlN and CrAlN coatings on the surface of Sialon ceramic cutting inserts were produced by the PVD technique (cathodic arc evaporation, CAE). TiAl and CrAl alloy targets were chosen as raw materials to prepare the coatings. The more details and technological parameters were used for the preparation of TiAlN and CrAlN coatings can be found in reference 7.

**Characterization of the Coatings before and after Turning Tests**

The surface and cross-sectional morphologies of the coated Sialon ceramic cutting inserts before and after turning tests were observed by SEM, and the elemental analysis was conducted by energy-dispersive spectroscopy (EDS, Oxford 6650, UK). The elastic modulus (E) and the hardness (H) were determined by a nano-indentor (G200, Agilent, USA) with a Berkovich indenter, the values were calculated by the Oliver-Pharr method according to the reference 25 and 26. Scratch tests for adhesion evaluation of the coated Sialon ceramic cutting inserts were applied on a CSM Revetest scratch tester (Anton Paar, USA). The details of these tests were shown in reference 7.

**Turning Tests of Coated and Uncoated Sialon Ceramic Cutting Inserts**

Turning tests were carried out on a computer numerically controlled center (CNC) lathe (ETC3650h, China). The spindle power of CNC lathe and maximum spindle speed are 15 KW and 4000 rpm, respectively. The test materials were chosen nickel-based alloys (Inconel 718, Shanghai Plate Rods Industrial Co., Ltd., Shanghai, China). The shape of the workpieces was cylindrical with diameter 100 mm and length 200 mm. The chemical composition of the workpieces mainly includes Ni, Cr, Fe. During the turning process, the cutting inserts have a shape of SNGN120712 (12.7 mm × 12.7 mm × 7.94 mm) and the tool holder was CSSNL 2525 M 12-IK7 with rake angle of -6°, relief angle of 0° and edge angle of 45°. The parameters of turning tests were as same with the ones in reference 7. A flank wear of 0.3 mm was used as tool life end criterion. A stereo microscope (OLYMPUS SZ61TR) was used to measure the flank wear width (VB) of the cutting inserts after every cut. In addition, the morphologies of the coated Sialon ceramic cutting inserts after turning tests were observed by SEM. For comparison, uncoated Sialon ceramic cutting inserts were used as well for turning nickel-based alloys under the same conditions.
Results and Discussion

Characterization of SL606 (sialon) and Inconel 718 (steel)

Figure 1. Surface morphology of the SL606 Sialon ceramic cutting inserts.

The main phase of the cutting inserts is $\beta$-Sialon ($\text{Si}_5\text{AlON}_7$, $z=1$), with a small amount of $\alpha$-Sialon ($\text{Y}_{0.68}\text{Si}_{8.8}\text{Al}_{3.2}\text{O}_{1.2}\text{N}_{14.8}$), which is reported in our previous work [7]. The phase ratio of $\alpha/\beta$-Sialon in SL606, calculated according to the literature [27], is about 8:90. In addition, a small amount of $\text{Y}_4\text{SiAlO}_8\text{N}$ is also detected in SL606 materials. It is obviously part of the intergranular phase in the Sialon ceramic. The surface morphology of the SL606 Sialon ceramic cutting inserts is shown in Figure 1. It can be seen that the cutting inserts mainly contains elongated grains ($\beta$-Sialon), which are beneficial to improve the fracture toughness of the cutting inserts due to the pull out and bridging toughening mechanisms. Therefore, the SL606 inserts exhibit excellent cutting properties. The density of the SL606 is 3.21 g cm$^{-3}$. The hardness and fracture toughness of the SL606 are about 16.5 ± 0.2 GPa and 5.4 ± 0.7 MPa m$^{1/2}$, respectively.

