Erosion Wear Behavior of CrAlN Coating Produced by Pulsed Filtered Vacuum Cathode Arc Deposition Assisted with Plasma

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Abstract. To improve the tribological properties, it is important to reduce the growth defects in PVD hard coatings. CrAlN coating was deposited on the substrate of a hard metal by pulsed filtered vacuum cathode arc deposition assisted with plasma (PFVCADP). The surface morphology of the original coating was examined by scanning electron microscope (SEM). SEM images of the coating surfaces showed that the surface growth defects in the CrAlN coating were reduced markedly. The coating was eroded by solid angular SiC particles. The analysis of the morphologies of the surface and cross section of the eroded coatings proved that the coating material was removed by brittle fatigue fracture of the coating material. The erosion wear of the coating behaved as brittle materials. The fragments were so fine that the eroded surface became smoother with the increase of the impacts from the particles and the particles impingements played a role of polishing to the coating surface.

Introduction

Vacuum cathode arc deposition (VCAD) is a suitable physical vapor deposition (PVD) method for hard, wear resistant coatings, with advantages of high deposition rate and high adherence between coating and substrate [1]. However, coatings produced by VCAD contain many growth defects formed during the deposition. The typical growth defects of the coatings produced by VCAD are macro particles and pits [2,3]. Growth defects in PVD hard coatings have detrimental influence on their properties [4-7]. To improve the tribological properties of PVD hard coatings, it is important to reduce the density of growth defects in the coatings. Though it is impractical to eliminate the growth defects in VCAD coatings completely [8], the growth defect density can be reduced greatly by selection of optimal VCAD technology [4]. Pulsed filtered vacuum cathode arc deposition (PFVCAD) technology was used to produce coatings with much fewer defects successfully [9-12].

Proper compressive residual stress in PVD coatings is benefit for erosion wear property [13]. The bombarding particles can cause an important compressive residual stress in PVD coatings. In this investigation, CrAlN coatings were produced by pulsed filtered vacuum cathode arc deposition assisted with plasma (PFVCADP). The coating is very dense resulted from the plasma bombardment and present compressive stresses. The plasma came from the plasma source in the top of the chamber. During the coating deposition process, plasma was used to bombard the depositing coating to clean the contaminations on the surface of the growing film so that the growing defects can be reduced. In addition, the adherence was improved as a result of the plasma bombardment. The aim of this study is to investigate the solid particles erosion (SPE) wear behavior of CrAlN coating produced by PFVCADP.

Experimental Details

Coating Deposition

A hard metal (HM, chemical composition (wt. %: 79WC, 15TiC, 6Co)), was used as the substrate material. The main mechanical and physical properties of the substrate were listed in table 1. In order
to improve the adhesion, the substrates were polished to a surface roughness of Ra 0.03μm before deposition to obtain high surface free energy, then ultrasonically cleaned in alcohol and acetone and finally dried before being placed in the chamber. Prior to the coating deposition, the substrates were cleaned with plasma at a bias of 500V at Ar pressure 0.5 Pa for 15 min and then the substrates were bombarded by Ti ions to improve the adhesion. The pulse plasma was created by igniting a vacuum arc between the anode and the cathode. The arc, sustained by a pulsed discharge current, generated the plasma, which was steered to the sample with the aid of a solenoid-generated magnetic field. During the transportation of the plasma, Cr and Al droplets emitted from the cathode were considerably filtered. In the vacuum chamber, the samples were mounted on the planetary rotating substrate holder. The distance between the substrates and the target was 350 mm in this test. Prior to the coating deposition, the substrates were heated and kept at a temperature of 200 °C for 30 min with the base pressure below 1.5×10^{-2} Pa. During the deposition, the plasma source was kept working and the duty ratio of the pulse bias was kept 0.2. In the process of deposition, CrAl target current was 90A. After the deposition, the samples were cooled in the vacuum chamber in Ar to below 100 °C.

### Table 1. Physical and mechanical properties of the substrate material.

| Coefficient of linear expansion | Elastic modulus | Poisson ratio | Flexural strength |
|-------------------------------|----------------|--------------|-----------------|
| $[\alpha \times 10^{-5}/K]$ (0-300°C) | E [GPa] | $\nu$ | $\sigma$ [MPa] | [MPa] | HRA |
| 6.51                          | 525           | 0.27         | 1300            | 91    |

### Characterizing of the Coatings

The micro-hardness of the coating was measured with a MH-6 micro-hardness tester under a load of 0.10N. The adhesion of the coating to the substrate was measured by the scratch test, under loads ranging from 0 to 100 N. The loading rate and the displacement speed of the indenter were 100N · min^{-1} and 10mm · min^{-1}, respectively. Three scratch test experiments were performed on each sample and the mean value of the critical loads was determined as the adhesion. The surface morphology of the coating was examined by scanning electronic spectrum (SEM). The thickness of the coatings was obtained by examining the cross section images of the SEM. The surface roughness was measured with the Veeco NT9300 optical profiler.

