The Evaluation of PVD Coated High Speed Steel End Mill

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Abstract. To enhance the cutting performance of high speed steel(HSS) end mill, single and multilayer coating is applied on the substrated of the HSS end mill. Coating material reduces cutting force and enhances resistance against abrasive wear. This paper presents the physical vapour deposition(PVD) coating technology and the machinability of PVD coated HSS end mill. The performance of coated HSS end mills are fifteen times better than uncoated HSS end mill on proposed cutting conditions. The TiAlN monolayer coated end mills(futura nano coating) are better than those of multilayer coated end mills(futura coating) on machined surface and tool wear.

1 Introduction

The current metal processing process is progressing with high precision and high efficiency. To improve the productivity of this metal cutting process, metal processing using high-speed steel (HSS) end mills with good toughness is the mainstream in the field. This end mill is an elongated, slender rotary tool that is widely used for the free machining of outlines and small spaces within parts with the development of machining centers

With the development of tool grades, starting from HSS tools, hard grade tools such as cemented carbide and cermet tools are becoming common. This good HSS end mill has a lot of market share. Although the HSS end mill has good toughness, it has poor wear resistance compared to cutting tools of other grades, so it is generally used by coating the end mill [1-3].

Coating methods for cutting tools are divided into chemical vapor deposition (CVD) and physical vapor deposition (PVD). Although the CVD method has a high adhesion between the coating and the base material, due to the disadvantages of high working temperature and environmental pollution, it is being replaced by PVD coating, which is economical and the process temperature is relatively low.

The tiN coating obtained by PVD coating improves the wear resistance of cutting tools. In the case of TiCN coating, it improves the tool life by having excellent hardness as well as wear resistance. In addition, in the case of TiAlN coating, the friction coefficient between the workpiece and the cutting tool generated during machining is lowered so that

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the tool can be operated without using coolant. It improves performance. In addition, it has low thermal conductivity, thermal stability, and excellent high-temperature corrosion resistance by removing the heat generated during processing together with the processing chip [4-6].

Recently, there has been a trend to improve the tool life and performance by treating the TiAlN coating as a multilayer coating instead of a single-layer coating to greatly improve the resistance to crack growth on the surface of the coating layer generated during operation.

Therefore, in this study, TiAlN single-layer coating(futura nano) and multilayer coating (Futura) coating by the PVD coating method of the HSS end mill were tested to evaluate the cutting performance according to the change of cutting speed and machining conditions of this coating tool [7-10].

2 Main Contents

2.1 PVD coating technology

For alloy coating such as TiAlN, it is preferable to apply the coating using Arc-type sputtering equipment. Fig.1 is an arc-type sputtering type BAI1200 PVD coating equipment that can coat TiN, TiCN, and alloy coatings such as TiAlN in a relatively low vacuum. The coating process is divided into four stages: Heating - Etching - Coating - Cooling, and the total coating process for TiAlN alloy coating takes about 9 to 10 hours.

Looking at the PVD coating mechanism, first, the target metal is vaporized and moved from the target material, and after the vapor is converted to an ion state by an auxiliary coating device such as plasma, it is deposited on the surface by the bias voltage applied to the object to be plated. As deposition proceeds in the form of ion plating, the adhesion between the base material and the coating layer increases, and the coating layer's porosity can be significantly reduced.

In general, the thickness of the PVD coating is determined by the coating time, and since the growth of the coating layer is different depending on the bias voltage or the temperature of the coating process during coating, the mechanical and physical properties of the coating layer can be controlled by these variables.

Fig.1. Balzers BAT1200 coating system and PVD coating mechanism

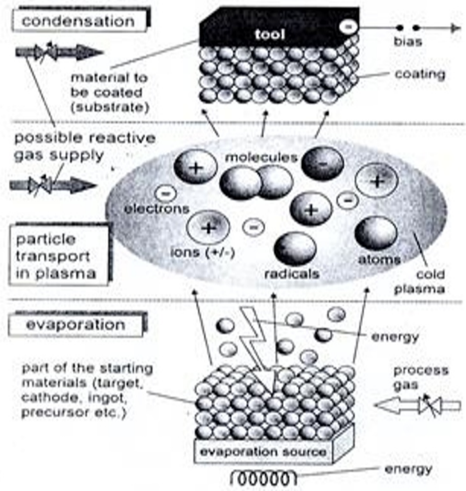
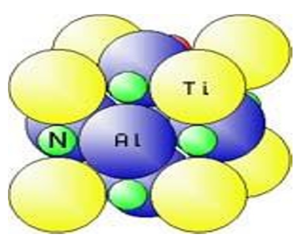


Fig. 2. The three phases of coating formation

The vacuum-deposited thin film in the PVD coating process has three phases, as shown in Fig.2. That is, 1) conversion of the coating material into a gaseous state by the physical evaporation principle 2) vapor transfer through the gas atmosphere (plasma) state between the evaporation source and the substrate 3) It is condensed in the form of a thin film on the surface of the substrate.

