

# Modeling and Analysis of Tool Wear Based on Cutting Force and Chip-Tool Interface Temperatures in Turning



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## 1 Introduction

Machining processes are very common in manufacturing technology. These operations are applied in manufacturing of almost every mechanical element. Because of their frequent use, these processes have to be efficient and economical. To lower manufacturing costs, many parameters need to be considered. Tool wear is one of the most important considerations in metal cutting operations as it affects surface quality, productivity, cost etc. In the modern era of intense competition, reduction of machining cost is the key to sustain. For this the, performance of cutting tool plays a vital role.

A tool life is directly related to the wear behavior of cutting tool. To predict tool life, it is necessary to identify the actual wear progress under practical conditions [1, 2]. Taking out the tool to the metrology lab and measuring the actual wear of tool is a difficult task and affects the cutting efficiency. If the tool wear rate prediction models are available in terms of chip-tool interface temperature or cutting forces, the machining efficiency can be improved. By changing the tool where the wear rate reaches a control values.

In turning operations, it is convenient to consider the forces as a three component system. These are main cutting force component, feed force component and radial force component. The components of the cutting forces and chip-tool interface temperatures in metal cutting operations provide a wealth of information on the metal removal process. Changes in these forces and cutting temperatures indicate changes in machining parameters and tool geometry, such as cutting speed, feed rate, depth of cut and condition of tool. Thus the accuracy of machining operations could be improves through the cutting force and chip-tool interface temperatures.

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A rubbing action takes place between tool flank and workpiece which removes material at the flank side. As the cutting velocity and feed rate increase, the temperature in the chip formation region also rises [3].

Chaudhary and Ramesh [4] have used an optical displacement sensor for online tool wear monitoring. A feed back control system to provide compensation for the tool wear and keep the dimensions of the workpiece within the tolerance zone has also been suggested. Luo et al. [5] have studied relationship between tool flank wear and operational conditions (cutting) speed, feed rate and depth of cut) in metal cutting process using carbide inserts. The wear of the cutting inserts is calculated and recorded using zygo new view 5000 microscope. The experimental results indicate that cutting speed has a more dramatic effect on tool life than feed rate [5]. Ozel and Karpas [6] developed predictive model of tool wear and surface roughness in hard turning by CBN tool using neural network and regression method. Trained neural network models were used in predicting tool flank wear and surface roughness for other cutting conditions. They concluded that decrease in feed rate resulted in better surface roughness but slightly faster tool wear.

Ramesh et al. [7] used RSM for minimizing the surface roughness in machining titanium alloy. The surface roughness model has been developed in terms of cutting parameters such as cutting speed, feed rate and depth of cut. Machining test has been carried out using CVD coated carbide cutting tools under different machining conditions using Taguchi's orthogonal array. The experimental data have been investigated using analysis of variance (ANOVA). The results indicated that the feed rate is the main influencing factor on surface roughness. Surface roughness is increased with increasing feed rate, but decreased with increasing cutting speed and depth of cut. Felix et al. [8] developed mathematical model for tool wear in turning operations using multiple regression method. A non-traditional optimization algorithm, genetic algorithm has been employed to find the optimal cutting parameters such as cutting speed, feed rate and depth of cut.

Modeling and optimization are necessary for the control of the hard turning process to achieve improved product quality, high productivity and low cost. Empirical models for tool life, surface roughness and cutting force are developed for turning of AISI302 by Al-Ahmari [9]. Anthony et al. [10] determined the influence of different cutting fluids on wear and surface roughness in turning of stainless steel. Noordin et al. [11] studied the application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel. The factors investigated were cutting speed, feed rate and side cutting edge angle. The response variables were surface roughness and tangential cutting force. ANOVA revealed that feed rate is the most significant factor influencing the response variables investigated. Huang et al. [12] observed that wear pattern depend on the tools used, workpiece material composition, and cutting conditions. They also concluded that generally, adhesion, abrasion and diffusion are considered to be main tool wear mechanisms in CBN hard turning. However, the individual effect of each mechanism depends on the combinations of the work materials, tools, machining conditions, tool geometry etc. It was found that the temperature rise during the machining could significantly reduce the strength of the

