

# A Study of Relation between Tool Wear and Dynamic Cutting Force Ratio in CNC Turning

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**Abstract.** Since tool wear directly affects the manufacturing cost in CNC turning process, the aim of this research is to study the effects of cutting conditions on tool wear and dynamic cutting force ratio. It also describes relation of tool wear and dynamic cutting force ratio. The results of experiment show that cutting speed is the most significantly influential factor followed by feed rate, depth of cut and nose radius respectively. In addition, effect of dynamic cutting force on the tool wear analysis show that trend of the dynamic cutting force is not changed even though the cutting condition is changed. Accordingly, the tool wear can be predicted by using the dynamic cutting force ratio in turning process.

## 1. Introduction

One of the material removal process is the turning process where a cutting tool with a single cutting edge is used to remove material from a rotating work piece to make a cylinder shape. The friction occurs at contacting surface between a cutting tool and chips during turning process by turning for a while. The heat accumulation is generated which affects the tool wear and the surface roughness. These directly reflect to the manufacturing cost. Due to the cutting tool necessary frequently replace and has highly price. Also defects occur from a poor quality of surface finishing. Base on economic production, the tool wear is primary factor to consider the way to extend the tool life as long as possible.

Base on cutting tool wear and cutting force theory show that wearing rate depends on various factors as follow: spindle speed, feed rate, depth of cut, rake angle, nose radius, work material, cutting fluid and etc. Previous researches have been studied the influence of cutting conditions on the tool wears [1]. After that, researchers found out that the tool wear has significantly associated with the cutting force [2, 3] and cutting force monitoring can estimate the tool wear. Due to the difficulty regarding influence of work material and cutting conditions on the cutting force, the cutting ratio has been developed [4] for surface roughness estimation. Similarly, the cutting force ratio can be utilized for estimating the tool wear which is better than that the real time monitoring. Therefore dynamic cutting force measurement was proposed [5]. In term of cutting force analysis, previous research has applied the fast flourier transform [6]. But in actual turning operation, there was many cutting force signal combination such as broken chip signal, chatter signal and tool wear signal and etc. The wavelet transform analysis is a better alternative for filter and separate their cutting force signal from each other[7].

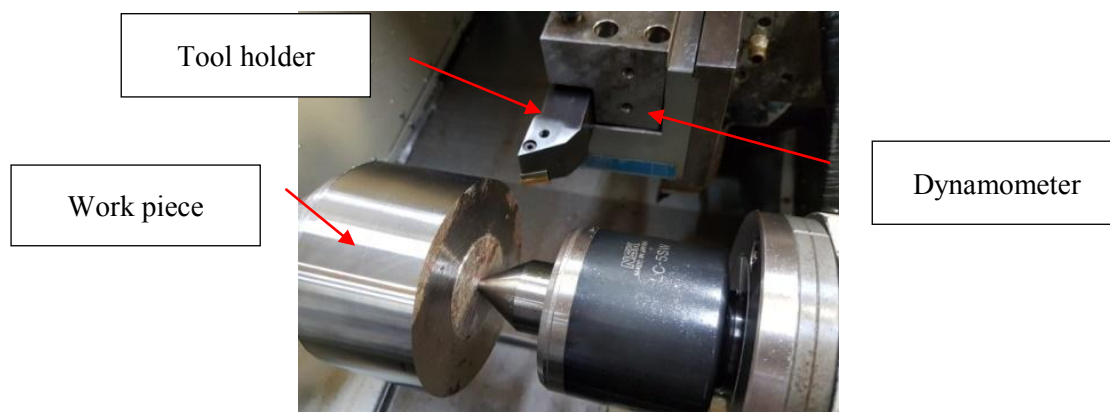
According to previous researches review, there was limitation in term of experiment cutting condition and cutting force analysis method. Thus, this study will provide more experiment cutting



conditions including cutting speed, feed rate, depth of cut and nose radius for giving more understanding about effects of various cutting conditions on the tool flank wear by utilizing wavelet transform analysis as cutting force analysis method. This study will lead to solving the tool wear problem, extending tool life and developing intelligent manufacturing in the future.