2.2 Structure of TiAlN

The TiAlN coating has the following FCC structure.
In the face-centered cubic structure of TiAlN, titanium atoms are located at the cube's vertices, and aluminum atoms are located at the plane's center. And the reacted nitrogen is in a form that penetrates the gap between the titanium atom and the aluminum atom.



At this time, it can be seen that one crystal structure contains one titanium atom, three aluminum atoms, and two nitrogen atoms. When these ratios are correctly combined, the color of a complete TiAlN coating can be obtained.

3 Cutting experiment

The machine tool used for the end mill cutting performance test was Daewoo Heavy Industries Co., Ltd. Machining Center (ACE-V400), and the workpiece material was alloy steel SCM4. The performance of the end mill was evaluated by applying TiAlN single-layer and multilayer coating to an HSS end mill of φ10 mm with four cutting edges.
It was cut at regular intervals after fixing the workpiece in a vise. Using a tool

dynamometer (Kistler 9257BA), the change in cutting force according to the abrasion of the end mill was acquired and analyzed using an A/D converter (DT3001).

To minimize the error caused by tool setting during the cutting experiment, the cutting force was measured while continuously changing the radial depth of the cut after setting a new cutting edge. When the end mill is mounted on the tool, the protrusion length significantly affects the tool's life and surface roughness. In this experiment, the protrusion length was fixed at 30 mm to minimize the error caused by the end mill protrusion length change. Tool wear was measured using a tool microscope (Mitutoyo TM). VBmax was constantly measured at 5 mm from the tip of the cutting edge for flank wear, and the wear amount VC of the minor cutting edge was measured.

4 Results and Discussion

4.1 Performance evaluation according to changes in cutting speed

In the performance evaluation according to the cutting speed of the HSS end mill, based on the cutting conditions recommended by the manufacturer of the test end mill, the feed rate and depth of cut are constant, and only the cutting speed is changed to investigate the wear and surface roughness of the coated tool at each cutting speed. In the cutting process, the wear phenomenon of the cutting tool appears in various ways depending on various variables. In particular, compared to the turning process, analyzing the characteristics of the milling process is difficult because the intermittent cutting process is performed. However, the wear of the cutting tool is most dominantly affected by the change in cutting speed.

Due to the high toughness of the uncoated HSS end mill, gradual wear is dominant on the flank surface of the cutting tool's main cutting edge according to the change of the machining length under the given machining conditions. Tool damage is predominant.

As shown in Fig. 3, up to the cutting speed of 37m/min, when the limit of flank wear is VB=0.2mm, it was possible to machine up to 4.5m in length, but as the cutting speed increased, HSS without coating End mills suffer from severe tool wear, so their performance is poor.

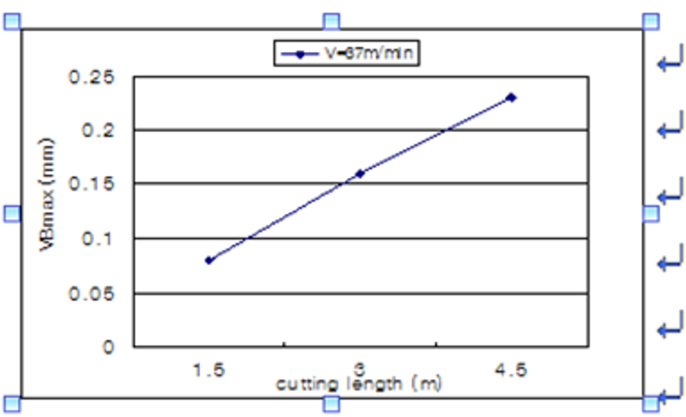


Fig. 3. Rack face wear (uncoating) at V=37 m/min

In Fig. 4, when the cutting speed (V) is 53m/min, In the case of the non-coated HSS end mill, the abrasion of the free surface of the main cutting edge exceeds 0.2mm even when the machining length is only about 3m. However, the PVD-coated end mill can process more than 45 m, showing a performance difference of about 15 times compared to the PVD-coated and non-coated tools.