Characterization of CrAlN and TiAlN Coatings Prepared by the PVD Technique

Figure 2 shows the surface and cross-sectional morphologies of the CrAlN and TiAlN coated SL606 Sialon ceramic cutting inserts. It can be seen that the surface of CrAlN coating is very rough (Figure 2a). The particles show lamellar structure. However, the zoomed image shows that the coating is very dense and essentially pore-free. The cross-sectional morphology of the CrAlN coating is illustrated in Figure 2b, the coating is very thin, with a thickness of about 0.5 $\mu$m. The coating exhibits good adherence to the substrate. The surface morphology of the TiAlN coating is shown in Figure 2c. It can be seen that the surface is much smoother than that of the CrAlN coating. There are many spherical particles on the surface. From the zoomed image, it can be seen that a small amount of liquid phase is formed and that there are some pores. The thickness of the TiAlN coating is about 1 $\mu$m, and the microstructure of the coating consist of particles with columnar shape (Figure 2d). This phenomenon is a typical characteristic of coatings deposited by the PVD technique.
Figure 2. Surface and cross-sectional morphologies of the CrAlN and TiAlN coated SL606 Sialon ceramic cutting inserts.

Figure 3. Load-displacement-load curves of the CrAlN and TiAlN coatings after nano-indentation tests.

The displacement-load curves of the CrAlN and TiAlN coatings after nano-indentation tests are shown in Figure 3. When the displacements into the surface of CrAlN and TiAlN coatings are about 1000 nm, the corresponding loads are about 310 mN and 238 mN ($P_{1\text{max}}$ and $P_{2\text{max}}$), respectively, indicating that the CrAlN coating is harder than TiAlN coating. From the Figure 3, it is also evident that the slope of the CrAlN coating is steeper than that of the TiAlN coating ($S_1$ and $S_2$ in Figure 3), which means that the load carrying ability of the CrAlN coating is higher than that of the TiAlN coating.

Table 1. Mechanical properties of CrAlN and TiAlN coatings.

<table>
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<tr>
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<th>Hardness (GPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Adherence force (N)</th>
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<tbody>
<tr>
<td>CrAlN</td>
<td>37.5</td>
<td>430.7</td>
<td>45</td>
</tr>
<tr>
<td>TiAlN</td>
<td>30.1</td>
<td>346.9</td>
<td>31</td>
</tr>
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</table>
Table 1 shows the mechanical properties of CrAlN and TiAlN coatings. It can be seen that the hardness values of CrAlN and TiAlN coatings are 37.5 GPa and 30.1 GPa, respectively. The elastic moduli of the CrAlN and TiAlN coatings are 430.7 GPa and 346.9 GPa, respectively, revealing that the stiffness of the CrAlN coating is better than that of the TiAlN coating. The adhesion force between the coating and the substrate, as measured by the CSM Revetest scratch tester, is higher for the CrAlN coating than for the TiAlN coating.

Wear Behavior of the CrAlN and TiAlN Coated and Uncoated Sialon Ceramic Cutting Inserts after Turning Tests

The VB of the CrAlN coated, TiAlN coated and uncoated Sialon ceramic cutting inserts as a function of the cutting length for turning nickel-based alloys are shown in Figure 4. As can be seen, the VB of uncoated Sialon ceramic inserts increases rapidly. When the cutting length reaches about 1000 m, the value of VB is about 375 µm, which indicates that it has already exceeded the tool life end criterion (300 µm), and the inserts are bound to fail. However, the VB of CrAlN coated ceramic cutting inserts increases relatively slowly at the beginning of cutting, but increases with increasing cutting length. The behavior of the TiAlN coated inserts is similar, with VB being slightly higher initially and slightly lower after large cutting length values, exhibiting a crossover at about 1341 m, meaning that the wear resistance of these materials decreases for large cutting lengths. Materials with TiAlN coating exhibit better wear resistance behavior than materials with CrAlN coating. In both cases the cutting length reaches about 2100 m, the corresponding VB of CrAlN coating and TiAlN coating being about 267 µm and 233 µm, respectively (the CrAlN coatings are thinner than the TiAlN coatings). To sum up, both CrAlN and TiAlN coatings can effectively improve the cutting performance and extend the tool life of Sialon ceramic cutting inserts.