## 2. Experimental step and cutting conditions

This study utilizes MAZAK Quick turn NEXUS 200MY/MSY, which is 4 axis CNC turning machine with dry cutting condition. The dynamometer is set up to measure the dynamic force signal as shown in figure 1. The experiment was performed on a rod steel S45C with hardness 200 HB and using an insert tool of the KYOCERA turning insert coated carbide.



**Figure 1.** The dynamometer set up for the dynamic force measurement.

During experiment as condition list shown in table 1 by Box-Behnken design of experiment with 4 cutting conditions and 3 levels, The dynamic cutting force data was transferred to the oscilloscope for record as real-time and also the tool flank wear ( $V_b$ ) was measured by using microscope of NIKON MM-60. These results were always collected at the same time until the tool flank wear equal to 2 mm or failure. After that a new insert was replaced then the next condition was started. The dynamic cutting force ( $dF_y$ ,  $dF_z$ ) analyzed by using wavelet transform then calculated its ratio by using the dynamic main force ( $dF_y$ ) divided by the dynamic feed force ( $dF_z$ ). The dynamic cutting force ratio ( $dF_y/dF_z$ ) and the tool flank wear ( $V_b$ ) were selected at 15 min of cutting time as the response.

**Table 1.** Experiment conditions and levels

Cutting conditions	-1	0	1	Fixed factors
Spindle speed; $v$ (m/min)	150	200	250	Dry cutting
Feed rate; $f$ (mm/rev)	0.10	0.15	0.20	Rake angle $-6^\circ$
Depth of cut; $d$ (mm)	1.0	1.2	1.4	
Nose radius; NR (mm)	0.4	0.8	1.2	

## 3. Results and discussions

The experiment results analyzed by statistics method that popularly used in many researches which is the analysis of variant (ANOVA) with 95% confidential and p-value 0.05 are considered as significant. The significant of cutting conditions can be ensured by p-value report from ANOVA. The effect of cutting condition on the response consists of tool flank wear ( $V_b$ ) and the dynamic cutting force ratio ( $dF_y/dF_z$ ) which are discussed through the main effect plot. The response of the Box-Benken experiment was provided by table 2.

**Table 2.** Experiment results of Box-Benkhen

Run order	Cutting conditions				Responses	
	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Nose radius (mm)	$V_b$	dFy/dFz
1	150	0.15	1	0.8	0.1464	0.8787
2	150	0.15	1.4	0.8	0.1562	0.8573
3	200	0.15	1.2	0.8	0.1671	0.7435
4	200	0.1	1.2	0.4	0.1350	0.8290
5	250	0.15	1.4	0.8	0.1949	0.6577
6	200	0.2	1.2	1.2	0.1828	0.7250
7	200	0.15	1.4	0.4	0.1657	0.7664
8	150	0.15	1.2	0.4	0.1427	0.8771
9	200	0.1	1.4	0.8	0.1587	0.7910
10	200	0.15	1.2	0.8	0.1637	0.7436
11	200	0.2	1	0.8	0.1642	0.7346
12	200	0.2	1.4	0.8	0.1939	0.7080
13	250	0.2	1.2	0.8	0.1998	0.6576
14	200	0.1	1.2	1.2	0.1526	0.7161
15	200	0.15	1.4	1.2	0.1669	0.7400
16	250	0.15	1	0.8	0.1695	0.6809
17	200	0.2	1.2	0.4	0.1809	0.7257
18	200	0.15	1.2	0.8	0.1639	0.7499
19	150	0.1	1.2	0.8	0.1221	0.8892
20	250	0.1	1.2	0.8	0.1570	0.7032
21	200	0.15	1	0.4	0.1539	0.7888
22	200	0.1	1	0.8	0.1412	0.8506
23	200	0.15	1	1.2	0.1590	0.7724
24	150	0.15	1.2	1.2	0.1577	0.8606
25	250	0.15	1.2	1.2	0.1855	0.6747
26	250	0.15	1.2	0.4	0.1844	0.6780
27	150	0.2	1.2	0.8	0.1680	0.8539

