ISSN 1392–1207. MECHANIKA. 2016 Volume 22(4): 303–307

Study on the high-speed cutting for plastic mould steel using Ball End Mill of AlTiN coating layers

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crossref http://dx.doi.org/10.5755/j01.mech.22.4.16157

1. Introduction

Needs for high-speed cutting on high hardness material, which shows superior durability and heat resistance in the applications of light weighted component and high strength in advanced industries, and moulding business have been increased [1-3].

The main reason for applying high-speed cutting is to improve cutting speed and enables faster feed rate on the material difficult to cut [4-6]. In addition, ball end mill for high-speed machining features low shear force and enables faster feed rate. Due to higher precision in the surface, the additional process is not required. Cutting heat is dissipate along with chipping, and it will prevent deformation by additional cooling [7]. Therefore, 1 ~ 4 layers of AlTiN was coated on cemented carbide ball end mill to evaluate machining capability on slanted material (15°, 30°, 45°). It was based on cutting performance and surface roughness.

Table 1

Machine specifications

ITEM	Unit	SIRIUS-UL+/12K
Stroke (X / Y / Z)	mm	1,050 / 600 / 550
Rapid Speed (X / Y / Z)	m/min	40 / 40 / 40
Working Surface	mm	1,200 × 600
Table Loading Capacity	kgf	800
Max. Spindle Speed	rpm	12,000
Spindle Motor	kW	22 / 18.5
Type of Spindle Taper Hole	-	BT-40 (Opt: BBT-40, CAT-40)
Tool Storage Capacity	ea	30 (Opt: 40)
Floor Space (Length X Width)	mm	2,720 × 3,215
NC Controller	-	Fanuc 31i-B

Table 2

Mechanical properties of KP4

Direction	T.S., GPa	Y.S., GPa	Elongation, %	Hardness, GPa
Longitudinal	1.06	0.88	23.13	1.03

Table 3

Chemical compositions of KP4

Elements	C	Si	Mn	Cr	Mo
wt, %	0.39~0.44	0.25~0.35	0.9~1.1	0.9~1.1	0.25~0.3

Table 4

Specification of ball end mill

Tool	Ball end mill
Tool diameter	Φ 8 mm
Tool radius	3 mm
Helix angle	30°
Length of Cut	14 mm
Overall Length	90 mm

Table 5

Cutting conditions of angle material

Spindle speed N rpm	Plane angle	Depth of cut, mm	Feed rat, mm min^{-1}					
			1,300 mm min^{-1} (a)		1,500 mm min^{-1} (b)		1,700 mm min^{-1} (c)	
			Up	Down	Up	Down	Up	Down
10,000	15°	0.3(I)	I-a-U	I-a-D	I-b-U	I-b-D	I-c-U	I-c-D
13,000	30°	0.6(II)	II-a-U	II-a-D	II-b-U	II-b-D	II-c-U	II-c-D
16,000	45°	1.0(III)	III-a-U	III-a-D	III-b-U	III-b-D	III-c-U	III-c-D

2. Experimental apparatus and method

In this study, cutting experiment was conducted using vertical type machining center, which can feature up to 20,000 rpm of main rotation speed (Hwa Cheon Sirius-UL(S)). Overall schematic diagram for the various measuring elements used in this experiment is show in Fig. 1 and Table 1.

For test specimen, KP-4 was selected among plastic mould steel, and it is widely used as automobile bumper, OA equipment, grill, etc. Slope angle was set to 15°, 30°, and 45° using the primary machining center. On Table 2, mechanical properties of the test specimen are shown, and chemical compositions are listed in Table 3.

Tool used in this experiment was Φ 8 mm cemented carbide (Co 12%, WC+Cr3+C2+VC 88%) ball end mill. AlTiN (Al 58%, Ti 33%, Si+N 9%) was coated on cemented carbide tool via physical vapor deposition (PVD) method. The number of coating layers was varied from 1 to 4, and specification for ball end mill is shown in Table 4.

