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Tool Material Dependence of Hard Turning on The Surface Quality

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ABSTRACT

This paper presents an experimental study of the effect of cutting tool materials on surface quality when turning hardened steels. Machining tests on a lathe are performed using polycrystalline cubic boron nitride (PCBN) and ceramic tools at various cutting conditions without coolant. From the experiments, it is observed that the radial force is the largest force component regardless the type of tool used. The specific cutting energy for the hard turning is estimated to be considerably smaller than the specific grinding energy. It is also found that cutting force and surface roughness with the PCBN tools are higher and better than those with the ceramic tools under the same cutting condition. It is due that the PCBN tools transfer the generated heat more effectively than the ceramic tools due to their higher thermal conductivity. The optimal cutting conditions for the best surface quality are selected by using an orthogonal array concept.

Keywords : hard turning; surface roughness; surface quality; orthogonal array, thermal conductivity

1. Introduction

Finish machining of hardened steels with geometrically defined cutting edges (hard turning) has been emerging as an alternative to grinding. It has become possible due to the development of superhard and low-iron-affinity tool materials such as polycrystalline cubic boron nitride (PCBN) and ceramics. Hard turning offers many possible benefits over grinding. Hard turning can be both the first and the last step in turning process, thereby enabling reduced setup and lower costs [1]. Also, hard-turned components have increased service life resulting from better geometry, an untempered martensite layer, and surface compressive residual stress [2]. Furthermore, sludge which grinding creates cannot be reused, but the clean chips formed in hard turning can be recycled [1].

In order to gain wide spread acceptance as a replacement of grinding, hard turning must be able to satisfy stringent quality requirements related to geometric accuracy and surface integrity of the workpiece in terms of tool wear and surface quality [3, 4, 5] process effect on white layer formation [6], etc. It has also been known that the thermal conductivity of tool materials has a significant influence on the tool-chip interface contact length in both flat-faced and grooved tools [7, 11].

During the finish machining of hardened steels, one of the factors that controls surface quality is the heat generated and hence the use of a cutting tool with a higher thermal conductivity might have a significant effect on surface quality. There exist, however, no detailed data on the effect of different cutting tools in terms of surface quality.

Thus, the objectives are two folds: Firstly to investigate the effect of cutting tool materials on surface quality of hardened steels experimentally, and secondly to select the optimal cutting conditions for the best surface quality.

2. Experimental Procedure

Hardened steel SKD11 (mass fraction of 1.5%

carbon and 12% chromium) is selected as the workpiece material due to its wide use in the mold and die industry. Bars, with 65 mm in diameter and 170 mm in length, are hardened as follows: pre-heating at 650°C for 1 hour, austenizing at 850° for 1 hour, air quench, and tempering at 500°C for 4.5 hours. Final hardness is in the range of 58 Rc to 60 Rc.

Two types of tool are used in the experiments: PCBN and ceramics. The PCBN tool contains 50% CBN by volume with a TiN binder. The ceramic tool is composed of Al_2O_3 and TiC. The designations for the PCBN and ceramic inserts are SNMA120408 and SNGN120408, respectively. Both tools are flat-faced. The chamfers and nose radius for the both grades are 0.2· 20 mm· ° and 0.8 mm, respectively. The toolholder type used is CSDNN2525M12 and provides the rake angle of -8° .

The cutting speed (V), feedrate (f), and depth of cut (t) are chosen as the experimental variables due to the results in the literature review. Selecting levels of each variable is based on the study objectives, material availability, and capability of the lathe. Selected variables and levels are shown in Table 1. Each variable has three levels, thus a 3^3 full factorial design is proper for the experimental design. It requires 27 numbers of experiments.

Table 1 Variables and their levels

Level	V, m/min	f, mm/rev	t, mm
1	50	0.06	0.1
2	90	0.12	0.2
3	185	0.24	0.4

The machining process used is OD turning on a lathe without coolant. Each workpiece is divided into three 20-mm sections along its length, as shown in Fig. 1. Each workpiece is machined with three different depths of cut, while the cutting speed and feedrate are fixed. The cutting force components in the tangential (z), radial (y) and feed (x) directions are measured through a Kistler piezoelectric dynamometer (type 9257B) which is connected to three Kistler charge amplifiers (type 5011) using high impedance cable. The signals proportional to the cutting forces generated are fed into a notebook through National Instruments DAQ1200, which are collected and analyzed by using LabVIEW. Figure 1 shows a schematic diagram of experimental setup.