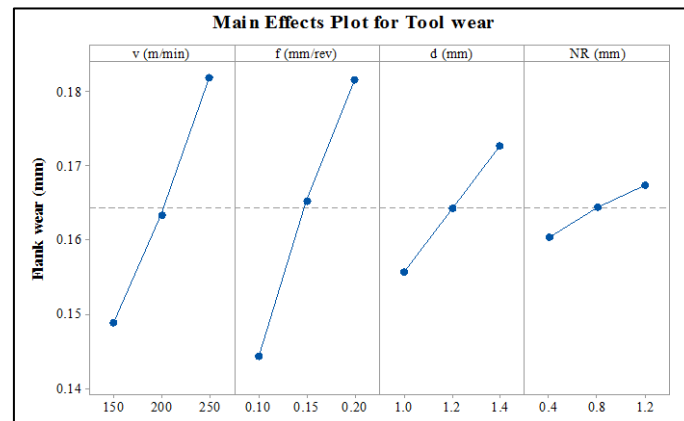
### 3.1. Tool wear analysis

ANOVA analysis is as shown in table 3. It is indicated that all cutting conditions have statistically significant effect on the tool wear in order to p-value less than 0.05. Thus, Cutting speed, feed rate, depth of cut and nose radius will be considered.

**Table 3.** ANOVA for response surface of too wear ( $V_b$ )

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remark
v (m/min)	1	0.008687	0.000620	22.14	0.000	Significant
f (mm/rev)	1	0.008423	0.002106	75.14	0.000	Significant
d (mm)	1	0.003263	0.003263	116.45	0.000	Significant
NR (mm)	1	0.004142	0.004142	147.79	0.000	Significant

The result of main effect plot reported that cutting speed is the most sensitive in term of direct variation on the tool wear followed by feed rate, depth of cut and nose radius respectively as shown in figure 2. The higher cutting speed accelerated the tool abrasion mechanical wearing due to frequently touching between work piece and tool on flank face. It causes a hard particle of work piece and removes a small portion of the tool.



**Figure 2.** Main effect plot of tool wear ( $V_b$ ).

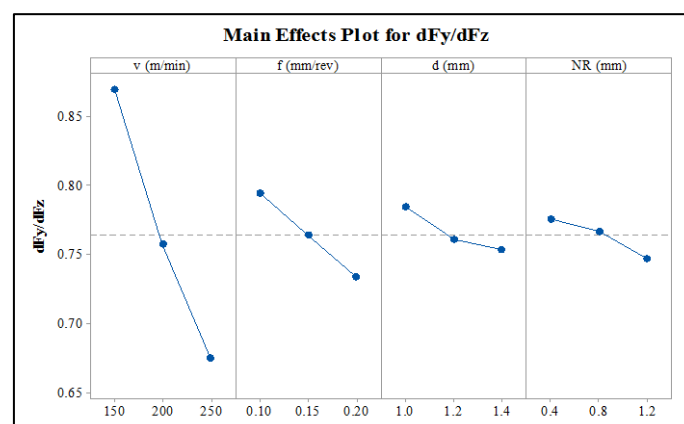
### 3.2. Dynamic cutting force ratio analysis

After ANOVA analysis, table 4 indicates that all cutting conditions have statistically significant effect on the dynamic cutting force ratio when p-value less than 0.05.

**Table 4.** ANOVA for response surface of dynamic cutting force ratio ( $dF_y/dF_z$ )

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remark
v (m/min)	1	0.134809	0.009629	23.75	0.000	Significant
f (mm/rev)	1	0.129119	0.032280	79.63	0.000	Significant
d (mm)	1	0.113052	0.113052	278.89	0.021	Significant
NR (mm)	1	0.010754	0.010754	26.53	0.030	Significant

The result of main effect plot reported that cutting speed is the most influential on the dynamic cutting force ratio ( $dF_y/dF_z$ ) followed by feed rate, depth of cut and nose radius respectively as shown in figure 3, is an inverse variation on the tool wear. In the other words, the tool wear ( $V_b$ ) is related to the dynamic cutting force directly and will be explained in the next. The higher cutting speed affects increasing of both dynamic feed force ( $dF_y$ ) and dynamic main force ( $dF_z$ ). Especially, dynamic main force ( $dF_z$ ) will increase more than dynamic feed force. Thus, cutting force ratio is rapidly decreased.