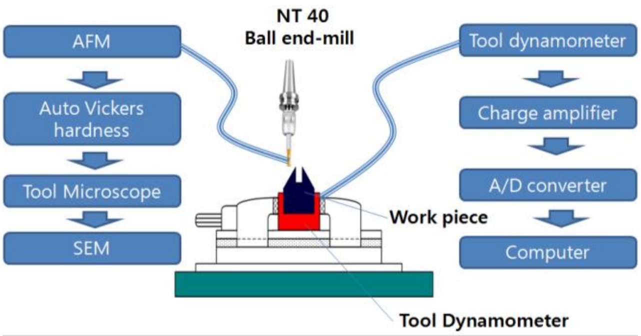


Fig. 1 Schematic diagram of measuring equipment

Cutting properties of coated tool with 1, 2, 3, and 4-layer of AlTiN on top of Φ 8 mm cemented carbide ball end mill were verified on KP-4 plastic mould steel. It was machined upward and downward direction slope. The program used in the experiment was “Cimatron” for 3D modeling and NC programming. “SurfCam” was used for configuring machining condition, and it was transferred to machining center via “data network”.

The cutting condition was varied as 10,000 ~ 16,000 rpm for main axial rotation speed, and feed rate of the ball end mill was set between 1,300 ~ 1,700 mm min^{-1}. The cutting depth was selected out of 0.3 ~ 0.9 mm range. After fix cutting parameter eventually, only slope angle and cutting direction was changed to evaluate cutting performance. Cutting condition used in the experiment is shown in Table 5.

Variable elements for cutting performance according to each test condition were measured with the piezo-type dynamometer, and surface roughness of machined face was evaluated with stylus profiler. 0.8 mm of cut-off value, 0.5 mm s^{-1} of feed rate, and 20 µm of measurement range were set. Measurement distance was set in the center of slope and round surface.

3. Experiment results and discussion

The surface roughness of coated tool was analysed with the atomic force microscope (AFM) from PSIA, and 20 × 20 µm area of the surface was scanned to check the roughness in the nanometer scale.

Fig. 2 shows the picture of scanning analysis on AlTiN coated tool using AFM. On Fig. 2, a and d, the hole could be found in the surface. For Fig. 2, a with single coating layer, surface groove in cement carbide tool was not fully covered with coating material, and it was detected as the irregular shape of the hole. Meanwhile, Fig. 2, b and c featured smooth surface after 2nd and 3rd layer of the coating. In case of Fig. 2, d, four times of coating might induce chemical change, and round shape of the hole was found.

The surface roughness of AlTiN coating on cemented carbide ball end mill can be denoted as RMS value and change in RMS value according to number of coatings was shown in Fig. 3 as µm dimension.

Automated micro surface hardness test was used to confirm surface hardness value of AlTiN layer. With consideration of coating depth, object lens for 4 ~ 40 µm of focus depth with 50X magnification was selected with 4.904 N of testing force.

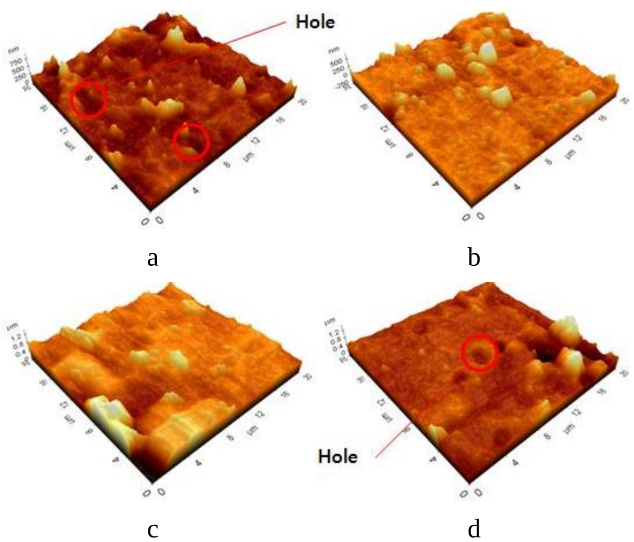


Fig. 2 Surface morphology of AlTiN coating layers by AFM (Scanning 20×20). a - Coating layer (1); b - Coating layer (2); c - Coating layer (3); d - Coating layer (4)

