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Effect of Ball End Mill Geometry and Cutting Conditions on Machinability of Hardened Tool Steel

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Abstract : Roughing of tool steel in its hardened state represents a real challenge in the die and mold industry and process improvement depends on research of tool material, coating technique, and lubrication. However, roughing of hardened steels generates extreme heat and without coolant flooding, tool material cannot withstand the high temperature without choosing the right tools with proper coating. This research conducted milling tests using coated ball end mills to study effects of cutting conditions and geometric parameters of ball end mills on the machinability of hardened tool steel. KP4 steel and STD 11 heat treated steels were used in the dry cutting as the workpiece and TiAlN coated ball end mills with side relief angle of 12° was utilized in the cutting tests. Cutting forces, tool wear, and surface roughness were measured in the cutting tests. Results from the experiments showed that 85 m/min of cutting speed and 0.32 mm/rev of feed rate were optimum conditions for better surface finish during rough cutting and 0.2 6mm/rev with the same cutting speed are optimum conditions in the finish cutting.

Keywords : Ball and mill, machinability, hardened tool steel

Introduction

Tool steel, STD 11 is frequently utilized in manufacturing die of the cold press and punch. Its hardness is usually Rc 17-20 and is increased to Rc 58-62 through heat treatment. Due to the difficulty in fabrication, the raw material is first machined to its shape and size and then, the machined die is heat treated to increase its hardness. However, the heat treatment causes distortion and surface crack to the machined die. This error may cause fatal problems to the semiconductor punch die that requires high precision. The way to eliminate such an error in manufacturing precision die is to replace the conventional process with hard machining.

Turning of hardened metals (hard machining), has been popular in recent years as an economic way of generating a high quality finish on steels with a hardness of 60-65 Rc [1-4]. Compared with grinding, hard turning can machine complex workpieces in one step. These materials include steels of Rc 45-70 and hard powder metal materials. Hard machining produces finishes approaching grinding quality. The average surface roughness (Ra) generated by hard turning is 0.2-0.6 μm [1]. The machining cycle times of hard machining can be up to three times faster than grinding, consume about five times less energy per volume of metal removed than grinding, and is more environmentally friendly. It is less time consuming, more flexible, and economical. Although grinding is the typical finishing process employed in industry, in many cases hard machining is a better option for internal and external finishing. Recent development of tool materials and coating technique make it possible to increase the productivity of hard machining and for manufacturing industries to adopt this process as the alternative way to replace the grinding for the environmental purpose.

Many researchers have focused their attention on the hard machining process. During the cutting of hardened steels, the temperature can reach extremes. Without coolant flooding, this high heat can be withstood only by choosing the right tools. Two most common insert materials for hard machining are cubic boron nitride (CBN) and Al_2O_3-TiC (aluminum-oxide titanium-carbide ceramic). These materials help to direct heat away from the machined part surface and into the chips. Carius [5] investigated the grinding process, with hard turning in the finishing operation, and reported that, under proper tolerance and surface finish control, hard turning might be the best way to finish hardened steel workpieces because of its great metal-removal efficiency and process flexibility. By using CBN tools, the acceptable cutting parameters for finishing steel by hard turning are between 80-100 m/min (cutting speed), 0.05-0.25 mm/rev (feed rate), and 0.1-0.3 mm (depth of cut). Noaker [6] reviewed several types of cutting tools that were commonly used for hard turning in industry. He suggested the cutting conditions for hard turning with Al_2O_3-TiC tools be in the range of 76-107 m/min (cutting speed), 0.13-0.2 mm/rev (feed rate), and 0.127-0.5 mm (depth of cut) without cutting fluid. Brandt [7] compared wear behavior of two ceramic tool materials (pure ceramic containing Al_2O_3 and ZrO_2 and mixed ceramic containing Al_2O_3 and Ti(N,C)) when cutting of steel

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that was heat-treated to a hardness of 300 HB. The experimental results showed similar wear mechanisms for both ceramic tool materials. It was also found that tool life was limited mainly by crater wear when using CBN tools. Tönshoff [8] studied the coolant effect in the hard turning process and demonstrated that the coolant was able to reduce tool wear as well as produce surface integrity of the workpiece. However, quench hardening occurred due to the high thermal gradient. Singh *et al.* [9] assessed the performance of high speed ball nose end mills for manufacture of hardened steel moulds, dies, and press tools. He found that the cutting forces increased proportionally to the hardness of workpiece and flank wear was the important wear shape of the mills. The wear depended on cutting conditions, rigidity of machine tool structure, and shape of tool itself.

