Study on the performance of physical vapor deposited multilayer AlCrN nanocomposite coating

ERGENG ZHANG*, ZEMING FU

School of Mechanical Engineering, Shanghai Institute of Technology, Shanghai 201418, China

Multi layer AlCrN nanocomposite coatings were prepared by arc source technology, the multi layer AlCrN nanocomposite coating is superior to single general gradient AlCrN coating. It was confirmed by the observation of microstructure, cutting experiments and the cutting edge of coated tool morphology analysis. Due to the presence of soft hard alternating Cr+CrN/AlCrN layers in the structure, multi layer AlCrN nanocomposite coating plays an important role in alleviating the stress concentration in the coating, resisting to external shocks and improving adhesion with the substrate. Especially in emulsion liquid cooling environment, multi layer AlCrN nanocomposite coatings exhibit excellent cutting performance. In term of the thick film, the multi layer AlCrN nanocomposite coating has also certain advantages more than single-layer gradient AlCrN coating, it plays an important role in the exploration and demonstration to improve future membrane structure of physical vapor coating.

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1. Introduction

Metal nitride coatings prepared by physical vapor deposition technology have been widely used to improve the surface properties and service life of tools and machinery parts [1,2]. With the development of technology, it is becoming increasingly common to improve coating performance by multi-element alloying. For example, AlCrN coating was prepared by adding Al element to CrN coating, the AlCrN has higher hardness than CrN, while the coatings still keep the performance of high temperature resistance and antioxidant properties [3,4].

Modern manufacturing is facing more and more difficult problems, such as high hardness, high temperature, high speed and difficult to machine materials (such as stainless steel, titanium alloy, high temperature alloy). Nonetheless, cemented carbide is still the mainstream of the tool material. Because of its poor chemical stability, it is difficult to meet the demanding of cutting, so it is particularly urgent to find out how to improve the performance of cemented carbide tool. Considering AlCrN coating’s high hardness, excellent mechanical properties and friction wear, it has very good abrasion resistance, antioxidant properties [5,6], moreover, the AlCrN has a high surface compressive stress and low residual stress and no delayed cracks, so AlCrN coated tool can meet actual needs in a certain extent [7,8]. Compared with CrN and TiAlN, AlCrN has better resistance to high temperature oxidation performance. Preparation of AlCrN begins from the addition of alloying elements in TiN. Because of the addition of Al element in the TiN, Al_2O_3 protective film makes coating resistance to high temperature oxidation temperature up to 800 ^oC. Gradually, the Al element was added into CrN, when the Al/Cr content ratio reached 3, the initial oxidation temperature is further increased [9], and finally the monolayer AlCrN coating is prepared.

Although AlCrN coating has good cutting effect for high temperature alloy, titanium alloy and other difficult-to-machine material, it still has failure phenomenon under high stress, such as friction oxidation, diffusion and so on [10,11], there is a considerable relationship with AlCrN micro membrane structure. AlCrN coating is a commercial for the excessive pursuit of high hardness, basically adopts single gradient micro membrane structure, which is not only caused the high state of stress within the coating, but also limits the thickness of the coating increases, because single coating thickness (such as the hob and die casting mould) of some tools should be reached 7 micron. If it is a single gradient AlCrN coating, due to the extremely high stress concentration in the membrane structure, single-sided coating thickness can only reach 3-4 micron, Otherwise, the coating will be peeled off quite easily during the working process. It also limits the wide application of AlCrN coating.

Author has engaged in multi layer hard films microstructure applied research over a period of time, and found that in many cases the application value of multi layer film is better than the single gradient films. In this paper, the author used physical vapor deposition alternating arc source technology to prepare multi layer AlCrN nanocomposite coating, then adopted relevant test methods to study its performance, and compared with the monolayer gradient AlCrN coating which is commercial, and study the differences in performance and application range.