Surface hardness test results according to different number of coating layers are shown in Fig. 4. Surface hardness of cemented carbide was Hv 1872.7, and single layer coating of AlTiN showed Hv 2329.4, which is about Hv 450 of hardness difference. The difference between 1 and two layers of coating was Hv 480, and the difference between 2 and 3-layer was Hv 213. The gap between 3 and 4-layer was Hv 149.9. Along with coating layer increment, the gap between surface hardness becomes less. 3-layer of AlTiN coating showed the highest surface hardness value.

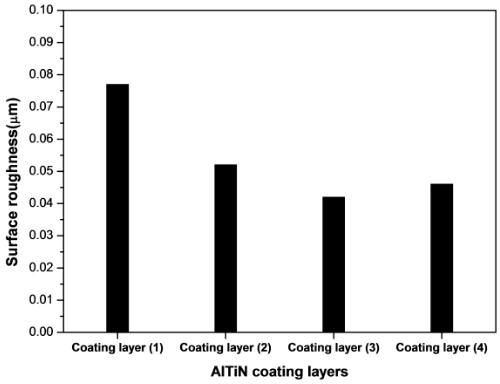


Fig. 3 Surface roughness of AlTiN coating layer measured by AFM

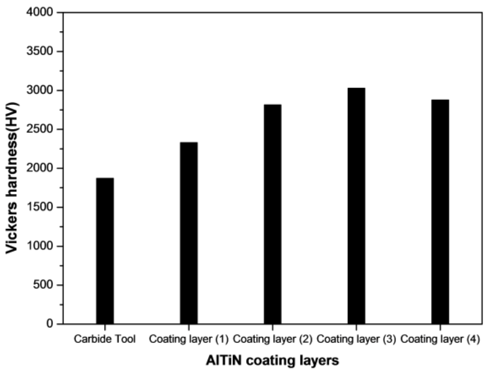
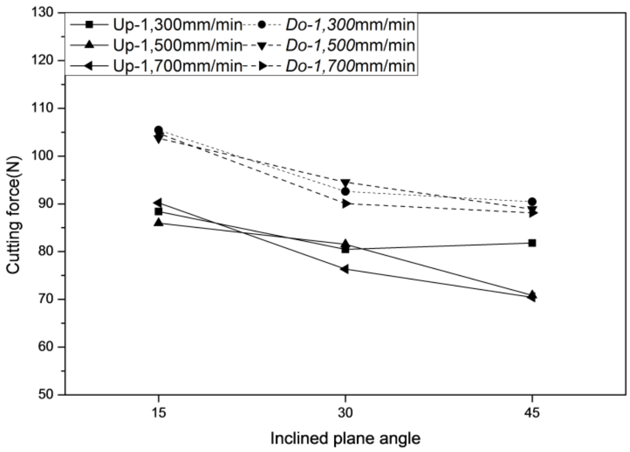


Fig. 4 Hardness values of AlTiN coating

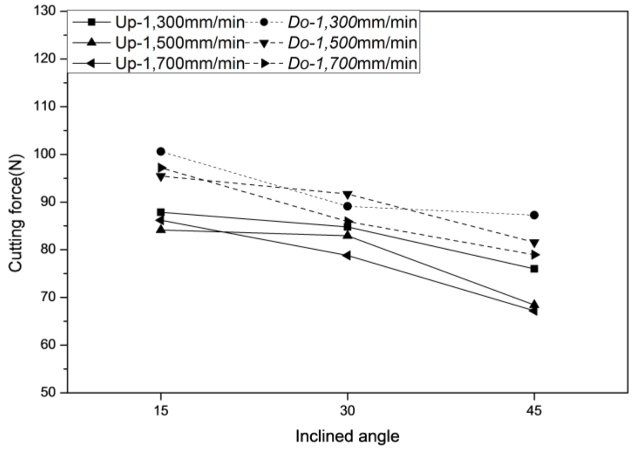
According to the slope angle of material, cutting component forces are decreased as shown in Fig. 5. Three component forces based on machining direction display the higher value for downward than upward for all condition. The reason for this result can be elucidated by the geometrical feature of ball end mill, which dynamically changes the diameter of the tool that is contacted with material depending on inclination angle. The Bigger inclination angle enables bigger effective diameter of the tool, and it will induce less force applied. For the downward direction of machining, the effective diameter of the tool is reduced than upward direction, and the corresponding cutting the component force is larger.