tool and hence the wear resistance of the tool [13]. Palanisamy et al. [14] developed a regression and ANN mathematical model to predict tool flank wear in terms of machining parameters such as cutting speed, feed rate and depth of cut. Predicted values of tool flank wear of the mathematical model compared with the experimental values. The Grey-Taguchi method was adopted to optimize the milling parameters of aluminum alloy with multiple performance characteristics and found that the flank wear decreased from 0.177 to 0.067 mm [15]. Abhang and Hameedullah [16] used the grey relational analysis technique and determined the optimum turning process parameters. Various turning parameters such as cutting speed, feed rate, depth of cut, tool nose radius and concentration of solid-liquid lubricants were considered and optimized by the grey relational grades obtained from the grey relational analysis for multi-performance characteristics (chip-tool interface temperatures, main cutting force and tool wear).

In the present study article an attempt has been made to perform experimental testing on turning operations in order to establish a relationship between chip-tool interface temperature with tool wear rate and three components of cutting forces with tool wear rate during turning of En-31 steel alloy using tungsten carbide inserts. The predicted results are compared with the experimental results to find the nearness of the predictions to the experimental values. Further to take into considerations these wears also use of machining ratio has been proposed as a new criterion for tool life assessment. Machining ratio is the ratio of volume of material removed to the volume of tool wear.

## 2 Experimental Procedure

The experiments were carried out on a HMT, heavy duty lathe machine without any coolant. The workpiece EN-31 steel was turned for a certain amount of time, while measuring average chip-tool interface temperature and cutting forces by on line and then machining was stopped and tool wear was measured by offline. The cutting tool holder used for turning operation is WIDAX tool holder SCLCR 1212 Fog13 and diamond shape carbide (CNMA 120408). The work piece material used has a dimension of 400 mm in length and 60 mm in diameter. This material is suitable for a wide variety of automotive type applications. Experiments were carried out under different cutting speeds in the ranges of 47–134–226 m/min. Feed rates employed were 0.06–0.10–0.15 mm/rev and depth of cut and tool nose radius was 0.4 and 0.8 mm respectively. The chip-tool interface temperature is measured using tool-work thermocouple designed, fabricated and calibrated in the lab by author. Tool wear rate is measured on a sensitive single pan balance (maximum 300 g and minimum scale is 0.01 mg). Tool inserts were properly cleaned before weighing so that dust or any other adhered particles are removed. Online measurements of cutting forces are carried out using lathe tool dynamometer.

### 3 Experimental Results and Mathematical Modeling

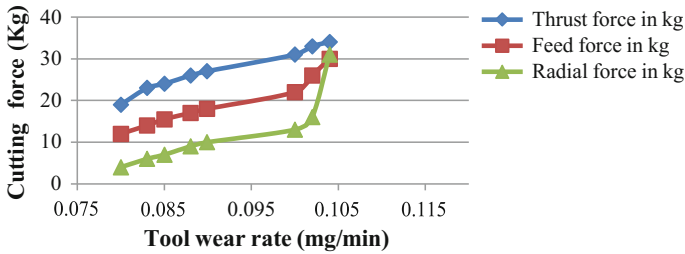
We first present the experimental results and then discuss the use of polynomial equations to express the relationship between the cutting forces with tool wear rate and cutting temperature with tool wear rate.