Since hard turning is getting recent attention in the machining industry, it is very important that production engineers be completely informed about the relationship between the characteristics of the machining process and the quality of the product [10-12]. The effect of machining on the mechanical properties of the surface layer must be understood so that remedial machining procedures can be introduced. For this purpose, cutting tests without coolants were performed using KP4 and STD 11 tool steels over the practical ranges of cutting conditions for the hard machining operation. This steel is frequently used in manufacturing dies and molds. KP4 steel was regular tool steel and STD 11 tool steel was heat treated to increase the hardness up to Rc 60 before machining to test machinability of hardened tool steel. WC-Co (10%) base-ball end mills with TiAlN coating were used in the experiments. Since heat generation in hard turning is higher and coolants are not often used, tool wear can be accelerated and roughness could easily exceed the roughness limits. Hence, the effects of variations in cutting parameters such as tool wear, surface roughness, and cutting forces during hard machining using coated ball end mills were investigated in this research.

Hard Turning Tests

A machining center with Fanuc controller was used in the cutting tests. Its maximum rotational speed is 6000 rpm. WC-Co (10%) ball nose end mills with TiAlN coating (HV 3500) were used to machine the workpiece. The shape of the ball end mill is shown in Fig. 1 and its specific size is enlisted in Table 1. Regular tool steel, KP4 and heat-treated tool steel, STD 11 were used as workpiece material. Table 2 shows the material properties of workpiece. To install the specimen on the machining center, the workpieces were machined and trimmed to the size as shown in Fig. 2. The hardness of heat treated workpiece was 60 Rc, which was measured using Rockwell hardness tester. Each workpiece was fixed on the machine tool bed as shown in Fig. 3 using vises. A schematic view of the experimental setup is shown in Fig. 3. Cutting forces were

Fig. 1. Shape of the ball end mill.

Table 1. Specification of the ball end mill

Specification Type	A Type
Diameter (mm)	Φ 12
Radial cake angle (°)	10
Radial celief angle (°)	12
Radial land width (mm)	2
Web thick (mm)	8
End gashing type	Middle Center

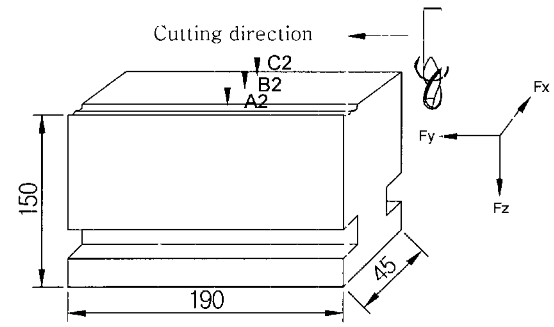

Fig. 2. Dimension of cutting test specimen.

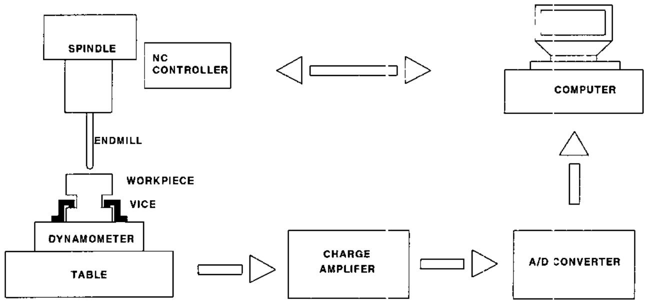

Fig. 3. Schematic diagram of experiment set-up to measure cutting force.