In terms of economy, the general HSS end mill (φ10) without coating is about 5,000 won; when it is coated, it is about 11,000 won. It can be said that the economic effect of the coating is large as it increases by about 15 times.

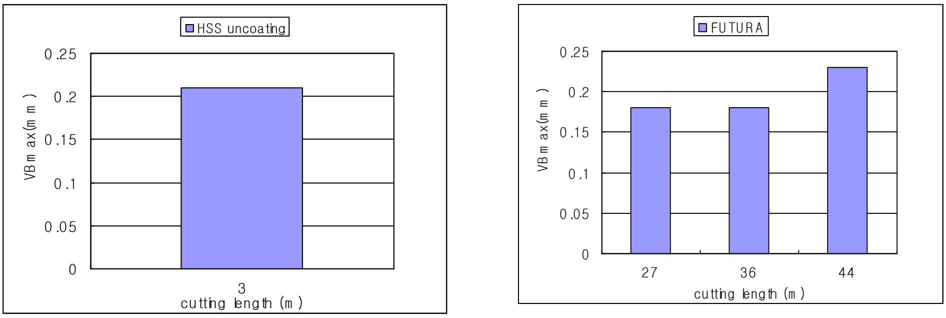


Fig. 4. Wear of Race face on V=53m/min (Futura coating & uncoating)

Fig. 5 and Fig. 6 show the test results by changing the cutting speed of the PVD-coated end mill to 100m/min.

As can be seen from the figure, in the Futura nano coating, the tip wear (VC) of the end mill was about 0.4 mm at a machining length of 84 m, but in the Futura coated end mill, the tip wear exceeded 0.4 mm at a machining length of 15 m.

The surface roughness of the Futura nano-coated end mill shows Rmax 12.2㎛, but the Futura-coated endmill shows 39.2㎛ when machining 12m at the same cutting length.

In conclusion, in the performance evaluation of end mills according to the change in cutting speed, PVD-coated tools can improve productivity significantly compared to uncoated tools. It is also shown to be excellent in tool wear and surface roughness.

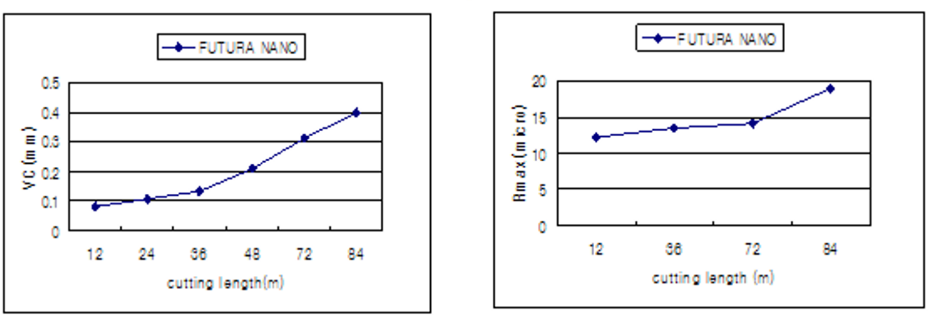


Fig. 5. V = 100m/min, flank wear and surface roughness (Futura nano coating)

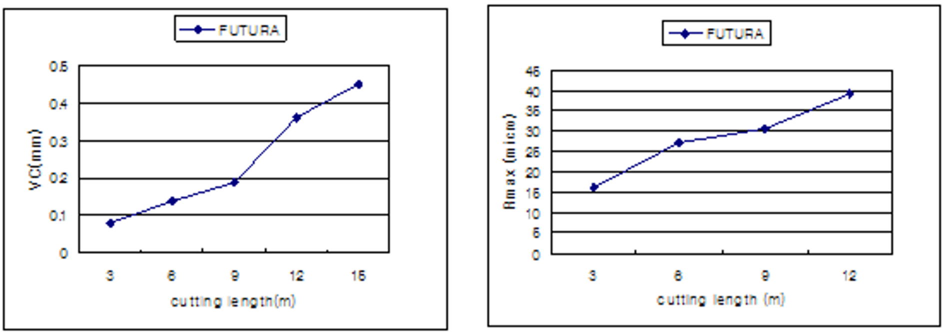


Fig. 6. V=100m/min, flank wear and surface roughness (futura coating)

4.2 Performance evaluation according to change in radial depth of cut (Rd)

Fig. 7 shows the cutting length by changing the axial depth of cut (Ad) to 10mm and the radial depth of cut Rd to 0.5mm, 1mm, and 2mm at a cutting speed of 100m/min, a spindle speed of 3183rpm, and a feed rate of 636mm/min. Changes in tip wear (VC) and surface roughness of coated end mills after 3 m machining were shown. As can be seen from the figure, as the radial depth of cut increases under the same machining conditions, the tip wear (VC) of the coated tool increases, and the Futura nano coated end mill shows less wear than the Futura-coated end mill.