#### 3.1 *Relationship Between Cutting Forces and Tool Wear Rate*

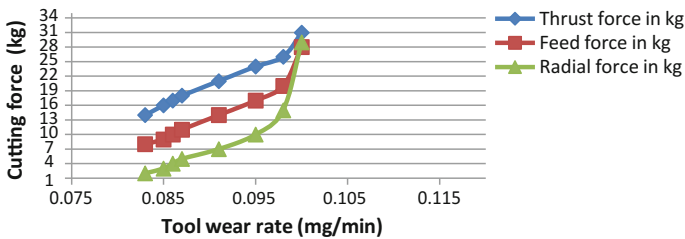
From the experimental results, Figs. (1, 2 and 3) show variations of three cutting force components with tool wear rate for different cutting speed and feed rate with constant depth of cut and tool nose radius. It can be seen from these figures that all cutting forces increase with the increase of total tool wear (flank and crater). Increasing tool wear results in an increasing area of contact between the tool-tip and the workpiece. The greater the value of tool wear, the higher the friction of the tool on the workpiece and high heat generation will occur; this ultimately causes the higher value of cutting forces. Table 1 shows experimental results for the first set of experiment, where the inserts begins to fail, all the three cutting forces increase rapidly. Figures (1, 2 and 3) show experimental results at stages where the tool insert begins to fail, for the cutting condition (cutting speed, feed rate, depth of cut and tool nose radius), thrust force and feed force increases slowly i.e. 8 and 17% and radial force increases (maximum) i.e. 70% during machining of EN-31 steel at present conditions. Figures (1, 2 and 3) show the relationship between tool wear and the cutting forces based on the experimental results. From the experimental results, we found that the radial cutting force was approximately (9–10%) larger than the feed force when the cutting tool begins to fail. This relationship is agrees with the results obtained by Noordin et al. [11]. Thrust force is the main force component responsible for material removal while feed force advances the cutting tool in the direction of feed. Radial force is the rubbing force. Polynomial mathematical models can be used to express the relationship between tool wear rate and the cutting forces based on the experimental results. Figure 4 shows the modeling results for the first set of models. It can be seen that the polynomial curves are very close to the experimental results.

#### 3.2 *Relationship Between Chip-Tool Interface Temperature and Tool Wear Rate*

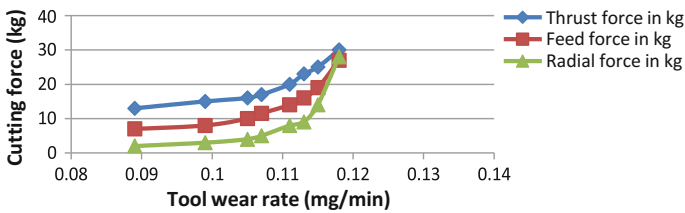
Experiments were continued until the tool wear became too high for the tool-work thermocouple technique to measure temperature accurately. Maximum tool wear was recorded. The results of the tool wear experiments are consistent with the



**Fig. 1** Cutting force versus tool wear rate (cutting speed 47 m/min, feed rate 0.06 mm/rev, depth of cut 0.4 mm and tool nose radius 0.8 mm)



**Fig. 2** Cutting force versus tool wear rate (cutting speed 134 m/min, feed rate 0.06 mm/rev, depth of cut 0.4 mm and tool nose radius 0.8 mm)

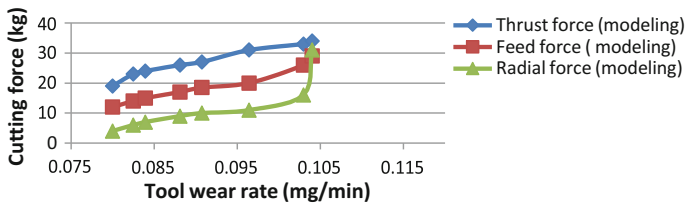


**Fig. 3** Cutting force versus tool wear rate (cutting speed 226 m/min, feed rate 0.06 mm/rev, depth of cut 0.4 mm and tool nose radius 0.8 mm)

results obtained by Tugrul et al. and Anthony et al. [6, 10]. Figures (5 and 6) clearly show that the wear increases with the increase cutting speed and feed rate. It can be seen from these figures that all chip-tool interface temperature increases with the increase in tool wear. When tool inserts begins to fail, all the chip-tool interface temperatures increase sharply. The experimental result shows in Fig. 5 is important when considering the temperature effects on tool wear, which is temperature dependent, i.e. when increasing tool, wear (flank and crater) then increases the chip-tool interface temperature during machining. Polynomial mathematical models