Table 2. Chemical composition and mechanical properties of workpieces

Material	Chemical composition					Mechanical properties			
	C	Si	Mn	Cr	Mo	T.S. (kgf/mm^2)	Y.S. (kgf/mm^2)	Elong ation (%)	hardness (HRC)
KP4	0.39~0.44	0.25~0.35	0.90~1.10	0.90~1.10	0.25~0.30	104	86	23.13	32
STD11	1.40~1.60	0.40	0.60	11.00~13.00	0.80~1.20	165	138	3.0	60

Table 3. Cutting conditions to study cutting speed effect

Work pieces Cutting condition	*Cutting Speed (m/min)	Feed per Revolution (mm/rev.)	Feed Rate (mm/min)	Cutting Depth (mm)
KP4	40	0.26	2.76	0.5
	55	0.26	3.79	
	70	0.26	4.83	
	85	0.26	5.86	
	100	0.26	6.90	
Hardened STD11	25	0.17	112.7	
	30	0.17	135	
	35	0.17	162	
	40	0.17	180.4	
	45	0.17	202.9	

Table 4. Cutting conditions to study effect of feed rate

Work pieces Cutting condition	Cutting Speed (m/min)	*Feed per Revolution (mm/rev.)	Feed Rate (mm/min)	Cutting Depth (mm)
KP4	85	0.2	451	0.5
	85	0.26	586	
	85	0.32	722	
Hardened STD11	30	0.134	106.5	
	30	0.17	135	
	30	0.204	162.18	

measured with a Kistler 9257B tool dynamometer and surface roughness was measured using a surface profilometer. 10 point roughness (Rz) were averaged. Tool wear was also measured using a universal measuring device (Helichek Model 7035). It could measure wear shape and amount of wear by reflection of laser and light. HP-Vee software was used for the data processing as well as data analysis. A stopwatch was used to determine cutting time. The cutting conditions listed in Table 3 and 4 are used to investigate the effect of cutting speed and feed per revolution. Although the cutting should be continued until the tool wear reached full limit, due to the limit size of the tool dynamometer (170 mm × 100 mm), only one side of the workpiece was milled repeatedly. As shown in Fig. 2, cutting forces at three positions (A, B, & C) were measured continuously after the signals reached the stable state. After each cut, the insert was removed from the tool holder and the average flank wear width was measured using the device. Cutting tests were continued until the average flank wear reached about 0.2 mm. This amount of tool wear could be identified using the cutting force variation. Since the cutting forces increased with the tool wear, cutting was continued until cutting forces reached about 400-500 N for KP4 steel and 450-500 N for STD 11 steel. The amount of flank wear was equivalent to 0.2-0 .3mm for KP4 steel and 0.08-0.18 mm for STD11 steel.

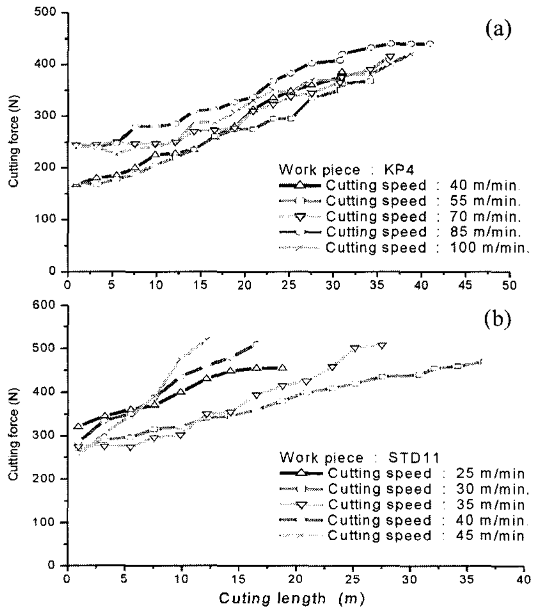

Fig. 4. Variations of the cutting forces (Fz) according to the cutting distance for the various cutting speeds (a) KP4 steel machining (b) STD 11 machining.