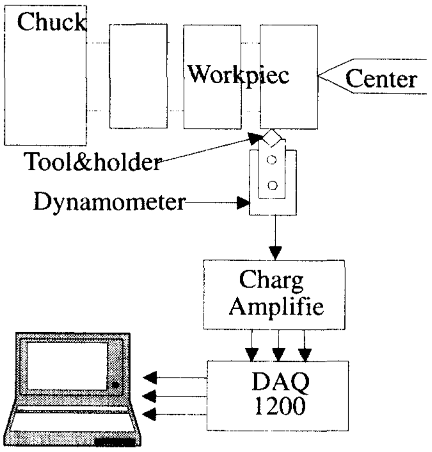


Fig. 1 Schematic diagram of experimental setup

After machining, each workpiece is cut to size for the subsequent measurements, i.e., surface roughness, with a Mitutoyo profilometer.

3. Results and Discussions

3.1 Forces and Specific Energies

Fig. 2 shows a typical cutting force data as a function of cutting time. It is observed that the radial force is the largest force component regardless the cutting conditions and type of tool used. This is due to the relatively small depth of cut compared to the nose radius, and the chamfering of the tool. The chamfers (T-lands and hones) strengthen the cutting edge by redirecting the cutting forces back into the insert.

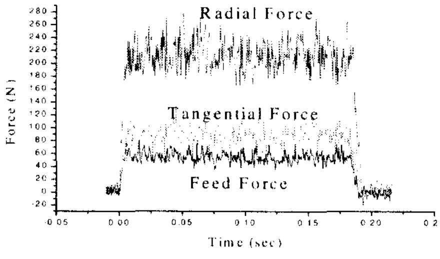


Fig. 2 Typical cutting force data: V = 90 m/min, f = 0.24 mm/rev, t = 0.2 mm, PCBN tool

It is also observed that the level of cutting forces with the PCBN tools is higher than that with the ceramic tools under the same cutting condition, as shown in Table 2. In Table 2, Fx, Fy, and Fz represent the feed force, radial force, and tangential force, respectively. It is well known that the cutting forces increase with an increase in cutting tool thermal conductivity when machining with flat-faced tools [11]. Since PCBN has a higher thermal conductivity than ceramic, the PCBN tools transfer the generated heat more effectively than the ceramic ones. Therefore, the tool-chip interface temperature is reduced with the PCBN tools, thus increasing the level of cutting forces.

Table 2 Measured cutting forces

No.	PCBN			Ceramic		
	Fx	Fy	Fz	Fx	Fy	Fz
1	31	86	17	10	60	19
2	63	163	60	36	122	51
3	132	333	157	120	285	157
4	45	104	19	26	71	24
5	104	218	91	75	160	80
6	20	112	27	10	69	30
7	72	149	56	58	101	48
8	9	71	20	19	60	23
9	37	156	56	32	145	69

The cutting force decreases with the increased cutting speed, while the cutting force increases with the faster feedrate and deeper depth of cut. The decrease of the cutting force with the increased cutting speed is due to the softening of the workpiece material at high temperature [8]. The increase of the cutting force with the faster feedrate and deeper depth of cut is normal phenomena when machinining metals.

The specific cutting energy is calculated from the measured cutting forces and the material removal rate (MRR) as the product of the tangential force and the cutting speed divided by the MRR. The specific cutting energy ranges between 1.3 and 4 GJ/m^3 which is considerably smaller than the value of 15 GJ/m^3 for the surface grinding of a tool steel [5]. The specific cutting energy tends to decrease with the increased cutting speed, feedrate, and depth of cut. These observations are consistent with the data found in the literature [8].

3.2 Surface Finish

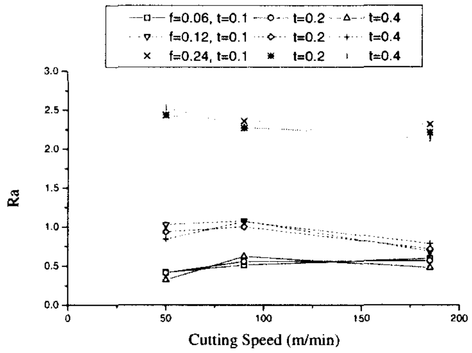
Figures 3, 4, and 5 show the variation of surface roughness at different cutting speeds, feedrates, and depths of cut, respectively. It is observed that the feedrate strongly affects surface roughness, while the effects of the cutting speed and the depth of cut on surface roughness are negligible.

