# Prediction of Tool Wear Volume in Polycrystalline Diamond Tool During MicroTurning of Single Crystal Silicon

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## Abstract

Tool wear is a noteworthy problem in micro machining. Since the nose radius and critical wear range of the tool are at micron level, accurate quantification of the tool wear is a challenging task. The tool wear, even in the range of submicron level, will adversely affect the surface quality of the workpiece and will lead to a premature failure of the tool. During machining of hard and brittle materials like Silicon, Germanium etc. using diamond tools, typically used in high precision optical application, the tool wear is a serious concern. Hence, prediction of the tool wear in micro machining of such materials is important. While using a polycrystalline diamond (PCD) tool, major wear is observed on the flank face because of friction resistance in both ductile and brittle regime machining of silicon. In this work, an empirical model based on Archard's wear equation is developed for machining of single crystal silicon to predict tool wear volume. The model is based on flank forces, sliding distance and frictional conditions in micro turning. Obtained results for wear volume are compared with the experimental data to find out the value of Archard's wear coefficient. The Archard's wear co-efficient is found to be equal to 0.22 $\mu m^3/m$ with 96.9% confidence level of model.

Keywords: Archard's wear theory, Flank force, Tool wear volume, Micro machining.

## 1. INTRODUCTION

Manufacturing of high quality aspheric mirrors and reflectors from brittle materials like single crystal silicon and germanium imposes challenges to conventional manufacturing techniques. Recent advances in micromachining have enabled the possibility of generation of high quality surfaces on brittle materials without any post processing with the surface roughness and form error below 100 nanometers. So such brittle materials can be used in the field of optics, electronics, computers, communications, medical instruments and aerospace. Polycrystalline diamond (PCD) inserts/tools are rapidly replacing carbide cutting tools in many non-ferrous machining applications. PCD tools are extremely cost effective and give improved cycle times and more parts per tool by enabling high material removal rates. One of the limitations is more tool wear is occurring on PCD toolswhen machining of brittle materials like Silicon, Germanium. Tool wear is not only raises the machining cost but also degrades the product quality. Wear rates of PCD tool depend on physical and chemical nature of workpiece material. It can be either abrasive or chemical in nature, or a combination of both. Recent investigations suggest that the role of tribochemistry being dominating causing the tool wear during diamond turning of silicon.

S, Goel*et al*. [1] reviewed that there is also a chemical activity between Silicon and Carbon at sufficient high temperature. It was noticed by many researchers that diamond tool wear starts with appearance of nanoscale grooves on the tool flank. X.P. Li *et al*.[2] performed nanoscale ductile mode cutting of silicon wafer with single crystal diamond tools. Flank wear causes sub-cutting edges of much smaller radii on the main cutting edge. As the grooves become deeper the sub-cutting edges extend towards the tool rake face.Durazo*et al*.[3] studied that the recorded flank wear land initially exhibits an approximate linear trend. A steady phase is then reached followed by a stage of accelerated growth which finally leads to brittle fracture. He also proved that diamond tools with a top rake angle of $-25^{\circ}$ to be more favourable to diamond turning silicon, yielding longer cutting distances than $-15^{\circ}$ and $-45^{\circ}$ diamond tools. M. Sharif Uddin *et al*.[4] observed that during ductile mode cutting of silicon work material at a smaller undeformed chip thickness, gradual flank wear in single crystal diamond tool was predominant. At higher cutting distance, some small grooves were observed on the flank face along with gradual wear. The SEM and EDAX analysis of tool wear surface and machined Silicon chips indicate that mechanical abrasion, adhesion and possible thermo-chemical effects are mainly responsible for this kind of wear showed by S. Goel*et al*. [1].From literature review, it was observed that tool wear in diamond turning process is a major concern. Many aspects of diamond turning are relying on empirical procedures and the technical skills of operators. Difficulty in obtaining good surface finish on brittle materials is due to excessive wear of tool even at smaller cutting distance..There is need to develop deterministic models and a strategy for predicting the cutting performance as well as optimal cutting parameters under various cutting conditions. Optical profilometers can capture images at micron level of tool surface. So it is possible to see the wear patterns at micro levels under such instruments. The wear land can be measured and hence approximate wear volume can be measured byoptical profilometer (Zeta).

This paper aims to develop a wear model for more effectively and accurately predicting tool wear volume based onArchard's abrasive wear model.

