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Experimental Investigationof the Tool Wear Mechanism during Micro Turning on Ti-6Al-4V Alloy

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Abstract

Tool wear is produced by the relative sliding at the tool-work piece interface, as well as the tool-chip interface under severe cutting conditions. The evolution of tool wear can be attributed to the mechanisms like material adhesion, abrasion, diffusion, etc. The chip formation during conventional machining mainly involves the shear deformation of the workpiece material. However in micro-machining, as the undeformed chip thickness becomes comparable with the cutting edge radius, the material deformation mechanism is influenced by size effect. Therefore, the tool experiences a nonlinear variation in cutting forces and specific cutting energy, which accelerates the tool wear. The present study is focused on the mechanism of tool flank wear during micro turning of Ti-6Al-4V alloy using un-coated carbide inserts, within the size affected domain. Cutting experiments indicate that, within the size affected domain,the flank wear depth increases withreduction in feed, which is contrary to the trend in the conventional machining.A survey of the different tool wear rate models for the prediction of tool wear rate during machiningis also performed in this paper.

Keywords: Micro Turning, Ti-6Al-4V, Carbide tool, Flank wear, Tool wear rate models

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1. INTRODUCTION

Growing demand for miniaturized components have made mechanical micromachining [1] a hot area of research for the past couple of decades. Detailed reviews of the works done by the researchers worldwide have been published by pioneers in the field over years [2 – 5]. Many researchers have studied the surface finish and the tool wear in conventional machining, mainly because of its influence on the economics and quality of the product manufactured. However, only a few works related to the tool wear mechanism during micromachining, considering the size effect have been reported. The nonlinear variation of specific cutting energy and cutting forces as the uncut chip thickness becomes comparable to the edge radius makes the mechanics machining at micro scale really complex.

The mechanism of tool wear has always been anarea of interest for researchers because of its influence on tool life, surface roughness, residual stresses, machining costetc. Tool wear is produced by the relative sliding at the tool-work piece interface, as well as the tool-chip interface under severe cutting conditions. Several factors affect the tool wear in metal cutting, which includes workpiece material and its physical properties, machining parameters, interface conditions like coolants etc.

The mechanism of tool wear is generally attributed to the combined effect of phenomenon like adhesion, abrasion, diffusion,etc.[6]

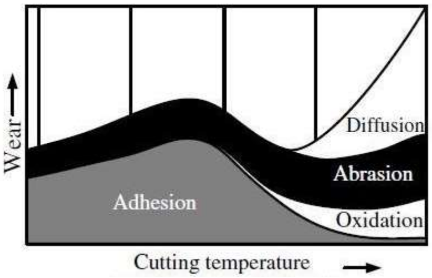

Fig.1. Mechanism of tool wear in metal cutting [6, 7]

a) Adhesive wear

The relative sliding between the tool and workpiece results in high temperatures at the tool workpiece interface. This causes the workpiece or chip fragments to adhere to the tool surface as micro welds. As the machining proceeds these welds get detached resulting in adhesive wear. This type of tool wear occurs at the flank face of the tool.

b) Abrasive wear

Abrasive tool wear is a result of the sliding of the hard components or particles produced during machining like tool fragments, chip particles etc., at the tool chip or tool workpiece interface.

c) Diffusion wear

As the chip flows over the rake face of the tool, transfer of atoms takes place between tool material and chip as a result of the difference in concentration. As the atoms move from tool material to the chip, diffusion wear occurs on the rake face of the tool, resulting in crater wear. Diffusion wear varies exponentially with respect to the temperature.

From Fig.1, it is evident that adhesive and abrasive mechanisms are the predominant tool wear mechanisms at lower temperatures. However, as the temperature increases,diffusion tool wear mechanism gains significance.

In micro machining as the cutting temperatures are much smaller compared to the conventional macro machining. Thus the primary tool wear mechanisms in micro machining are adhesive and abrasive mechanisms. In micro-machining, as the undeformed chip thickness becomes comparable with the cutting edge radius, the material deformation mechanism is influenced by size effect. Therefore, the tool experiences a nonlinear variation in cutting forces and specific cutting energy, which accelerates the tool wear, resulting in ploughing. This makes the mechanism of tool wear at the micro scale more complex and difficult to predict.

Even though several researchers have studied the tool wear mechanism in machining, the literatures pertaining to micro machining are minimal. The present study is focused on the

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mechanism of tool flank wear during micro turning of Ti-6Al-4V alloy using un-coated carbide inserts, within the size affected domain.