2. Experiment

2.1 Preparation of multi layer AlCrN nanocomposite coating

In the model for the ICS-04 ARC PRO (shown in Fig. 1) physical vapor deposition device, which has four targets, two pieces of Al70Cr30 target, two pieces of pure Cr target. Multi layer AlCrN nanocomposite coating and a single gradient AlCrN coating are prepared in the cemented carbide substrate, both AlCrN film structure are using Cr + CrN as the basal layer, microscopic structure as shown in Fig. 2. Fig. 2 shows a cross-sectional morphology that is composed of the substrate - (Cr + CrN) - (AlCrN): the bottom is the substrate, the middle layer is very thin columnar Cr + CrN, the outermost layer is thicker smooth compact AlCrN. Preparation of multi layer AlCrN nanocomposite coatings were used alternate arc source technology, the technology controlled ignition cycle, arc time of Al70Cr30 target , pure Cr target and alternating deposition of Cr + CrN / AlCrN. In which, pilot arc cycle control layers, pilot arc time control the thickness of each layer. The microstructure of multi layer AlCrN nanocomposite coating and monolayer gradient AlCrN coating prepared are shown in Fig. 3 and Fig. 4. The microscopic structure of multi layer AlCrN nanocomposite coating was got by the section structure observation in Fig. 3, the one-dimensional nanometer structure is very obvious, special, between layer and layer similar to the fingerprint, it also looks like map contour, ups and downs, scattered and orderly, each of the Cr+CrN/AlCrN film thickness is about 5nm, further enlargement of the nano structure morphology is shown in Fig. 5. In Fig. 5, the thin black band is Cr+CrN, the broad white band is the AlCrN layer, Cr+CrN and AlCrN layers of alternating distribution is saw clearly. In this paper, the layer of the multi layer AlCrN nanocomposite coating was prepared 50 layer, the number of layer was chosen randomly for experiment, author has not yet studied how many layers are the best. In Fig. 4, monolayer gradient AlCrN coating microstructure was obtained by observing ball milling dent on the surface of coating, the trace shows the dents from bottom to an inclined surface, However, it looks like a plane in view of the lens. The microstructure is similar to the annular eclipse of the sun. At the centre of the circle shows light grey, it is substrate. followed by a narrow brown yellow band that makes people feel like protrusions is Cr+CrN, then the outer gray wide band is AlCrN, the outermost layer of the coating surface. Comparing Fig. 3, Fig. 4 and Fig. 5, you can image that the multi layer AlCrN nanocomposite coating was prepared which's total thickness is about 5nm, and composed of monolayer gradient AlCrN coating alternately deposited. It is a thin Cr+CrN film that between two relatively thick hard films AlCrN, whose structure likes hard steel below adding a damping spring.

Fig. 1. Physical vapor deposition (PVD) coating equipment.

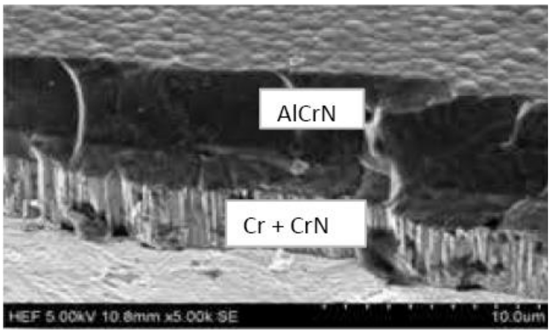


Fig. 2. PVD Cr + CrN / AlCrN coating SEM photos.

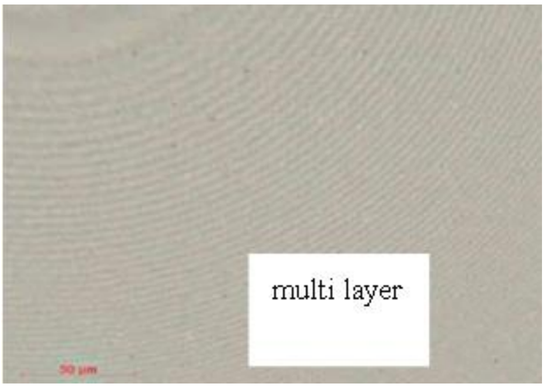


Fig. 3. Microstructure of multi layer AlCrN nanocomposite coating.

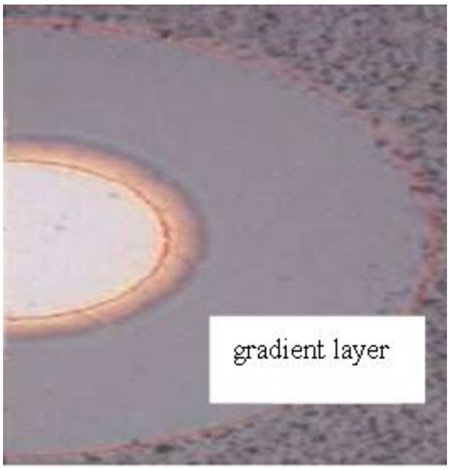


Fig. 4. Micrograph of monolayer gradient AlCrN coating.