## 2. WEAR MODEL

This Archard's abrasive wear model is based on cutting force, normal force and sliding distance. The wear constant is calculated from the actual experiments. This model is also validated by the experiments

ISBN: 978-93-80689-28-9

### 2.1 Archard'sWear Model

The Archard's wear equation is a simple model used to describe sliding wear and is based on the theory of asperity contact. It is valid only when wear mechanism is abrasive in nature.It concludes that the volume of the removed debris due to wear is proportional to the work done by friction forces. Wear is assumed only on flank face, so modified wear equation is given by B. M. Lane *et al*. [5].

$$V_w = A_w . w = k . F_f . d_s \qquad (1)$$

Where $V_w$-Volume of wear($\mu$m$^3$) , $A_w$-worn area ($\mu$m$^2$) , $w$-wear land width ($\mu$m), $k$-Archard wear coefficient, $F_f$ -Average flank force (N), $d_s$-sliding distance (km).

### 2.2 Average Flank Force ($F_f$)

$F_f$ can be obtained by resolving forces in vertical and horizontal directions as shown in fig.2.1.$F_f$is dependent on $F_T$ and $F_c$ which can be measured during experimentation by Kistler Mini Dynamometer (9256 C2) along with data acquisition card and inbuilt computer software LABVIEW.

$$F_f = \frac{FT(cos\alpha + \mu_r . sin\alpha) - Fc(sin\alpha - \mu_r . cos\alpha)}{cos\alpha . (1 - \mu_r . \mu_f) + sin\alpha . (\mu_f + \mu_r)} (2)$$

Where $F_f$ -Average flank force (N), $F_T$ -Thrust or Force (N), $F_c$ -Cutting Force (N), $\alpha$ – Rake angle(˚),$\mu_r$- Rake Friction Coefficient,$\mu_f$-Flank Friction Coefficient.

To obtain the magnitude of average flank force ($F_f$) following terms need to be calculated. This includes maximum uncut chip thickness, shear angle and frictional coefficients. Archard's wear coefficient (k), The value of k can be calculated by equating the eq. (1) with the actual wear volume obtained from tool wear characterization. Shear angle, ϕ can be calculated from eq. (3).

$$tan\phi = \frac{cos\,\alpha}{£ - si} \;;\; £ = \frac{t_c}{t_0}, \quad (3)$$

Where $\phi$- Shear angle, $\alpha$ – Rake angle(˚),£ - Chip thickness ratio, $t_c$ – Chip thickness before cutting, $t_o$ - Chip thickness after cutting.

Equation (3) is obtained from mechanics of metal cutting. It depends on rake angle and chip thickness before and after deformation. Collection of chips after machining is a very difficult. So chip thickness ratio (£) can be assumed within range or equal to 1. So shear angle will depend only on rake angle of the tool. Friction coefficients, $\mu_r$ *and* $\mu_f$

$$\mu_r = \frac{\cos\phi - (\sin\phi/\sqrt{3})}{(\cos\phi/\sqrt{3}) + \sin\phi} \qquad (4)$$

The relation between coefficient of rake friction ($\mu_r$) and shear angle (ϕ) was established by Arcona et al.[6] Coefficient of flank friction ($\mu_f$) can be calculated from actual sliding experiment. For diamond tool on single crystal silicon it was found to be 0.31[7].

## 3. EXPERIMENTAL SETUP

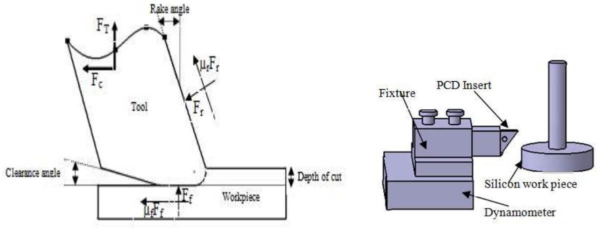
This section contains specification of workpiece and tool material, turning setup, measurement of force, and parameter selection for carrying out the experiments.

### 3.1 Workpiece Material

Single crystal silicon workpiece is prepared for turning on the periphery which is having of 25mm diameter and 6.5mm thickness.

### 3.2 Turning Setup

The turning experiments were conducted using the set-up prepared on micro-machine as shown in Fig.1(a). Thrust force (normal to workpiece surface) and cutting force measurement were taken simultaneously during turning.



(a) (b)

**Fig.1: (a)Side view schematic of wear parameters used in force and wear calculations (b)Schematic of experimental set-up for Micro turning**

A fixture was prepared to fix the tool shank as shown in Fig.1 (b). The same was mounted on the dynamometer using bolts. Dynamometer was clamped to the work table of the machine.

### 3.3 Force Measurement

The normal force, feed force and cutting forces are measured by a Kistler (Mini 9256 C2) Dynamometer which has piezoelectric sensors which sense the thrust force (Normal to the workpiece surface along the rake face), feed force and cutting force. It's very low threshold allows it to measure forces less than 1N. The charge amplifiers are connected to the dynamometer and it amplifies the voltage signals coming from the dynamometer into the force signal. Force signal is acquired with the NI DAQ 9234 card supported with LABVIEW programmed data acquisition. The sampling frequency for force measurement was set to 100Hz.