In the case of surface roughness, there is no general tendency for the surface roughness to increase or decrease as the cutting depth in the radial direction gradually increases.

It can be seen that the surface roughness of the Futura nano coating tool is relatively superior to the surface roughness of the workpiece according to the change of coating. As can be seen from the change in the length of the tip wear according to the change in the radial depth of cut, the Futura nano-coated tool has less wear than the Futura-coated tool, so the surface roughness is also improved.

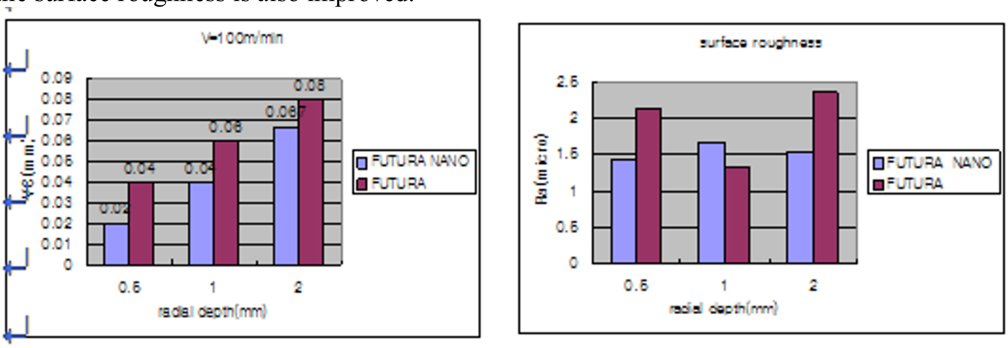


Fig. 7. Changes in VC and Ra according to radial depth of cut change
(cutting length=3m, V=100m/min)

According to the change of the radial depth of cut in high-speed machining using an end mill, the Futura nano coating causes less wear at the tip than the Futura coating and shows excellent properties in terms of surface roughness.

4.3 Changes in cutting force due to coating

Fig. 8 shows the average values of the cutting forces in the X, Y, and Z directions when the radial cutting force Rd is changed to 0.5mm, 1.0 mm, and 2.0 mm under dry cutting at a cutting speed of 100 m/min and a feed rate of 626mm/min was shown.

In fact, as the radial depth of the cut increases, the cutting force increases. Under the conditions of this experiment, the cutting forces in the X and Y directions are generally similar. Still, the Z direction is smaller than the cutting forces in these two cutting directions.

The difference between the cutting forces of Futura nano and Futura coated end mills is not constant in the cutting forces in the X and Y directions.

It can be seen that the end mill with Futura nano coating in the Z direction takes less cutting load according to the change in cut depth than the Futura coating case.

Table 1. Performance of Z-direction cutting force according to coating

Rd / coating	0.5mm	1mm	2mm
futura nano	34N	53N	92N
futura	44N	66N	102N
performance(%)	22%	19%	9%

Table 1 quantitatively shows the change in cutting load according to the change of the radial depth of cut in Futura nano coating and Futura coating in the Z direction.

Here, it can be seen that the smaller the Rd value, the better the cutting load performance of the futura nano coating.

The Z direction is a component of the cutting force acting in the axial direction of the end mill and greatly influences the workpiece's surface roughness.

Therefore, it is suggested that the HSS end mill is coated with a single layer (Futura nano) in high-speed machining at a cutting speed of 100 m/min to reduce the radial depth of cut, thereby improving the performance of the cutting load.

Fig.9 and Fig.10 show the cutting force signals of futura nano and futura coating.

Fig. 11 shows the change in cutting force in the X, Y, and Z directions as the machining length of the coated end mill changes at a cutting speed of 100 m/min.

As can be seen from the figure, the cutting force in the x-y direction increases as the machining length increases, but the change in the machining length in the z-direction changes slightly.