2. MICRO TURNING EXPERIMENTS

2.1. Workpiece Material

Titanium alloy (Grade 5) rods with 6mm diameter are used as the workpiece material for the present study. Ti-6Al-4V is becoming increasingly important for several industries like biomedical, aerospace, etc., due to its excellent properties that include high hardness, hot hardness, specific strength and corrosion resistance. However, this alloy is found to be difficult to machine due to low thermal conductivity, spring back effect, residual stresses, high chemical reactivity with cutting tool materials, sticky nature etc.

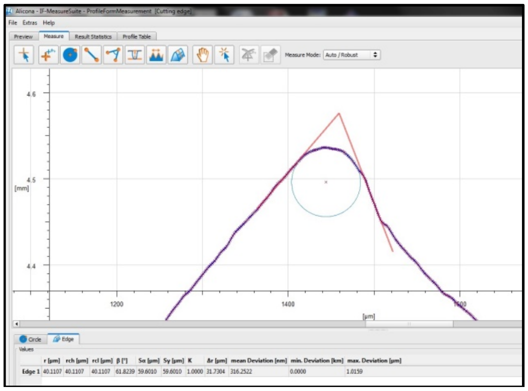
Table 1

Percentage composition and properties of Ti-6Al-4V

Material	Composition (%)	Property	Values
Titanium	Balance	Density	4.42 g/cm3
Vanadium	3.5 – 4.5	Melting Point	1650 ^{0}C
Aluminium	5.5 – 6.76	Thermal Conductivity	7.2 W/mK
Iron	0.25 (max)	Specific Heat	526 J/kgK
Carbon	0.08 (max)	Hardness	36 HRC
Oxygen	0.2 (max)	Elastic Modulus	114 GPa
Hydrogen	0.0125 (max)	Tensile Strength	1000 MPa

2.2. Cutting Tool

Uncoated Tungsten Carbide inserts (SUMITOMO TCMT090204) were used for the experiments. The cutting edge radius measured (Fig. 2) using 3D non-contact optical profiler (Alicona InfiniteFocus G5) was found to be 40µm.



Measure Mode: Auto / Robust

	r [µm]	rch [µm]	rcl [µm]	β [°]	Sα [µm]	Sγ [µm]	K	Δr [µm]	mean Deviation [nm]	min. Deviation [km]	max. Deviation [µm]
Edge 1	40.1107	40.1107	40.1107	61.8239	59.6010	59.6010	1.0000	31.7304	316.2522	0.0000	1.0159

Fig.2. Measurement of cutting edge radius

2.3. Experimental Setup

Micro turning experiments were carried out using a 3 axis multipurpose micromachining center (DT110-MIKROTOOLS, Singapore). The insert was attached to the tool shank (Sumitomo type STGCR1010-09), mounted above the dynamometer. The cutting forces encountered during machining were recorded using the Mini-Dyn Multi-component mini dynamometer (KISTLER Type 9256C2) coupled with a multi-channel charge amplifier (KISTLER Type 5070A) and Data Acquisition System (KISTLER Type 5697). The experimental set up is shown in Fig.3.

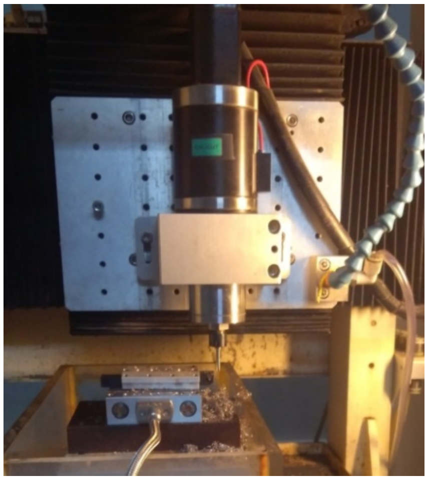


Fig.3. Experimental setup for micro turning experiments

2.4. Methodology

In this study, micro turning experiments were carried out in dry conditions by considering feed rates well below the edge radius of the tool, so that the influence of size effect can be analyzed in detail. The cutting speedand depth of cut were kept as constants. The machining operation was interrupted at specific intervals, and the resulting flank wear was measured using 3D non-contact optical profiler (ALICONA InfiniteFocus G5) shown in Fig.4.

The flank wear obtained after 7 minutes of micro turning, at feed rate of 16µm/rev measured using the 3D non-contact optical profiler, can be observed from Fig.5. The cutting force and flank wear data for the complete experimentation is displayed in Table 3.