Results and Discussions

Fig. 4 shows variations of cutting forces (Fz) according to the increase of cutting speeds at fixed feed rate and depth of cut. For the case of KP4 steel cutting, cutting speed was varied between 40 m/min to 100 m/min at a fixed 0.5 mm of depth of cut and 0.26 mm/rev of feed rate. For machining STD11

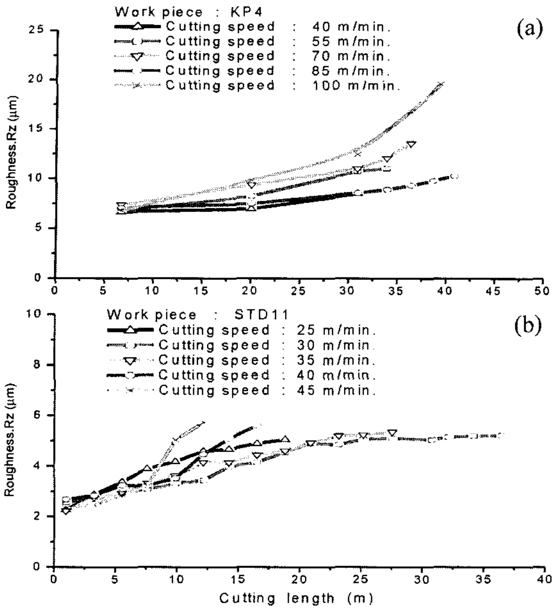

Fig. 5. Variations of the roughness (Rz) according to the cutting distance for the various cutting speeds (a) KP4 steel machining (b) STD 11 machining.

Fig. 6. Wear types at the tool edge.

hardened steel, 0.4 mm of depth of cut, 0.17 mm/rev of feed rate,and cutting speeds between 25 m/min and 45 m/min were varied. Figures showed that 85 m/min in KP4 milling and 30 m/min in milling STD 11 steel were optimum for longer tool life, respectively. Fig. 5 shows variations of surface roughness in terms of cutting distance from the milling at the same cutting conditions of Fig. 4. Figures showed that roughness generally increased with cutting distance. Since tool wear increased with the cutting, the frictional force between

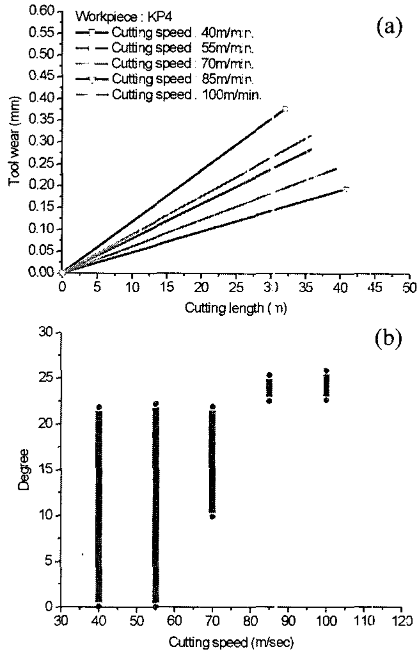

Fig. 7. Tool wear in Milling KP4 steel (a) Variations of the tool wear for the various cutting speeds in machining the KP4 (b) Major cutting angles where wear occurred in terms of cutting speeds.

the worn tool and machined surface increased, resulting in the roughness increase. Results also showed that roughness increased with cutting speeds except cutting KP4 steel at 85 m/min. For the case of milling STD 11 steel, roughness increased sharply for 40 m/min and 45 m/min of cutting speed, which were equivalent to 15 m and 10 m of cutting distance. This result could be considered by the micro-crack and wear of tool edge due to the high hardness of workpiece and high cutting speed.

Effect of feed rates on surface roughness was also investigated using three different. For machining KP4 steel, 0.2 mm/rev, 0.26 mm/rev, and 0.32 mm/rev were used, and for machining STD 11 steel, 0.134 mm/rev, 0.17 mm/rev, and 0.204 mm/rev were utilized. Out of three feed rates, 0.26 mm/rev for KP4 steel and 0.17 mm/rev for STD 11 were the optimum feed rates for the better surface roughness.