As shown in Fig. 5, a, component force of Fz in downward direction for 0.3 mm, 0.6 mm, and 0.9 mm cutting depth of 15° inclination material and 0.3 mm cutting depth of 30° inclination material showed higher value due to "chisel edge" contact, which features 0 of cutting linear velocity. Therefore, component force of Fz is higher than the one of Fx and Fy.

As shown in Fig. 5, c, magnitude of three component forces, Fx, Fy, and Fz on 45° inclination material showed higher component force in Fx in all machining condition. The reason for the higher component force of Fx can be explained as follows: Machining is started from tool edge of the ball end mill. Even for downward direction, machining will start from side portion, which is away from "chisel edge" and finish at the area (45°) away from the center of the tool. Therefore, the component force of Fx will increase over the process.



a



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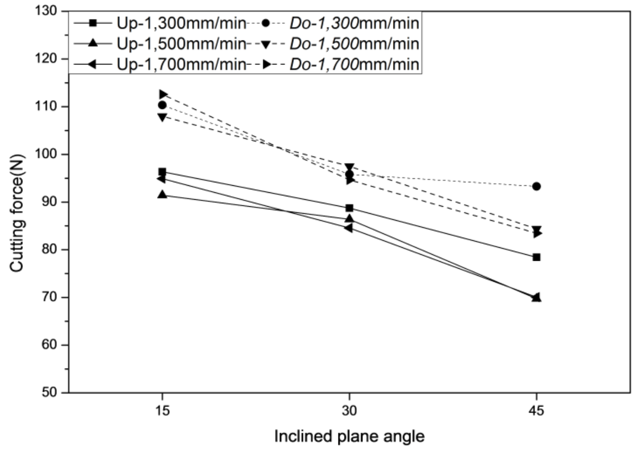
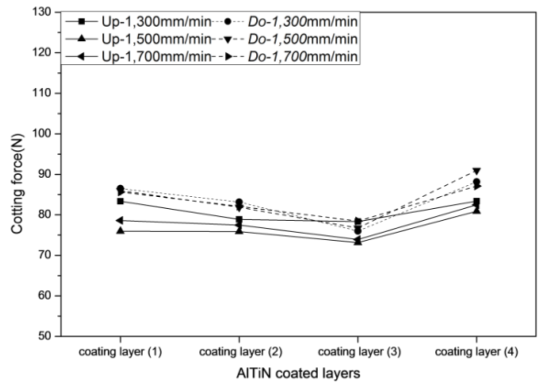


c

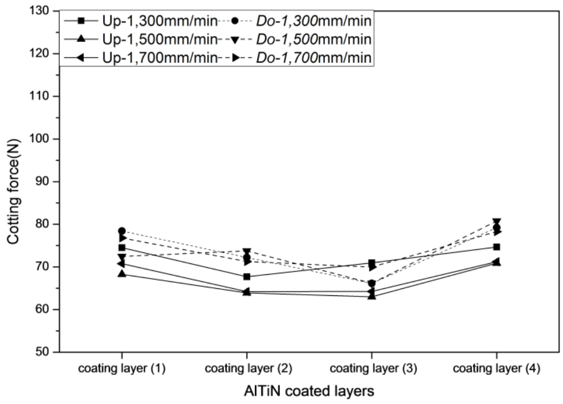
Fig. 5 Three component forces of cutting with the material of inclination according to of c coating layer (d = 0.3 mm, rpm = 13,000). a - Component of forces (Fx); b - Component of forces (Fy); c - Component of forces (Fz)

Three component forces according to AlTiN coating number showed stable value, as shown in Fig. 6. This phenomenon is also repeated at the inclined material (15°, 30°, 45°) for all conditions. The cutting component force with 4-layer coated cemented carbide ball end mill is relatively higher.