**Figure 3.** Main effect plot of dynamic cutting force ( $dF_y/dF_z$ ).

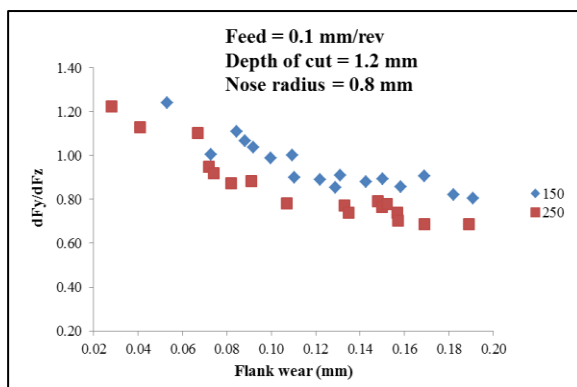
Base on the main effect plot analysis, it is found that cutting speed, feed rate, depth of cut and nose radius have the influence on both the tool flank wear ( $V_b$ ) and the dynamic cutting force ( $dF_y/dF_z$ ). In addition, these responses have relation in each other.

### 3.3. Effect of dynamic cutting force on tool wear analysis

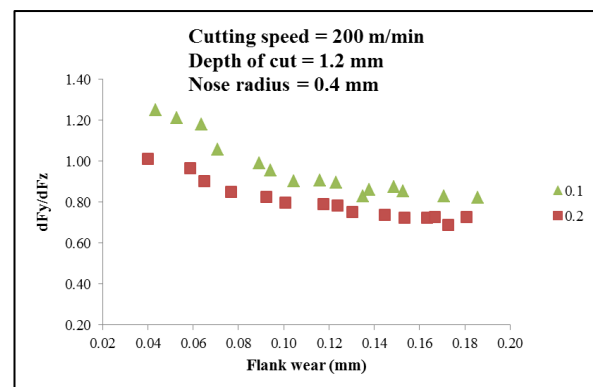
The result of experiment about relation of dynamic cutting force and tool wear will be provided for more understanding as shown in figure 4-7, under cutting conditions which varies from the lowest level (-1) to the highest level (1).

Figure 4 shows that the trend of both cutting speed 150 and 250 m/min are slightly decreasing of the dynamic cutting force ratio ( $dF_y/dF_z$ ) when the tool flank wear grows up. In order to dynamic main force ( $dF_z$ ) is the same direction as the cutting speed. If the cutting speed is high, the tool flank wear will increase. It causes the nose radius to be bigger which make a large contacting area between work piece and cutting tool and also leads to a high vibration. For these reasons, the dynamic main force ( $dF_z$ ) is higher than the dynamic feed force ( $dF_y$ ) then produces decreasing of the dynamic cutting force ratio.

Figure 5 shows that the trend of both feed rate 0.1 and 0.2 mm/rev are slightly decreasing of the dynamic cutting force ratio ( $dF_y/dF_z$ ) when amount of the tool flank wear is increased. According to faster feed rate leads to bigger tool wear. It causes cutting to be harder due to a large contacting area which directly affect to the dynamic main force ( $dF_z$ ). In addition, a faster feed rate leads to more surface roughness which affects the dynamic feed force ( $dF_y$ ) to be increased. However, the dynamic main force ( $dF_z$ ) is influenced by a faster feed rate much more than the dynamic feed force ( $dF_y$ ). Thus, the dynamic cutting force ratio ( $dF_y/dF_z$ ) is decreased.



**Figure 4.** Example of dynamic cutting force ratio ( $dF_y/dF_z$ ) versus tool flank wear under cutting speed 150 and 200 m/min, feed rate 0.1 mm/rev, depth of cut 1.2 mm and nose radius 0.8 mm.