### Sand Erosion Tests

The sand erosion tests were conducted with a gas blast erosion apparatus in which the erodent particles were accelerated in the stream of compressed air along a parallel cylindrical nozzle, whose diameter is 2 mm. The samples were mounted with their surfaces normal to the nozzle axis. The distance from the exit of the nozzle to the sample surface was 20 mm. The erodent velocity was varied by controlling the air pressure at the top of the accelerating nozzle. Angular SiC solid particles with an average diameter of 124 um were used as erodent. SiC particles were fed at a rate of 4.5 g · min^{-1} by a vibration feeder and an air pressure of 25 psi was maintained in the tests. The erosion wear loss of the coatings after each test was too small to be resolved by weighing. Instead, the wear depth of the erosion scar of the coating was designated as the erosion wear loss. The erosion wear depth, which is the distance between the original surface and the eroded surface at the deepest position of the circle erosion scar, was measured with the Veeco NT9300 optical profiler. SEM was used to observe the erosion surface morphology of the coating after the erosion test.

### Results and Discussion

#### Characterizing of the CrAlN Coating

The main physical and mechanical properties of the CrAlN coatings on substrate HM were listed in table 2. As presented in table 2, the CrAlN coating had roughness of 0.12 μm which was higher than
that of the polished substrate. The coating was hard with a hardness of 29.10GPa. The critical load was 85.32N, indicating that there was a good adhesion between the coating and the substrate.

### Table 2. Main physical and mechanical properties of the coatings.

| Thickness[μm] | Roughness[μm] | Hardness[GPa] | Elastic modulus[GPa] | Critical load[N] |
|---------------|---------------|---------------|---------------------|------------------|
| 2.02          | 0.12          | 29.10         | 502                 | 85.32            |

Fig. 1 showed the SEM morphology of CrAlN coating deposited by PFVCADP. As can be observed in Fig. 1, the coating was smooth with fewer growth defects compared to that deposited by VCAD. The growth defects in the coating included macro particles, voids and pits. There were two kinds of macro particles, illustrated by arrows A and B, respectively in Fig. 1. The majorities of the small particles (diameter less than 0.1μm) illustrated by arrow A were spherical and the minorities with large sizes (diameter about 1μm, showed by arrow B) were irregular. The irregular large macro particles were incorporated by multiple small ones which covered on the as formed small particles in the growing film. It was obvious that there were very few round voids (showed by arrow C in Fig. 1) in the surface of the coating. The voids had an average diameter of 1.2 μm. The pits showed by arrow D in Fig. 1 were irregular and shallow. The pits might be formed as a result of the rolling out of the particles from the coating when the macro particles were bombarded by plasma during the deposition.

Fig. 2 presented the phase compositions of the CrAlN coating on the hard metal HM. CrAlN was the solid solution of Al atoms in CrN with Cr atoms substituted by Al atoms. As the result of the diameter of Al atom being smaller than that of the Cr atom, the lattice parameter of CrAlN was smaller than that of CrN. Therefore, the diffraction peak of CrAlN was wider compared with the X-ray spectrum of CrN.

**Surface Characterization of Erosion Wear of the CrAlN Coating**

Fig. 3 described the surface images of the coating after impacted by angular solid SiC particles. As shown in Fig. 3(a), after 15 s of erosion operation, no obvious change was found in the erosion image of the coating surface compared with the image of the original coating shown in Fig. 1. The surface growth defects including the macro particles and voids in the eroded coating remained well as that in the surface of the original coating. The image of the erosion surface of the coating after 60 s erosion operation described in Fig. 3(b) showed that the macro particles, voids and pits disappeared. Most area of the erosion surface was smooth apart from a few shallow cutting traces illustrated by arrow A in Fig. 3(b). The very few shallow cutting traces meant that the removal of the coating material in the smooth area through micro cutting was very minor. This fact suggested that the removal of the coating material in the smooth area behaved in brittle way mainly. The small fragments in the irregular pits illustrated by arrow B were the results of the brittle fatigue fracture of the coating material at the edge of pits. It was concluded that the coating material was removed mainly by brittle fatigue fracture during this 60 s erosion operation.
The SEM photographs of the coating surfaces being eroded for 120 s and 180 s were presented in Fig. 3(c) and Fig. 4(d), respectively. As described in Fig. 3(c), the pits in the surface of the coating eroded for 120 s became shallower than that eroded for 60 s shown in Fig. 3(b). By comparing the images in Fig. 3(c) and Fig. 3(d), it was found that the erosion surfaces got smoother with the increase of the erosion duration. As shown in Fig. 3(c) and Fig. 3(d), no obvious cutting traces could be found after 120 s and 180 s erosion operation. This meant that the erosion of the coating material behaved as the erosion of brittle materials. The following analysis to the cross section image of the coating eroded would support this conclusion.

Figure 3. SEM surface morphologies of the erosion wear scar after SPE operation of (a) 15s, (b) 60s, (c) 120s and (d) 180s.

The cross section image of the coating eroded for 180 s shown in Fig. 4. As the details shown in Fig. 4(b), there were many lateral cracks, parallel to the erosion surface, which resulted in the removal of the coating material during the solid particle erosion. The distance between two contiguous lateral cracks was about 40 nm along the depth of the coating and no radial cracks were found. Therefore, the removed coating fragments were very fine and the erosion surface of the coating was smooth (Fig. 3(d)) as if the impacts from the solid particles made the coating surface polished and without further damage to the coating.

Figure 4. SEM morphology of the cross section of the coating after erosion operation 180 s: (a) smooth area in the wear scar, (b) details of the area illustrated by rectangular in (a).
Summary
The following can be concluded from this investigation.
(1) The CrAlN coating on the hard metal deposited using the deposition technique of PFVCADP had smooth surface and very few growth defects in the surface.
(2) The erosion behavior of CrAlN coating presented as brittle fatigue fracture with the removal of very fine fragments of the coating material.

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