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Wear mechanism of thermally transformed CVD Al_2O_3 layer

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Abstract

Wear mechanism of the thermally transformed CVD α-Al_2O_3 that was produced from as-deposited κ-Al_2O_3 by different heat-treatment processes have been investigated. For alloy steel turning, the wear of the transformed α-Al_2O_3 produced by a heat-treatment through a cooling process after κ-Al_2O_3 deposition was uneven, that is, small chippings and flakings of the layer occurred on the wear surface, although its wear resistance was higher than that of as-deposited α-Al_2O_3 and as-deposited κ-Al_2O_3. On the other hand, the transformed α-Al_2O_3 produced by the heat-treatment without a cooling process but in connection to κ-Al_2O_3 deposition showed an excellent wear resistance without uneven wear. For the α-Al_2O_3 transformed without a cooling process, crack generation during the cooling is inhibited by the microcracks that have been generated before the cooling by a phase transformation of $\kappa \rightarrow \alpha$. Wear resistance is improved because the cooling cracks with a wide width, which will act as starting points of the uneven wear, decrease.

Keywords: CVD; Al_2O_3; Heat-treatment; Cutting tool; Wear

1. Introduction

The practical use of coated cutting tools by a chemical vapor deposition (CVD) method on cemented carbide began with the TiC coating in 1969. They rapidly penetrated a market in the world because of its excellent balance of wear resistance and toughness since when the coated cutting tools of which coating layer consists of multi-layer of TiC, TiCN, TiN, and Al_2O_3 were introduced to the market in the middle of 1970s [1–3]. They have been widely used as a main cutting tool material to machine iron parts since the introduction, because a lot of improvements in a performance have been continuously done by energetic research and development.

In the field of machining in recent years, a wrestle with the high efficiency machining, that is, higher cutting speed and/or higher feed rate machining, increases from a viewpoint of the reduction of a consumption energy and machining cost by the productivity improvement. In case of the high speed and high feed rate machining, the heat generation developed at a cutting edge substantially increases, because the chip volume removed by the cutting edge for every unit remarkably increases. The hardness decrease of the tool material and the increase of the oxidation rate under such a high temperature and pressure result in the remarkable increase of the wear progress.

Al_2O_3, which maintains high hardness and excellent oxidation resistance under such a severe condition, is one of the most important cutting tool materials that can mainly govern the tool life. Al_2O_3 has a several different crystal forms, however, the κ phase of the metastable system and the α phase of the stable system have been mainly used for the Al_2O_3 layer of the cutting tool. A number of researches for nucleation, crystal growth mechanism, microstructure of crystal, comparison of physical characteristics and wear mechanism have been accomplished for both κ- and α-Al_2O_3 [2–14]. Above all, many researches have been done regarding the heat transformation of $\kappa \rightarrow \alpha$ [15–21]. For the wear mechanism of thermally transformed α-Al_2O_3, Larsson et al. reported that κ-Al_2O_3 transformed to α-Al_2O_3 on a rake face during turning and crater wear developed by the plastic deformation of the transformed α-Al_2O_3 [21], however, the difference of the

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wear mechanism between the as-deposited and transformed α-Al_2O_3 has not been clear yet.

In this paper, the wear mechanism of the thermally transformed CVD α-Al_2O_3 that was produced from as-deposited κ-Al_2O_3 by different heat-treatment processes has been investigated. Alloy steel turning was performed in order to evaluate the difference in wear. The different wear mechanisms of the transformed α-Al_2O_3 by the different processes are discussed from the results of the microstructural investigation of the layer and wear surface mainly by means of scanning electron microscopy (SEM).

2. Experimental details

Cemented carbide inserts that have a Co enriched surface tough layer were used as substrates. Ti(C,N) layer of 8 μm and Al_2O_3 layer of 7 μm were deposited in a usual hot wall CVD reactor. Following four kinds of Al_2O_3 layer were produced:

Test No. 1: It was cooled just after deposited as α-Al_2O_3.
Test No. 2: It was cooled just after deposited as κ-Al_2O_3.
Test No. 3: It was cooled once after deposited as κ-Al_2O_3 in the same deposition condition as Test No. 2, and thereafter heat-treated at 1020 °C for 2 h in H_2 atmosphere in the same CVD reactor once again.
Test No. 4: It was heat-treated in the same condition as Test No. 3 but in sequence, without cooling, after deposited as κ-Al_2O_3 in the same deposition condition as Test No. 2.