### 3.4 Parameters Selection

The PCD insert used for experimentation work has following geometrical properties: Rake angle = -10$^0$, Nose Radius = 0.2mm, Clearance angle = 10$^0$.

Three experiments were performed by varying cutting parameters. Cutting parameters were chosen on the basis of industries data and the past experiments of the authors. Two fresh PCD tools were used, one for actual experimentation and other one for validation experimentation. The selected process parameters are Spindle speed -2000rpm, Feed Rate -1mm/min, Depth of cut -50µm.

## 4. PCD TOOL WEAR MEASUREMENT BY OPTICAL PROFILOMETER(Zeta-20)

The images of tool were taken by Zeta (Optical Profilometer) at magnification of 50X. Images of both the rake and flank face were taken. So the complete profile of a wear has been visible.

The tool wear images were taken at the regular interval of 5km of tool travel or after each 5 passes to see the variation in wear after e

**Condition of fresh tool    Condition of tool after 20km**

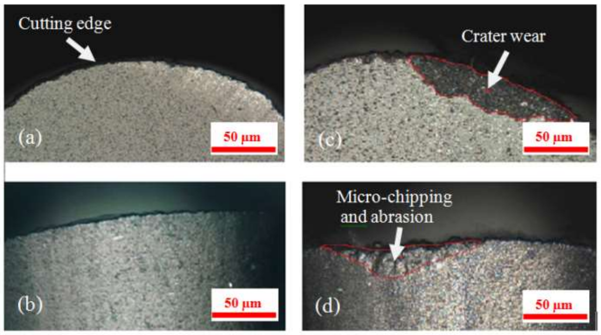


**Fig.2. (a) Rake face (c) Flank face of fresh PCD tool (b) Rake face (d) Flank face of PCD tool after 20km of tool travel**

The tool flank wear length, wear width, wear area and average roughness at the wear zone were measured for the analysis purpose. The wear volume is calculated by multiplying flank wear area and the average roughness at wear zone. Top view of the rake and flank face of fresh PCD tool is shown in Fig. 4(a) and (c) respectively. Fig. 4(b) and (d) shows the same tool after 20 km of tool travel. Micro-chippings and gradual wear have been seen on the flank face and crater wear on the rake face. The wear pattern was observed at the cutting edge of tool matches with the wear pattern observed in the literature.

## 5. RESULTS AND DISCUSSIONS

This section includes results of experimental work and tool wear characterization. Archard's wear coefficient for diamond (PCD) tool on silicon is calculated and plots of tool flank wear length, tool wear volume and cutting forces against sliding distance are analyzed.

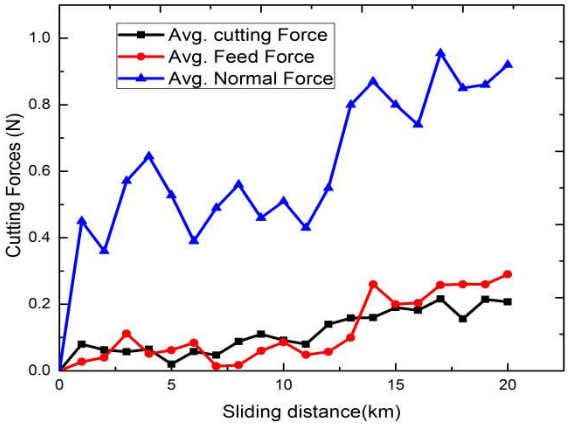


**Fig.3.Variation in cutting, normal and feed force with sliding distance**

### 5.1Analyses of Tool Force*:*

The Fig.3 shows the components of tool forces obtained against the sliding distance in kilometers. It was observed that tool forces increases with the sliding distance due to increases in tool wear. When cutting single crystal silicon at the micron level, i.e. in brittle mode cutting, fractureoccurs to the work material, forming micro craters in front of the cutting edge [8]. Such micro impacts occur at a very high frequency, resulting into the edge chippings. Hence cutting forces shows lot of fluctuation during machining. The measured cutting forces showed that only the normal cutting force component had significant magnitude and major increase with the sliding distance. These results obtained from force analyses demonstrated the possibility of monitoring the tool wear using normal force signals. On the other hand, change in the magnitude of cutting force and feed force was found to be very marginal throughout the experimental trials.