In case of the PCBN tools, increasing the cutting speed at the feedrate of 0.06 and 0.12 mm/rev deteriorates surface roughness, though increasing the cutting speed at the feedtate of 0.24 mm/rev generally improves surface roughness. In case of the ceramic tools, the increase in the cutting speed at the feedrate of 0.06 and 0.12 mm/rev initially deteriorates, then improves surface roughness, though the increase in the cutting speed at the feedtate of 0.24 mm/rev improves surface roughness. The improvement of surface roughness with the increase of the cutting speed is not unusual in machining, but the explanations are usually related to the formation of a built-up edge (BUE). However, the formation of BUE is not the reason because a new cutting tool is used for each experiment. Therefore, the phenomenon needs further explanation. The properties of metals are influenced by the deformation velocity [13]. The higher deformation velocity, the less significant the plastic behavior will be.

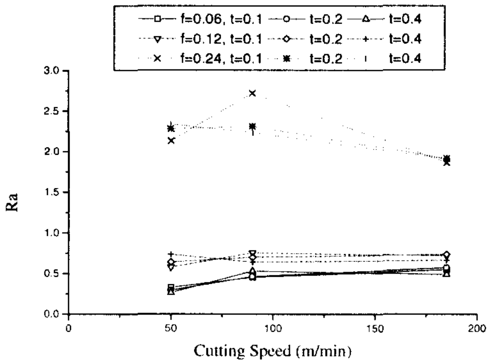
Surface roughness increases with the increase in the feedrate. Theoretically, changing feedrate by a factor of 2 changes surface roughness by a factor of 4. In case of the PCBN tools, surface roughness is increased by 56% and by 220% whenever the feedrate is doubled. In case of the ceramic tools, surface roughness is increased by 81% and by 158% whenever the feedrate is doubled.

It is also found that surface roughness with the PCBN tools is better than that with the ceramic tools under the same cutting condition. It is known that the hardness of PCBN decreases with increments in temperature, but that its hardness remains higher than ceramic. Thus, the combined capability of the PCBN tools, which retains hardness at high temperature and transfers the generated heat more effectively, results in the improvement of tool. Therefore, the PCBN tools give the better surface roughness than the ceramic tools.

Figure 6 shows the relationship between the calculated specific energy and surface roughness. The specific energy tends to decrease as surface roughness increases, and saturates at a certain level. While a better surface roughness can be produced by resorting to finer feedrates, this will cause the unit volume of material removed to be smaller, thus raising the specific energy. Theoretically, increasing specific energy by a factor of 0.71 deteriorates surface roughness by a factor of 2 [12]. This trend agrees well with the experimental observations.