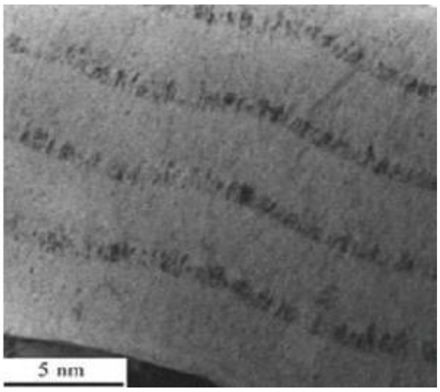


Fig. 5. Nano structure of multi layer AlCrN nanocomposite coating.

2.2 The performance experiment

The cutting experiment used special machine tool (shown in Fig. 6), the coated tool after reciprocating milling became the plate with a certain width, then measured the flank maximum wear width, as a measure of abrasion resistance index of coated cutting tool. This machine carries with automatic cutting force measuring device, and monitors the change of cutting force on-line. Once the tool wear badly or break, tipping, edge collapse etc., cutting force will appear abnormal increasing, suggesting that the cutting experiments must end immediately. This experiment is taken to test the single-side thickness of 2.5~3 micron for the coating tool, and the type of coating is multi layer AlCrN nano composite coating and single gradient AlCrN coating. After measurement of tool wear condition under the microscope. The cutting experiment carries three times totally, the selected parameters for each experiment are shown in Table 1.

Fig. 6. Cutting experimental device.

Table 1. Cutting experiment parameters.

Experiment times	The first time	The second times	Third time
Tool material	2 edges of cemented carbide milling cutter	2 edges of cemented carbide milling cutter	2 edges of cemented carbide milling cutter
Tool specification	Ø9×Ø10×19×69	Ø6×Ø6×10×57	Ø9×Ø10×19×69
Materials to be processed	DIN Standard CK45 (HRC20)	DIN Standard CK45 (HRC20)	JIS Standard KP4M (HRC35)
ν_c (m/min)	31.102	136.659	111.212
f (mm/min)	130	870	705
f_z (mm/min)	0.059	0.060	0.060
a_p (mm/min)	4.5	3	3
Cooling-down method	6% emulsion	oil mist	oil mist

The results of three cutting experiments are shown in Fig. 7, Fig. 8 and Fig. 9. Interestingly in the three cutting experiments, the single gradient AlCrN coating tool were broken in cutting process when milling to a certain length, so its total life is far less than the multi-layer AlCrN nanocomposite coating. From the cooling process of multi layer AlCrN nanocomposite coating, the effect of tool oil mist cooling is better than 6% emulsion, and the wear life is longer. Even for the single gradient AlCrN coating tool, for the first time, the cutting tool was broken when it milled only 3 meters cooled by 6% emulsion, the second and third time, it was not broken until tool milled 40 meters and 45 meters cooled by oil mist. So through comprehensive comparison, selection of cooling way to improve coating tool life is also very critical.

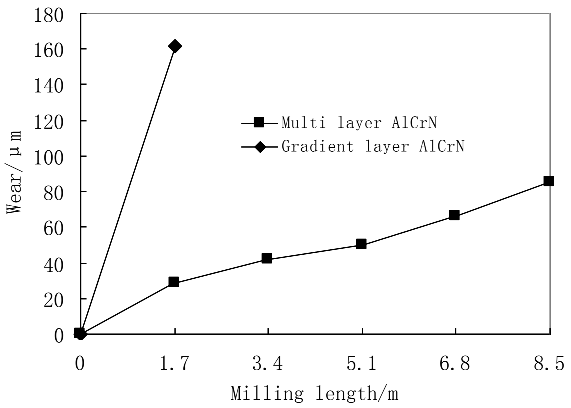


Fig. 7. The first cutting experiments.

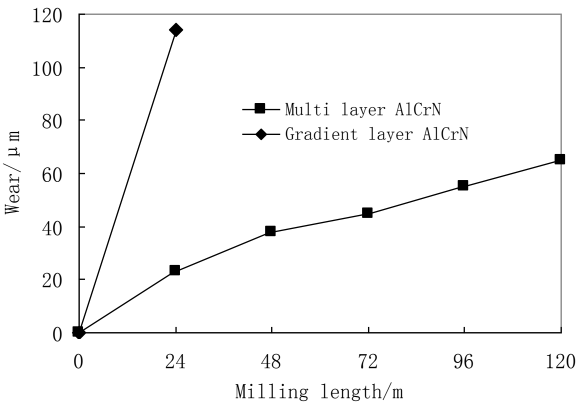


Fig. 8. The second cutting experiment results.