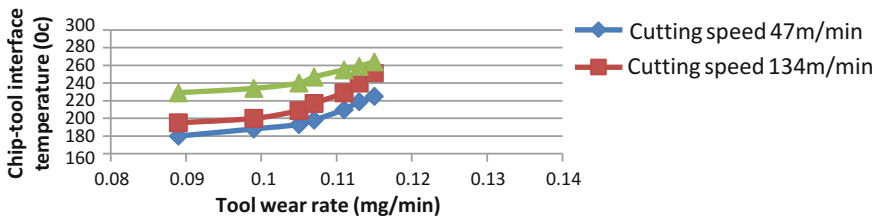
**Table 1** First set (cutting speed = 47 m/min, feed rate = 0.06 mm/rev, depth of cut = 0.4 mm, nose radius = 0.8 mm)

Exp. no.	Cutting time (min)	Tool wear rate (mg/min)	Thrust force (Kg)	Feed force (kg)	Radial force (kg)
1	10	0.08	19	12	4
2	20	0.083	23	14	6
3	30	0.085	24	16	7
4	40	0.088	26	17	9
5	50	0.089	27	19	10
6	60	0.10	29	20	11
7	70	0.102	33	26	16
8	80	0.104	34	30	31



**Fig. 4** Cutting force versus tool wear rate (cutting speed 47 m/min, feed rate 0.06 mm/rev, depth of cut 0.4 mm and tool nose radius 0.8 mm)

also used to express the relationship between tool wear rate and the cutting temperature based on the experimental results. Figure 6 shows the modeling results for the first set of models. It can be seen that the polynomial curves are very close to the experimental results. Similar results were obtained for other sets of model. Therefore a good relationship between the chip-tool interface temperature and tool wear rate can be established from the experimental results. Since we obtained eight sets of data for each experiment, all in limited range, polynomials of the fourth degree were used. The polynomial coefficients were found by MATLAB.



**Fig. 5** Chip-tool interface temperature versus tool wear rate (cutting speed 47 m/min, feed rate 0.06 mm/rev, depth of cut 0.4 mm and tool nose radius 0.8 mm)

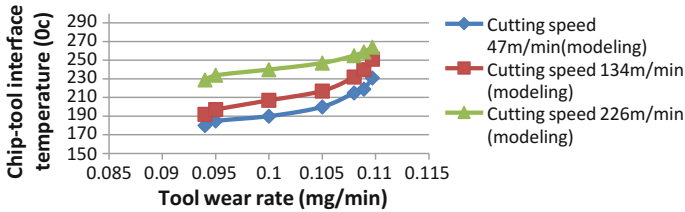


Fig. 6 Chip-tool interface temperature versus tool wear rate (cutting speed 47 m/min, feed rate 0.10 mm/rev, depth of cut 0.4 mm and tool nose radius 0.8 mm)

### 3.2.1 Polynomial Models

Thrust force = (X):

- Cutting speed = 47 m/min, feed rate 0.06 mm/rev.  
 Tool wear rate =  $-2.021 \times 10^{-6} X^4 + 0.0001931 X^3 - 0.006697 X^2 + 0.1012 X - 0.4863$   
 Feed force (X):  
 Tool wear rate =  $1.47 \times 10^{-6} X^4 - 0.0001307 X^3 + 0.004155 X^2 - 0.05423 X + 0.3282$   
 Radial force (X):  
 Tool wear rate =  $1.534 \times 10^{-6} X^4 - 9.474 \times 10^{-5} X^3 + 0.001828 X^2 - 0.0113 X + 0.1021$
- Cutting speed = 134 m/min, feed rate 0.06 mm/rev. Thrust force (X):  
 Tool wear rate =  $-1.21 \times 10^{-6} X^4 + 0.0001007 X^3 - 0.003044 X^2 + 0.003193 X + 0.09383$   
 Feed force (X):  
 Tool wear rate =  $-2.047 \times 10^{-8} X^4 - 5.159 \times 10^{-6} X^3 + 0.0002824 X^2 - 0.003193 X + 0.09383$   
 Radial force (X):  
 Tool wear rate =  $3.664 \times 10^{-7} X^4 - 1.932 \times 10^{-5} X^3 + 0.0002609 X^2 + 0.0002727 X + 0.0818v$
- Cutting speed = 226 m/min, feed rate = 0.06 mm/rev. Thrust force (X):  
 Tool wear rate =  $-1.275 \times 10^{-6} X^4 + 0.000124 X^3 - 0.00449 X^2 + 0.0726 X - 0.3318$   
 Feed force (X):  
 Tool wear rate =  $-2.003 \times 10^{-6} X^4 + 0.0001394X^3 - 0.003525 X^2 + 0.03941 X - 0.05588$   
 Radial force (X):  
 $-2.218 \times 10^{-6} X^4 + 0.0001249 X^3 - 0.002332 X^2 + 0.01806 X + 0.06185$   
 Chip-tool interface temperature:  
 Cutting speed = 47 m/min, feed rate = 0.10 mm/rev.