Machining precision and surface roughness during moulding and machining is dependent on the tool. Even the same machine is used, erosion, condition of cutting tool, composition, habit, surrounding, etc. changes the outcome. The relative motion of tool and article will be made during machining, and as results, shape and face of the article are processed [8-10]. Surface roughness gauge for this experiment was stylus profiler, which has the measuring range of 12 mm. Its cut-off is 0.8 mm.



a



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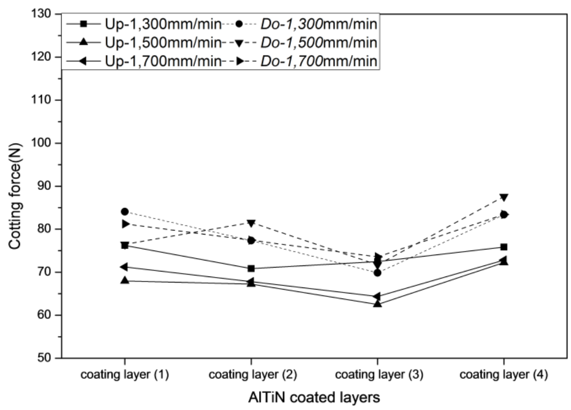
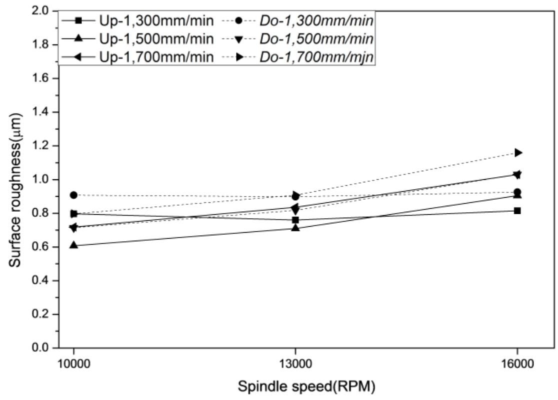
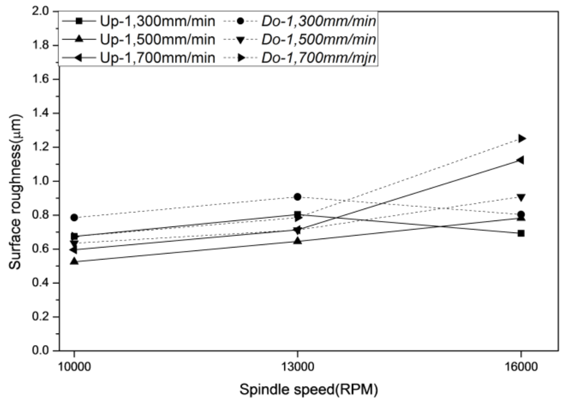


c

Fig. 6 Three component forces of cutting with the material of inclination according to AlTiN coating layer (d = 0.3 mm, rpm = 10,000). a - Component of forces (Fx); b - Component of forces (Fy); c - Component of forces (Fz)



a



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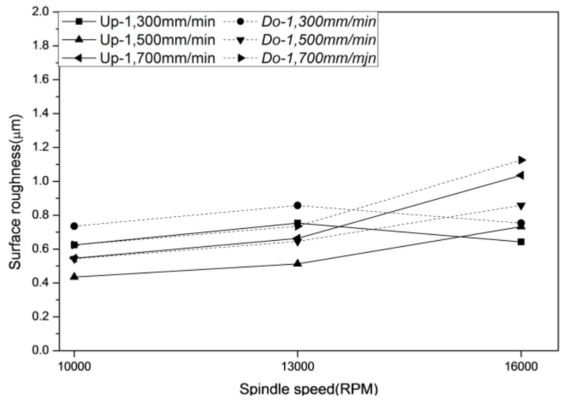