The types of tool failure occurred in milling using ball end mills are flank wear, crater wear, and chipping, etc. As shown in Fig. 6 the flank wear is the most general type of wear occurred in ball end milling. Fig. 7-a shows progress of flank wear during milling of KP4 steel for various cutting speeds. Feed rate and depth of cut were set at the same values of Figs. 4 and 5. Fig. 7-b shows ranges of major cutting angle of ball end mill where most flank wear occurred for various cutting speeds. Results showed that amount of wear was inversely proportional to the cutting speed. About 0.2-0.25 mm of flank wear was generated for 85-100 m/min of cutting speeds, and 0.3-0.4 mm of wear was generated for the lower speeds of 40-70 m/min. Hence, higher cutting speed is better than lower speed to get the lower tool wear. The proper cutting speed in

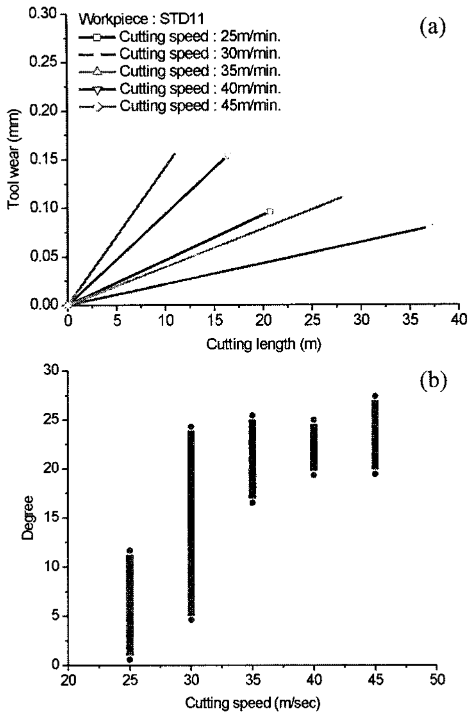

Fig. 8. Tool wear in milling STD11 steel (a)Variations of the tool wear for the various cutting speeds in machining the STD11 (b) Major cutting angles where wear occurred in terms of cutting speeds.

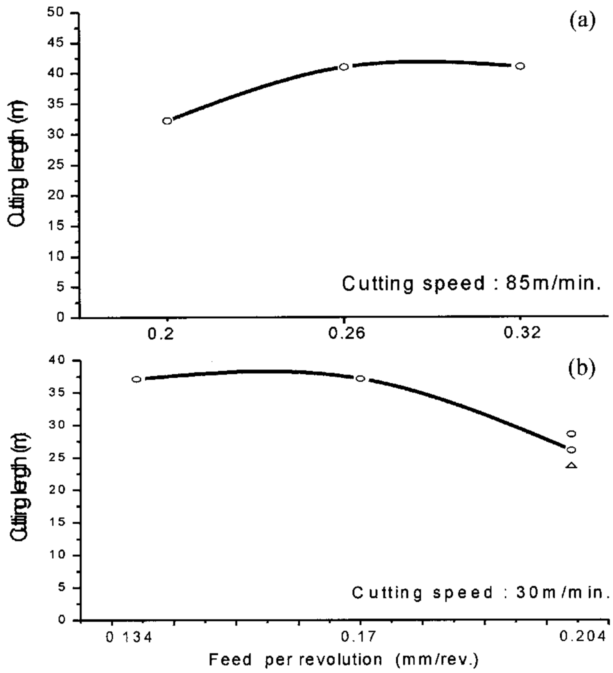

Fig. 9. The maximum cutting length for the feed per revolutions (a) milling KP4 (b) milling STD 11.