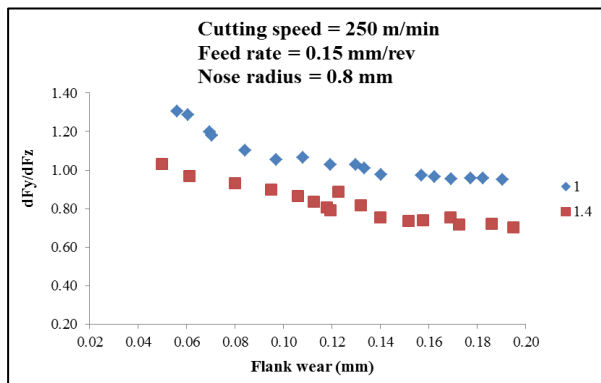


**Figure 5.** Example of dynamic cutting force ratio ( $dF_y/dF_z$ ) versus tool flank wear under feed 0.1 and 0.2 mm/rev, cutting speed 200 m/min, depth of cut 1.2 mm and nose radius 0.4 mm.

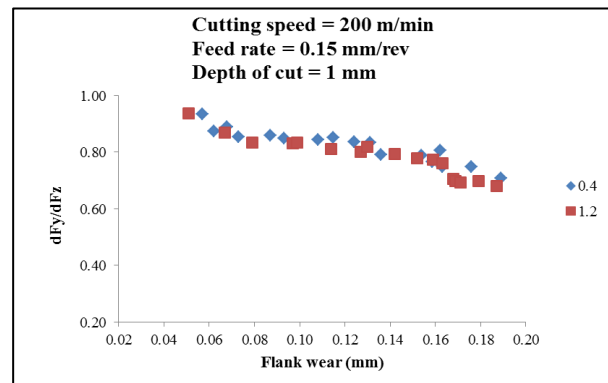
Figure 6 shows that the trend of both depth of cut 1 and 1.4 mm are slightly decreasing of the dynamic cutting force ratio ( $dF_y/dF_z$ ) when amount of the tool flank wear is bigger. The larger depth of cut means the larger contacting area between work piece and side cutting edge which leads to the cutting force is highly generated due to harder cutting and also there is risky vibration or chatter occurred which obtain more rough surface. Therefore, the dynamic main force ( $dF_z$ ) is higher than the dynamic feed force ( $dF_y$ ). Thus, the dynamic cutting force ratio ( $dF_y/dF_z$ ) is decreased.

Figure 7 shows similar trend with other cutting conditions. The dynamic cutting force ratio ( $dF_y/dF_z$ ) is decreased when the tool flank wear ( $V_b$ ) is bigger for both nose radius 0.4 and 1.2 mm. According to wearing not only occurs on the side cutting edge but also extend to the nose radius area that stimulated the vibration or chatter which affect roughing surface and a higher cutting force. In addition, the larger nose radius causes the contacting area to be larger, thus leading to the cutting force is highly generated and also less the dynamic cutting force ratio ( $dF_y/dF_z$ ).

Base on analysis results, relation between the dynamic cutting force ratio ( $dF_y/dF_z$ ) and the tool flank wear ( $V_b$ ) were pointed out. The bigger tool flank wear means smaller dynamic cutting force. Even the cutting conditions is changed, the dynamic cutting force ratio still keeps the same trend.



**Figure 6.** Example of dynamic cutting force ratio ( $dF_y/dF_z$ ) versus tool flank wear under depth of cut 1 and 1.4 mm, cutting speed 250 m/min, feed rate 0.15 mm/rev and nose radius 0.8 mm.



**Figure 7.** Example of dynamic cutting force ratio ( $dF_y/dF_z$ ) versus tool flank wear under nose radius 0.4 and 1.2 mm, cutting speed 200 m/min, feed rate 0.15 mm/rev, depth of cut 1 mm.

#### 4. Conclusions

According to experiment results, the conclusion can be explained as following.

- The most influential factors on the tool wear and the dynamic cutting force ratio are cutting speed followed by feed rate, depth of cut and nose radius respectively.
- The dynamic cutting force ratio directly associates to the tool wear. The dynamic cutting force ratio is slightly decreased when the tool wear is growth.
- The experiments demonstrate by varied cutting speed, feed rate, depth of cut or nose radius which was not differentiated the relation of dynamic cutting force ratio and the tool wear. The trend of dynamic cutting force ratio was slightly decreased even any cutting condition was changed.
- The most advantage of this study proved that it can predict the tool wear by utilizing of the dynamic cutting force ratio and also can be useful for the tool wear prediction mathematic model in turning process development in the future.

#### Acknowledgement

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