$$\text{Tool wear rate} = 4.03 \times 10^{-10} X^4 - 3.19210^{-7} X^3 + 8.696 \times 10^{-5} - 0.008731 X + 0.2693$$

Cutting speed = 47 m/min, feed rate = 0.06 mm/rev

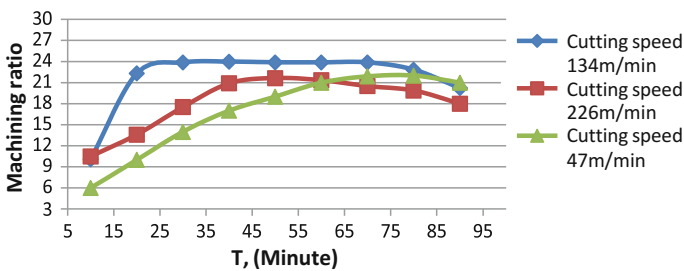
$$\text{Tool wear rate} = 4.19 \times 10^{-9} X^4 - 3.88 \times 10^{-6} X^3 + 0.001337 X^2 - 0.2024 X + 11.45.$$

### 3.2.2 Maximum Machining Ratio

Machining ratio is given by the following equation.

$$MR = vdf t/V = vdf t \rho/w \tag{1}$$

where,  $v$  = cutting speed (m/min),  $f$  = feed rate (mm/rev),  $d$  = depth of cut (mm),  $t$  = machining time (minute),  $V$  = volume of tool wear ( $\text{cm}^3$ ),  $w$  = weight of tool wear (mg) and  $\rho$  = density of tool material ( $15.8 \text{ g/cm}^3$ ) etc. For different machining conditions the values of machining ratio are shown in Fig. 7. It indicates that machining ratio first increases rapidly and reaches up to maximum value, then this value remains constant for some period after which it falls sharply. Machining ratio is inversely proportional to the tool wear rate. The tool wear rate shows a decreasing trend with respect to machining time and then it reaches to a certain value after which it starts increasing rapidly. The maximum machining ratio can be used as a suitable criterion for tool life. The tool life in case of maximum machining ratio criterion will be defined as the time when the machining ratio reaches its maximum value and when it begins to fall sharply. It is a dimensionless quantity and is based on combined wear of flank, crater, chip notching, primary and secondary grooving.



**Fig. 7** Machining ratio versus cutting time (feed rate 0.06 mm/rev, depth of cut 0.4 mm and nose radius 0.8 mm)



## 4 Conclusions

- (1) All cutting forces increase with increase of tool wear. The rate of cutting force increase (thrust force increases by approximately 8%, feed force increases by approximately 17% and the radial force increases by approximately 70%) of feed force and radial force is higher than the thrust force. The radial force was also found to be slightly larger than the axial force when tool insert begins to fail.
- (2) The study also presented the analysis of the relationship between tool wear and temperature by applying the tool work thermocouple technique. The temperature measured by the tool-work thermocouple method shows that temperature has a strong effect on tool wear.
- (3) There is a maximum value of machining ratio and can be taken as a criterion of tool failure.

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