### 5.2Tool Flank Wear Volume

The increase in the wear volume as a function of sliding distance is illustrated in Fig.5.2. As observed, just after the sharp cutting edge recedes, an accelerated volumetric phase of tool wear rate follows. This phase continues till the sliding distance reaches approximately 20km. Similar trends have been presented by Cardens*et a*l. [3]

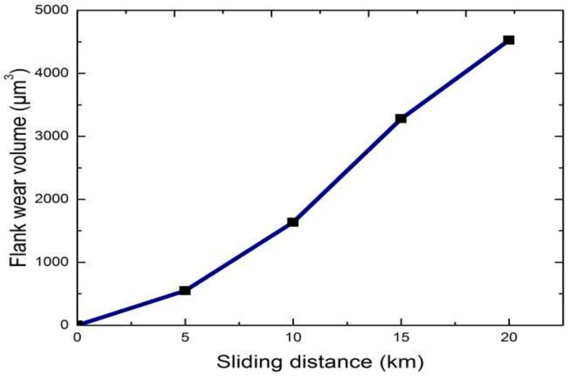


**Fig.4. Flank wear volume progression with sliding distance**

The Flank wear volume was calculated by multiplying flank wear area and the average roughness (Ra) obtained at the wear zone. Up to 5km of tool travel wear volume was increased to 548µm$^3$. At the end of second cycle it was increased from 548 to 1634µm$^3$. During third and fourth cycle, rate of increase in wear volume was nearly same.

Wear volume rate at the first cycle is less as compared to overall experiment because the tool-workpiece contact area was less at the beginning. At the end of experiment flank wear volume was increased to 4527µm$^3$.

### 5.3 Determination of Archard's Wear Coefficient

The Fig. 6 shows the experimental wear volume plotted against the average normal flank force multiplied by the values of corresponding sliding distance. From Archard's wear equation, the relation between wear volume and forces is Vw = k*Ff*ds, hence the slope of above graph directly gives the value of k i.e. Archard's wear coefficient for (PCD) diamond on single crystal silicon. It was found that the value of Archard's wear coefficient is equal to 0.222µm$^3$/m with the confidence level of 96.9%.

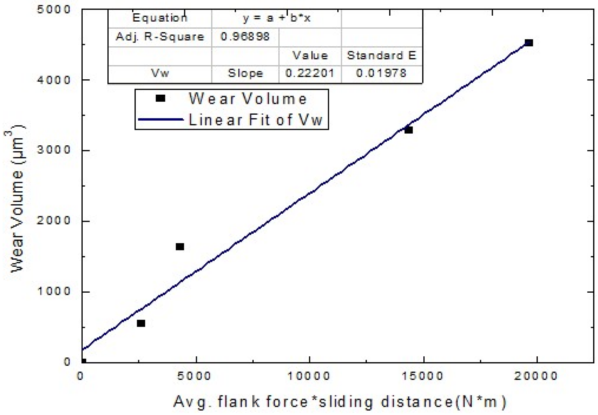


**Fig.5. Archard's wear coefficient for PCD tool on Single crystal silicon**

### 5.4Result Of Validation Experiment

Results of the validation experiment are shown in table 1. Cutting parameters considered for the validation experiment as discussed in Section 3.4. During this experiment PCD tool was travelled near about 6.5km within 10 passes. Dynamometer has recorded the cutting and thrust forces during entire validation experiment. Flank force varying with the wear could be calculated from equation (2).

**Table 5.1: Results of validation experiment**

| Cutting distance (km) | Wear volume (Experimental) ($\mu m^3$) | Wear volume (Model) ($\mu m^3$) |
|---|---|---|
| After 10 pass (distance 6.5km) | 1657 | Vw = k*Ff*ds = 222*0.7298*6.5<br>1053.18 |

Archard's wear coefficient was known for this particular tool workpiece combination from the actual experimentation (experiment no. 1). Its value was 222$\mu m^3$/km. After 6.5km of tool travel, model predicts tool wear volume equal to 1053.18$\mu m^3$. By actual measurement of tool wear volume using zeta profilometer the value obtained was equal to 1657$\mu m^3$. The difference between experimental value and model value is due to the following reasons.The wearmechanismsof PCD toolare not only abrasive but also has micro-chippings due to some of the grains are detached during machining as shown in Fig.2 (d). But the Archard's wear model doesn't account for themicro-chipping on tool. So the experimental value of wear will be more than theoretical model of the wear in PCD tool.

## 6. CONCLUSIONS

A method for monitoring the life of diamond tools based on the observation of cutting and normal force was evaluated. The tool wear characterization is done with zeta (optical profilometer). The cutting and normal forces were analyzed and co-related to tool wear progression. . The major conclusions are as follows:

- There was rapid wear at the beginning then wear get stabilises for few passes and again it increases drastically. It follows the actual or general trend of wear.
- The normal cutting force was increasing with the wear because of the friction at the tool-workpiece contact area. These results demonstrated the possibility of monitoring the tool wear using normal force signals.
- The Archard's wear coefficient for PCD tool on single crystal silicon is found to be 0.222$\mu m^3 N^{-1} m^{-1}$.

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