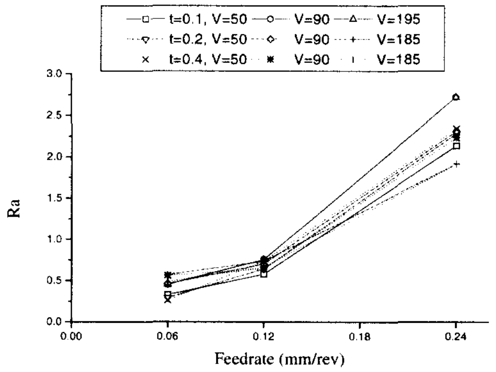


(a) with PCBN tools

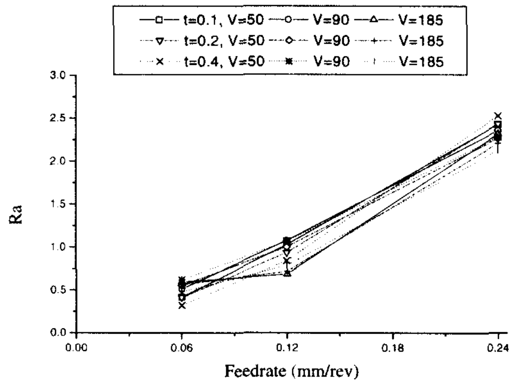


(b) with ceramic tools

Fig. 3 Cutting speeds vs. surface roughness

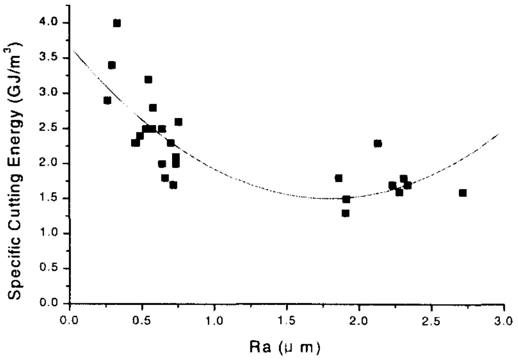


(a) with PCBN tools

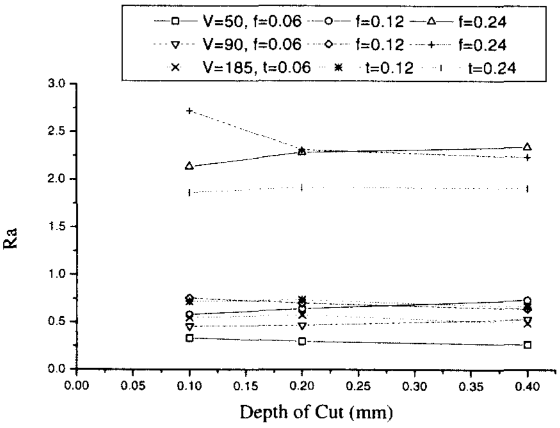


b) with ceramic tools

Fig. 4 Feedrates vs. surface roughness

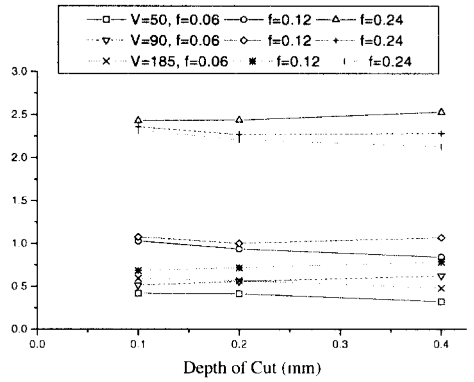


(a) with PCBN tools

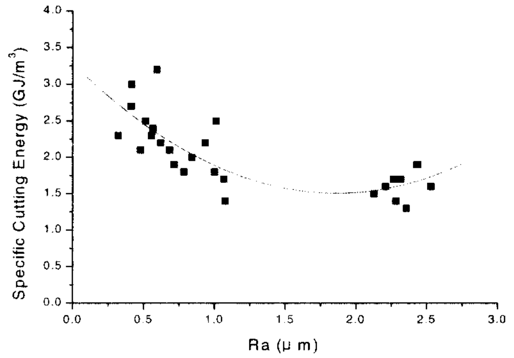


(b) with ceramic tools

Fig. 5 Depths of cut vs. surface roughness



(a) with PCBN tools



(b) with ceramic tools

Fig. 6 Relationship between specific cutting energy and surface roughness

3.3 Optimal Cutting Conditions

The primary goal for the experiment is to select the optimal cutting conditions for the best surface quality. For this purpose, the experimental data collected by using 3^k factorial design are selectively rearranged with an orthogonal array concept [9, 10]. Using the rearranged data, the S/N ratio, η, can be calculated by the following formula:

$$\eta = -10 \log_{10} (\mathrm{MSD}) \qquad (1)$$

where, MSD is the mean squared deviation for the output characteristic. In this case, the output is surface roughness.

The lower-the-better-quality characteristics for surface roughness should be taken for obtaining optimal cutting performance. It means that the quality loss should be minimized by maximizing the S/N ratio. The MSD for the lower-the-better-quality characteristics can be expressed as:

$$\mathrm{MSD} = \frac{1}{n}\sum_{i=1}^{n} SR_i^2 \qquad (2)$$

where, SR_i is the measured surface roughness in the i th experiment, and n is the number of experiment.

Table 3 shows the experimental results for surface roughness and the corresponding S/N ratio using Eqs. (1) and (2). In Table 2, SR, η, P, and C represent surface roughness, S/N ratio, PCBN tool, and ceramic tool, respectively. The overall mean value for each tool (m_{PCBN} and $m_{Ceramic}$) is obtained by averaging the S/N ratios for the nine experiments, and is 1.73 and 0.007, respectively. The mean S/N ratio for each variable level, i.e., m_V, m_f, and m_t, is can be calculated by averaging the S/N ratios for the experiments 1-3, 4-6, and 7-9, respectively, and is shown in Table 4 as the S/N response table.