Wear characteristic of each sample was evaluated by external turning of steel bar using the inserts of CNMG120408 geometry. The cutting condition was as follows: cutting speed, 300 m min^{-1}; feed rate, 0.3 mm rev^{-1}; depth of cut, 1.5 mm with cutting fluid. The workpiece material was the alloy steel (AISI:4140, DIN:42CrMo4, JIS:SCM440) that had 220HB hardness.

The crystal forms and orientation of each sample were confirmed by the X-ray diffraction. With regard to the orientation of α-Al_2O_3, a texture coefficient, TC, was calculated from [22]

$$\mathrm{TC}(hkl) = I(hkl)/I_0(hkl) \times \left[1/n \times \sum I(hkl)/I_0(hkl)\right] \tag{1}$$

where $I(hkl)$, measured intensity of the (hkl) reflection; $I_0(hkl)$, standard intensity of the ASTM standard powder pattern diffraction data; n, number of reflections used in the calculation, (hkl) reflections used are (012), (104), (110), (006), (113), (024), (116). The surface and cross-sectional microstructure of each sample and the surface of the flank face wear after the cutting test were examined in detail by SEM.

3. Results and discussion

3.1. Phase and orientation analysis

The texture coefficient, TC, that was calculated from the X-ray diffraction results is shown in Table 1. As a result of the X-ray diffraction, TC(01−12); TC of the (01−12) plane, of α-Al_2O_3 of No. 1 (hereinafter referred to as "as-deposited α-Al_2O_3") is high. As for κ-Al_2O_3 of No. 2 (hereinafter referred to as "as-deposited κ-Al_2O_3"), (013) plane is the strongest peak. (002) and (210) planes become the following peaks. In case of the Al_2O_3 of No. 3, κ-Al_2O_3 was transformed into α-Al_2O_3 by 100% (hereinafter referred to as "separately transformed α-Al_2O_3"). In this case, TC(006) is remarkably high, which is completely different from the result of as-deposited α-Al_2O_3. As for Al_2O_3 of No. 4, κ-Al_2O_3 was also transformed into α-Al_2O_3 by 100% (hereinafter referred to as "continuously transformed α-Al_2O_3"). The TC was similar to that of separately transformed α-Al_2O_3.

3.2. Microstructural characterization

Fig. 1 shows the SEM micrographs of the surface and cross-sectional microstructures of each sample. The microstructures of the as-deposited κ-Al_2O_3 and as-deposited α-Al_2O_3 consist of columnar grains and equiaxed grains, respectively, which are the same microstructures as those of former reported [15]. Not a great difference in the grain size of crystals is observed between the as-deposited α-Al_2O_3 and as-deposited κ-Al_2O_3, but for the flatness of the surface, the surface of the as-deposited κ-Al_2O_3 is flatter. This difference in the flatness is attributed to the different orientation of the Al_2O_3. Little difference is observed in the surface and cross-sectional microstructure comparing the as-deposited κ-Al_2O_3, separately transformed α-Al_2O_3 and continuously transformed α-Al_2O_3.

The cooling cracks that are observed in the SEM photograph are schematically drawn in low row of Fig. 1. The cracks exist in a similar density and similar crack width in both the as-deposited κ-Al_2O_3 and as-deposited α-Al_2O_3. On the other hand, the crack density of the separately transformed α-Al_2O_3 is higher than that of the as-deposited κ-Al_2O_3. New cracks are generated between

Table 1
Texture coefficient of the as-deposited and transformed α-Al_2O_3

	(012)	(104)	(110)	(006)	(113)	(024)	(116)
As-deposited α-Al_2O_3	2.41	0.22	0.80	0.00	0.86	2.20	0.52
Separately transformed α-Al_2O_3	0.03	0.08	0.15	6.63	0.06	0.01	0.03
Continuously transformed α-Al_2O_3	0.06	0.21	0.19	6.33	0.07	0.04	0.09