Failure Mechanisms of Uncoated, CrAlN Coated and TiAlN Coated Sialon Ceramic Cutting Inserts after Turning Tests

The flank face morphologies and the EDS analysis results for the uncoated, CrAlN coated and TiAlN coated Sialon ceramic cutting inserts after the nickel-based alloy turning tests are shown in Figure 5. As can be seen, there are many grooves on the flank face of the uncoated inserts (Figure 5a), revealing that the dominant failure mechanism is abrasive wear when turning nickel-based alloys under dry conditions. Moreover, there exists a collapse phenomenon in the corner of the inserts. In addition, a few adhering particles and fragments from the workpieces can be found in the
flank wear face, as shown in Figure 5a. This proves that adhesive wear is another failure mechanism of the uncoated Sialon ceramic cutting inserts. The EDS analysis result for point $P_1$ in Figure 5b is shown in Figure 5b. This area mainly contains the elements Si, Al, O and N, which all belong to the Sialon ceramic. Figure 5c illustrates the morphology of flank wear face of the CrAlN coated Sialon ceramic cutting inserts. It is found that abrasive and adhesive wear are the main failure mechanisms. Many grooves and adhered particles are on the surface. The grooves are formed probably due to the thin coating. However, compared with the uncoated ceramic inserts, the abrasive wear level of CrAlN coated ceramic inserts is weaker. Figure 5d shows the EDS analysis result of point $P_2$ in Figure 5c. It can be seen that at this point the materials mainly contains Si, Al, O, N, Ni, Cr and Fe. The elements of Ni Fe and partly Cr come from the workpieces during the turning process, while part of Cr, Al and N may belong to the CrAlN coating. The morphology of TiAlN coated Sialon ceramic cutting inserts after turning test under dry condition is shown in Figure 5e. Compared with
the uncoated and CrAlN coated inserts, there is only one obvious groove in the corner. Therefore, abrasive wear is not the main failure mechanism of the TiAlN coated inserts. The EDS analysis results of point $P_3$ is shown in Figure 5f and shows that this area mainly contains N, O, Cr, Ni, Fe, Al, Si, and Ti. As with the CrAlN coated inserts, the Si, Al, O, and N belong to Sialon ceramic, the Cr, Ni, Fe belong to nickel-based alloys and part of Ti, Al and N may come from the TiAlN coating. The dominating failure mechanism of the TiAlN coated inserts is adhesive wear. It noteworthy, however, that there exists a spalling phenomenon on the surface of the TiAlN coating (Figure 6), indicating that spalling is another failure mechanism of the TiAlN coated Sialon ceramic cutting inserts.

![Figure 6. Detail image of the TiAlN coating.](image)

**Summary**

TiAlN and CrAlN coatings were deposited on the surface of Sialon ceramic cutting inserts by the PVD technique. The microstructures, mechanical properties, cutting performance and wear mechanisms of the coated inserts were studied to compare the properties of the two coatings. The following conclusions can be drawn:

(1) The surface morphology of the TiAlN coating is much smoother than that of CrAlN coating produced by the PVD technique. The hardness of CrAlN and TiAlN coatings are 37.5 GPa and 30.1 GPa, respectively, and the elastic moduli of the two coatings are 430.7 GPa and 346.9 GPa, respectively. The adhesion forces of the CrAlN coating and TiAlN coating on the surface of Sialon ceramic are about 45 N and 31 N, respectively.

(2) The cutting performance of Sialon ceramic cutting inserts is improved remarkably by producing CrAlN or TiAlN coatings on the inserts for nickel-based alloys turning under dry conditions.

(3) The dominant failure mechanisms of the CrAlN coated inserts are abrasive and adhesive wear, whereas adhesive wear and spalling are the main failure mechanisms of the TiAlN coated inserts.

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