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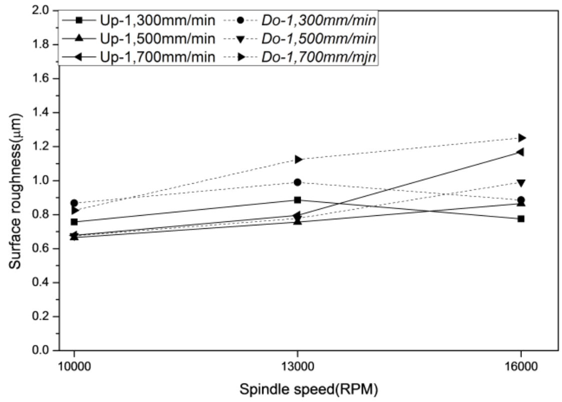

d

Fig. 7 Results of surface roughness between AlTiN coating layer and the material on 45° angle of inclination according to cutting conditions (d = 0.3 mm). a - Coating layer (1); b - Coating layer (2); c - Coating layer (3); d - Coating layer (4)

For the accurate measurement on the inclined face of the article, X-Y stage was installed at surface plate, and roughness value of article with slope was measured. Surface roughness will be increased along with cutting depth, and higher inclination shows good surface roughness. Less inclination displays higher surface roughness. For 45° sloped material, the best surface roughness value, Ra 0.51 μm was achieved at 10,000 rpm of main axis rotation and 1,500 mm min^{-1} of feed rate as shown in Fig. 7, c. In all machining condition, 3-layer of AlTiN coating exhibits the better surface roughness. This trend occurs all inclined material. For 30° sloped material, Ra 0.56 um was measured at 13,000 rpm of main axis rotation and 1,700 mm min^{-1} of feed rate. For 15° inclined material, 13,000 rpm of main axis rotation and 1,500 mm min^{-1} of feed rate showed the best roughness, Ra 0.66 μm.

4. Conclusions

In this study, AlTiN coated cement carbide ball end mill was used for high-speed machining of plastic mould steel. The cutting performance and surface roughness were evaluated according to AlTiN coating layer, and the following results were obtained.

1. The cutting component force at upward direction is 10 N less than the one of downward direction. Depending on each shape, 15° is 96.34 N, 30° is 88.73 N, and 45° is 78.42 N.
2. Cutting component force is reduced along with inclination angle and “chisel edge” contact at the center of tool. Therefore, larger effective diameter shows less force value.
3. Surface roughness at the upward direction of machining is Ra 0.1 μm less than the upward.
4. Tool with 3-layer coating showed better roughness value, and 15 Ra 0.66 μm for 15°, Ra 0.56 μm for 30°, and 45° Ra 0.51 μm for 45° was achieved for upward direction, respectively.

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STUDY ON THE HIGH-SPEED CUTTING FOR PLASTIC MOULD STEEL USING BALL END MILL OF ALTIN COATING LAYERS

S u m m a r y

This paper investigated into process characteristics of AlTiN coated layers for machining to the direction of upper and lower in plastic mould material (KP-4). It was used the cemented carbide ball endmill with the diameter of 8mm coated AlTiN layers (1 ~ 4) step by step using machining center. The material used in experiments is KP-4 that cut by three types of inclined angles; 15°, 30° and 45°. As estimated mechanical properties of AlTiN coated layers, it was shown the most result in the condition of three layered coating that the coating that the coating depth, the hardness of the coated layer. The surface roughness of the coated layer was 13 μm, Hv 3027.3 and 0.042 μm, respectively. The cutting component was better at the condition of upper direction than that of lower direction in all experimental conditions, and indicated to be less which the bigger angle of the material increase the effective diameter of the tool.

Keywords: High-Speed Machining, Plastic Mould Steel, Cutting Force.

Received September 15, 2015
Accepted July 04, 2016