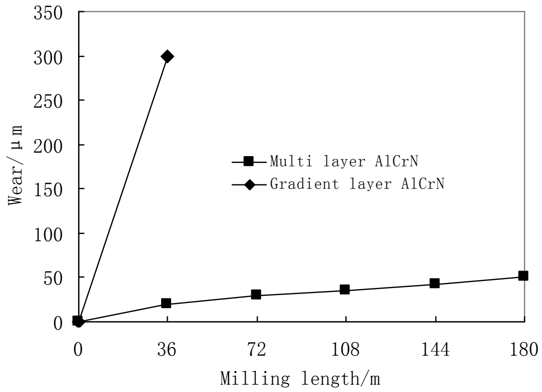
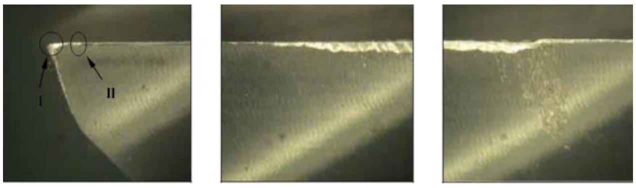


Fig. 9. The third cutting experiment results.

Fig. 10 shows edge wear morphology of multi layer AlCrN nanocomposite coating tool in the first cutting experiment, in which, Fig. 10 (a)showed the heavily worn parts only appear at the tip (I part) and rear face (II part) that the main cutting edge close to the workpiece. Fig. 10 (b) and (c) showed the wear parts II were amplified from left to right respectively. As you can see from Fig. 10, the multi layer AlCrN nanocomposite coating tool has more serious wear and tear because of the low intensity of the tip (I part) and poor conditions of heat dissipation; rear face (II part) that the main cutting edge close to the workpiece. It is mainly because, in the process of cutting, the compressive stress and shear stress on rake face and flank which is nearby the edge of a tool is large, but the stress on the cutting edge of the workpiece at the outer surface drop suddenly, it caused the formation of a high stress gradient and great shear stress, at the same time, the cutting temperature on the rake face is high, and due to the air or cutting fluid cooling of contact points on the outer surface of the workpiece, resulting in high temperature gradient, it also caused a lot of shear stress. It is this combination that results in boundary wear at the tool flank of the main cutting edge. On the whole, the multi layer AlCrN nanocomposite coating has no phenomenon of local shedding, although the high cutting temperature, the coating surface has no high temperature burn marks. It has stronger combination of surface coating and tool, good high temperature resistance, and the photo of the wear morphology indicates that wear is not serious which belongs to the category of normal wear.

During the first cutting experiments, the single gradient AlCrN coating tool was broken down prematurely, the Fig. 11 showed the blade fracture morphology observed under the microscope. Fig. 11 can be found that the initiation point of fracture is located near the tool tip, because of the coating shedding obviously as well as burn marks. Analysis of the reasons are that after the coating shedding, in addition to the friction, the cutting temperature is further increased and the quenching effect of emulsion made the propagation of crack, then end up the break of tool. Before the experiment, the binding force of single gradient AlCrN coating and the substrate are strictly tested in accordance with the relevant standard and is fully qualified, but the coating is premature loss in the actual use of the process, it also shows that gradient AlCrN coating layer has high stress, thus the temperature difference stresses caused by the subsequent severe working environment of hot and cold, and making the coating damage and the coating shedding prematurely, as a result the tool matrix lose the protection of coating. The results of the analysis can be indicated that the rupture of cutting tool is caused by premature failure of single gradient AlCrN coating.



(a) (b) (c)

Fig. 10. The first cutting experiment of multi-layer AlCrN composite coating tool edge wear morphology (a-Edge wear parts; b-II wear parts left amplification; c-II wear parts right amplification).

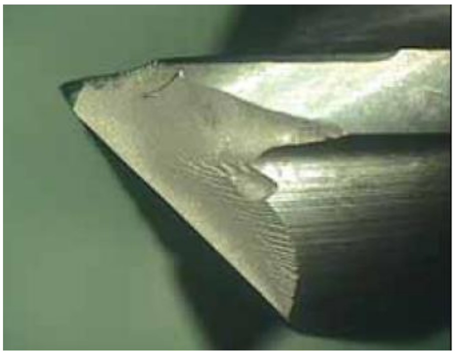
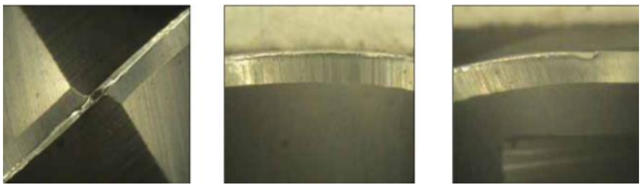


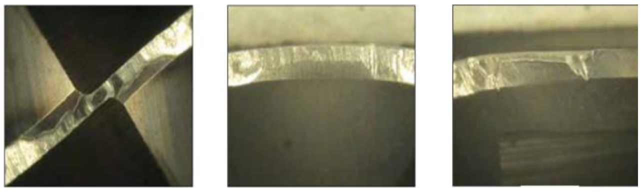
Fig. 11. The first cutting experiment of single gradient AlCrN coating tool edge fracture morphology.