The optimal level for each variable is the level that has the highest S/N ratio, and identified by the thick and underlined values. It means that the cutting speed at level 3, and the feedrate at level 1 are optimal for the both tools. The optimal depths of cut are at level 1 and at level 2 for the ceramic and for the PCBN tool, respectively. The prediction of η , under the optimal conditions can be possible using the following equation:

$\eta_{opt}=m_{PCBN}+(m_V - m_{PCBN})+(m_{f1}-m_{PCBN})+(m_{t2}-m_{PCBN})$ = 9.58 dB for the PCBN tools, and

$\eta_{opt}=m_{Ceramic}+(m_V - m_{Ceramic})+(m_{f1}-m_{Ceramic})+(m_{t1}-m_{Ceramic})$ = 8.45 dB for the ceramic tools.

Using Eq. (1) and calculated η_{opt}, the optimal surface roughness under the optimal cutting conditions can be predicted as 0.33 μm for the PCBN tools and as 0.38 μm for the ceramic tools, respectively. The measured surface roughness under the optimal cutting conditions is 0.57 μm for the PCBN tool, and 0.60 μm for the ceramic tool, respectively.

Table 3 Summary for measured surface roughness and corresponding S/N ratios

No	V	f	t	SR, μm		η , dB	
				P	C	P	C
1	1	1	1	0.33	0.42	9.66	7.60
2	1	2	2	0.64	0.93	3.86	0.59
3	1	3	3	2.34	2.53	7.38	- 8.06
4	2	1	2	0.46	0.56	6.69	5.10
5	2	2	3	0.64	1.07	3.86	- 0.56
6	2	3	1	2.72	2.36	- 8.69	- 7.44
7	3	1	3	0.49	0.48	6.23	6.41
8	3	2	1	0.72	0.68	2.88	3.30
9	3	3	2	1.92	2.21	- 1.55	- 6.68

Table 4 S/N response table

	Level		
	1	2	3
	P/C	P/C	P/C
m_V	2.05/0.04	0.62/-0.97	**2.52/0.94**
m_f	**7.53/6.37**	3.53 / 1.11	-5.87/-7.46
m_t	2.40/**1.15**	**3.00**/-0.40	0.90/-0.74

The analysis of variance (ANOVA) is performed to investigate which experimental variables significantly affect the surface quality. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the experimental variables and the error.

Tables 5 and 6 are the results of ANOVA for the PCBN and the ceramic tools, respectively. In Tables 5 and 6, DF, SS, MS, F, % represent degree of freedom, sum of squared deviation, mean of squared deviation, F-ratio, and percent contribution, respectively. The significance of a variable on the quality characteristic can be evaluated by using F-ratio. The F-ratio is the ratio of MS to the error. Generally, when F is greater than 4, it means that the change of the experimental variables has a significant effect on the quality characteristic. From Tables 5 and 6, it can be inferred that feedrate is the most significant variable affecting surface roughness for the both tool materials. This inference agrees well with the experimental results shown in Fig. 5. The depth of cut is a significant variable for the PCBN tools, but not for the ceramic tools. The cutting speed is not a significant variable for the both tools.

Table 5 ANOVA for PCBN tools

Var	DF	SS	MS	F	%
V	2	5.87	2.94	1.62	1.83
f	2	283.95	141.98	78.44	88.61
t	2	27.03	13.52	7.47	8.44
Error	2	3.61	1.81		1.12
Total	8	320.46			100.00

Table 6 ANOVA for ceramic tools

Var	DF	SS	MS	F	%
V	2	5.47	2.74	0.20	1.58
f	2	292.38	146.19	10.74	84.67
t	2	20.23	10.12	0.74	5.86
Error	2	27.22	13.61		7.89
Total	8	345.31			100.00

Since the error refers to unknown or uncontrolled factors, the percent contribution due to error provides an estimate of the adequacy of the experiment. If the percent contribution due to error is 15% or less, then it can be assumed that no important factors have been omitted from the experiment. Percent contribution for the both tools is less than 15 %, it can be said that no important variables have been omitted from the experiment.

4. Conclusions

This paper has discussed the effect of cutting tool materials on surface quality when turning hardened steels. The followings can be concluded:

1) The radial force is the largest force component

regardless the cutting conditions and type of tool used.

2) The specific cutting energy is considerably smaller than the specific grinding energy.

3) Surface roughness with the PCBN tools is better than that with the ceramic tools under the same cutting condition.

4) Feedrate strongly affects surface roughness, while the effect of the cutting speed and depth of cut is negligible.

5) The optimal cutting conditions for the best surface quality are selected by using an orthogonal array concept.

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