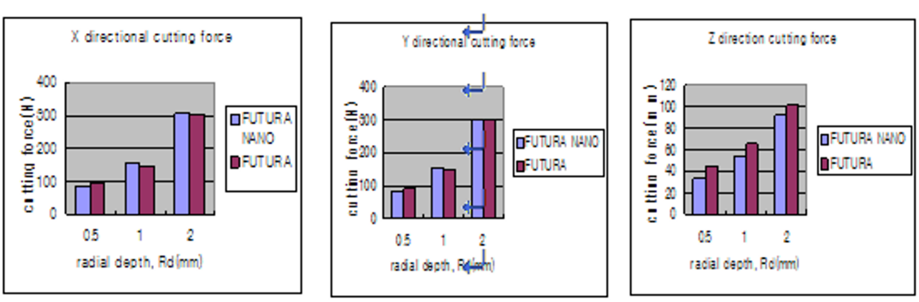


Fig. 8. Effect of cutting force according to radial depth of cut

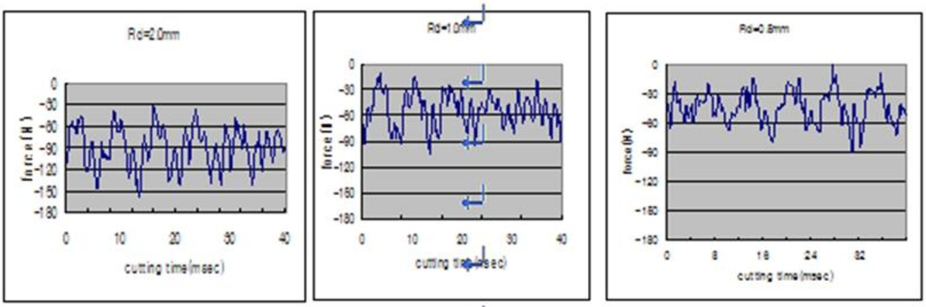


Fig. 9. Cutting force signal according to radial depth of cut (futura coating)

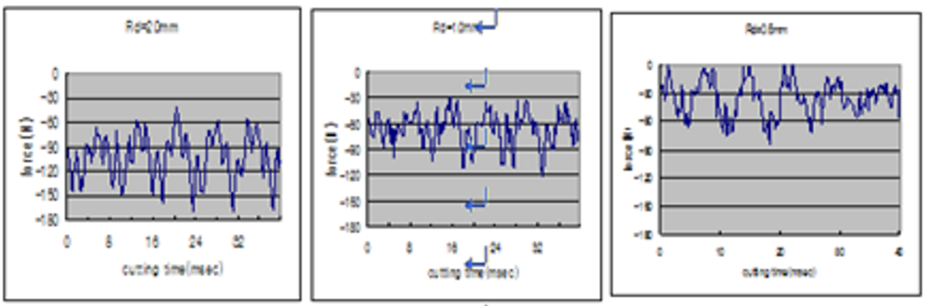


Fig. 10. Cutting force signal according to radial depth of cut (futura nano coating)

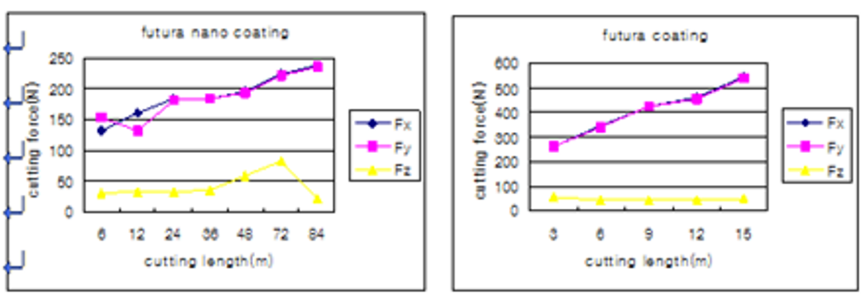


Fig. 11. Cutting force in the 3-axis direction according to the machining length

5 Conclusions

In this study, the PVD coating technique of the HSS end mill with excellent toughness and low price was presented, and the performance of the PVD coating coated end mill was tested according to changes in cutting conditions.

Through this study, we would like to present the following conclusions.

1) By applying PVD coating to HSS tools, machining speed can be improved, and tool performance is significantly increased. In this experimental condition, the PVD-coated end mill has about twice the unit price compared to the non-coated tool, but in terms of performance, it shows a performance difference of about 15 times.

2) Regarding the surface roughness of the workpiece, Futura nano coating shows better results than Futura coating.

3) In the performance evaluation of the coated tool, according to the change of

machining conditions, the tip wear (VC) of the coated tool increases as the radial depth of the cut increases under the same machining conditions.

In addition, Futura nano coated end mills show less wear than Futura-coated end mills.

4) The cutting force applied to the coating tool increases as the radial depth of the cut increases. According to the change in depth of cut, the end mill with Futura nano coating takes less cutting force than the case with Futura coating.

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