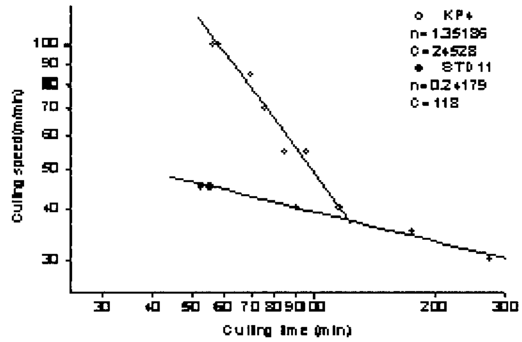

Fig. 10. The relation between cutting speeds and tool life in machining KP4 and hardened STD11.

milling KP4 steel was 85 m/min. Most of flank wear occurred around 0° of major cutting angle at 40-55 m/min, and around 22-25° at 85-100 m/min. Results from milling STD11 steel in Figs. 8a and 8b, showed that about 0.1 mm of flank wear was generated at relatively lower speeds 25-30 m/min and 0.15 m/min at 40-45 m/min. The proper speed for milling STD11 steel was 30 m/min, and most flank wear were generated around 5-12° of major cutting angle at 30 m/min and 20-27° at 40-45 m/min of cutting speeds. These results from the cutting tests could be considered using the cutting geometry since most of the contact between tool and workpiece occurred around 23.6° at 0.5 mm of the depth of cut.

Taylor's tool life equation $VT^n = C$ was identified using 0.5 mm of depth of cut and 0.26 mm/rev of feed rate in milling KP4 steel and 0.5 mm and 0.26 mm/rev in milling STD 11 steel. $n = 1.352$ and $C = 24528$ for KP4 steel, and $n = 0.242$ and $C = 118$ for STD 11 steel milling were obtained for Taylors tool life equation. Fig. 9 shows the Taylor tool life equation for milling KP4 and STD11 steels. Fig. 10 shows the maximum cutting distance by varying feed rates at a fixed 85 m/min of cutting speed in milling KP4 steel and 30 m/min in milling STD11 steel. 0.5 mm of depth of cut was used in all the cutting tests. 0.26 mm/rev of feed rate was proper for finish cutting and 0.3 2mm/rev for rough cutting in milling KP4 steel. 0.17 mm/rev for finish cutting and 0.134 mm/rev for rough cutting were recommended from the cutting tests of STD 11 steel. The milling tests using KP4 and STD 11 steels showed that effects of feed rate on cutting force variation, roughness, tool wear, and cutting distance were relatively smaller than those of cutting speed, and the most important cutting parameter was cutting speed. Fig. 10 also showed the optimum feed rates for the higher cutting distance in milling KP4 and STD 11 steels using ball end cutters.

Conclusions

Hard turning is a way to achieve high machining efficiency in an environmentally-acceptable manner and a new technology to machine hardened parts processed by forging or casting [1-6]. Compared with grinding, hard turning can machine some complex workpieces in one step. The machining cycle time of hard turning can be up to three times faster than grinding. Hard turning also consumes about one-tenth of the energy per unit volume of metal removed than grinding and is more environmental friendly. In this research, cutting forces, surface roughness, and tool wear were measured during hard turning of hardened die steel, STD11 using ball end milling cutters and results from the cutting tests were compared with those from ball end milling of regular die steel, KP4. From the observations made during experiments, following conclusions can be derived

1. 85 m/min for milling KP4 steel and 30 m/min for milling STD11 steel were the optimum cutting speeds when considering cutting forces, surface roughness, and tool wear

2. When milling KP4 steel at 85 m/min of cutting speed, the optimum feed rate was 0.32 mm/rev for rough cutting and 0.26 mm/rev for finish cutting.

3. When milling STD 11 heat-treated steel at 30 m/min of cutting speed, the optimum feed rate was 0.17 mm/rev for rough cutting and 0.134 mm/rev for finish cutting.

4. Results form milling KP4 and STD 11 steels showed that most of tool wear took place around 0° of major cutting edge angle at lower cutting speeds and 20-25° at higher cutting speed when 0.5 mm of depth of cut was used.

5. Although milling KP4 steel generated lower cutting forces than milling STD 11 steel did, roughness of milled STD 11 steel showed lower roughness than that of KP4 steel.

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