The microstructures morphology are shown in Fig. 12 and Fig. 13, which were got by observed tool edge from the different angles for the cutting experiment of multi layer AlCrN nanocomposite coating in the second times. See from Fig. 12, the multi layer AlCrN nanocomposite coating tool has uniform wear and high temperature oxidation trace locally, but on the whole, there is no coating shedding phenomenon, the width of wear band is uniform and normal. From Fig. 13, the fracture initiation sites of crack tool edge also appeared shedding phenomenon of the coating can be seen obviously, similar to the phenomenon shown in the Fig. 11, the difference is that even the fracture occurred in the edge and corner sites at the same time, but the initiation point of shedding is located in the tip site, related to the high stress concentration of coating. The phenomenon of coating tool edge observed in third cutting experiment is similar to the second times.



Tip 45° 90°

Fig. 12. The second cutting experiment of multi-layer AlCrN composite coating tool edge wear morphology.



Tip 45° 90°

Fig. 13. The second cutting experiment of single gradient AlCrN coating tool edge local fracture morphology.

2.3 Comprehensive analysis

The key to improve the performance of physical vapor deposition coating is to reduce the stress between coatings and to increase the hardness of the coating, which is precisely contradictory between the two aspects. Because of the high hardness and high stress gradient of coating, making the internal stress larger, so the coating acted upon by an outside force and alternating fatigue load, it is easy to crack in combination with the coating and tool substrate as well as the outer surface of coating, the stress concentration of crack tip is high, in addition to the original high stress of coating, it is easy to promote crack extend rapidly so as to cause the coating fall off.

Multi layer AlCrN nanocomposite coating is that a layer of soft, thin Cr+CrN (hardness HV1800) as buffer layer is added in each of two layer high hardness AlCrN (hardness HV3500), it is equivalent to add a soft buffer spring between the two layers of high hard steel plate. In the process, even when the outer hard AlCrN impact, the soft Cr+CrN can also absorb the effect of the external force, such countless soft buffer layer with enough thickness will eventually dissolve, absorb these external shocks. In addition, the degree of stress concentration at its tip is different when the crack extend in such a soft hard alternating film. When the crack extends from the hard AlCrN to the soft Cr+CrN layer, the degree of stress concentration of the tip can get decrease and release due to the deformation of the coating, thereby greatly delay the crack propagation rate, showing good adhesion of coating and longer service life.

According to the above analysis results, the existence of the buffer layer alleviates the degree of stress concentration in the coating, hinders the crack propagation rate, so the coating can be deposited thicker without shedding. The author also conducted the following experiment, the results show that the binding force between the coating and cemented carbide is still good, while multi layer AlCrN nanocomposite coatings can be unilateral deposited 10 micron on cemented carbide. But the binding force of the matrix has reduced, while single gradient AlCrN coating thickness can be unilateral deposited about 5 microns. This also shows that, the multi-layer AlCrN nanocomposite coating can be get more application in need of thick film environments (such as die-casting mould and hob coating), but the number of layers of multi layer there is no quantitative study.

3. Conclusions

The following conclusions can be drawn from the experiments:

(1) Wear resistance of multi layer AlCrN nanocomposite coating is better than that of single gradient coating in the same usage environment, also the binding force with the substrate tool is good, and there is no shedding phenomenon for coating;

(2) Multi layer AlCrN nanocomposite coating adopted Cr+CrN/AlCrN alternately superimposed manner, the microstructure shows each layer is a nanometer structure, the total thickness of the Cr+CrN/AlCrN layer is about 5 nm, the coating with the soft and hard alternation structure can greatly reduce the interlaminar stress;

(3) Multi-layer AlCrN nanocomposite coating can be deposited more thicker film than others, the binding force of the coating and the substrate is good at the same time, to the need for the applications of thick film environment, multi layer AlCrN nanocomposite coating is an ideal choice;

(4) During the cutting process, the ideal cooling way of both multi layer AlCrN nanocomposite coating and single gradient AlCrN coating is the oil mist instead of emulsion.

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*Corresponding authors: ergengzhang@163.com