Table 2

Experimental Plan

Machine tool	Micro machining centre (DT110, MIKROTOOLS, Singapore)
Cutting speed (m/min)	40
Depth of cut (mm)	0.1
Feed (µm/rev)	4, 8, 12, 16, 20
Cutting tool	Uncoated Tungsten Carbide Insert (TCMT090204)
Workpiece Material	Ti-6Al-4V rods
Dynamometer	KISTLER 9256C2
3D non-contact optical profiler	Alicona InfiniteFocus G5

Fig.4. 3D optical profiler (Alicona InfiniteFocus G5)

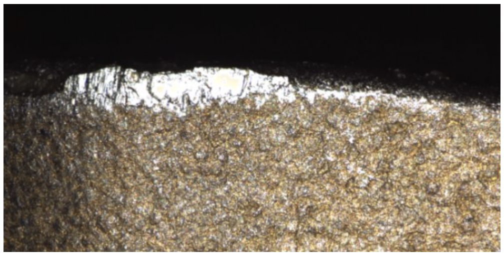


Fig.5.Flank wear after t = 7 mins for feed rate 16µm/rev

Table 3

Experimental tool wear in 3D micro turning

Feed	Time	Flank Wear	Cutting Force
f (µm/rev)	t(mins)	V_B (µm)	F_Y(N)
4	3	84.1	19.03
	6	85.6	28.44
	9	88.1	14.48
	12	116.6	18.77
	15	138.7	19.21
8	3	68.1	19.43
	6	83.8	28.93
	9	93.3	30.39
	12	104.1	31.53
	15	131.5	18.4
12	3	67.9	19.28
	6	85.9	19.42
	9	94.5	20.12
	12	96.5	20.43
	15	109.24	29.35
16	3	51.1	21.19
	6	57.4	22.47
	9	66.2	23.24
	12	94.7	27.14
	15	101.8	32.33
20	3	64.8	21.4
	6	67.9	22.11
	9	76.4	25.53
	12	77.6	34.69
	15	80.6	32.65

3. RESULTS AND DISCUSSION

Based on the results obtained from the experiments and the FEM simulationthe tool wear progression isanalyzed in detail. The specific cutting energy during the cutting operation was calculated using the equation (1).

$$\text{Specific Cutting Energy} = \left(\frac{F_C \times V_C}{D \times V_C \times f}\right) \qquad (1)$$

where, F_C is the cutting force, V_C the cutting speed, D the depth of cut and f the feed rate.

The variation of specific cutting energy with feed rate can be observed from Fig.6.As the feed rate approaches the edge radius of the tool, an increase in the specific cutting energy can be observed from the graph. The sudden increase in the specific cutting energy, as the feed rate decreases below 20µm/rev indicates the influence of the size effect on the cutting mechanism [8].

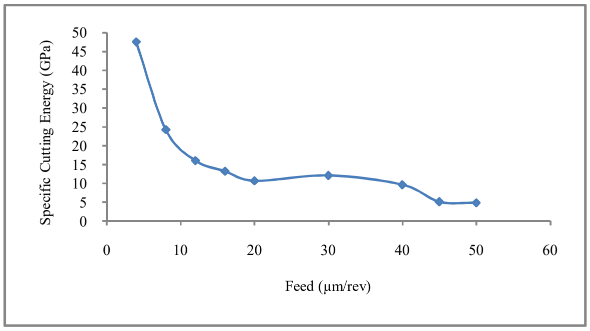


Fig.6. Variation of Specific Cutting Energy with feed rate

The flank wear depth measured during the micro turning experiments reveal the influence of size effect on the tool wear mechanism as the feed rate reduces below the edge radius value. The variation of flank wear with time for different feed rates based on the results obtained during the experimental investigation is displayed in Fig.7. The graph shows that flank wear increases with decreasing feed rate, which is contrary to the trend observed in macro machining [9]. This can be attributed to the increased ploughing mechanism at lower feeds.

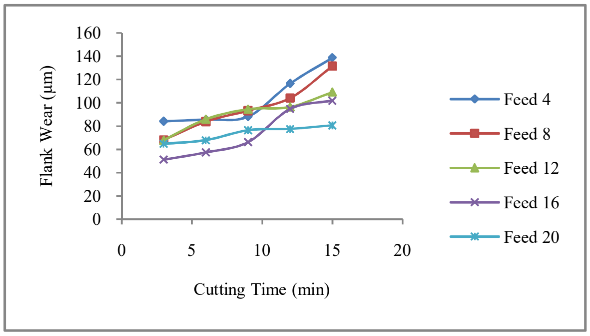


Fig.7. Variation of flank wear with cutting time

4. TOOL WEAR RATE MODELS

Analytical models have been used to obtain the wear rate as a function of process parameters like cutting velocity, feed rate, etc., of the material and geometry of both the tool and workpiece. The tool wear rate models describe the rate of local volume loss on the rake or flank face per unit area per unit time. Several researchers have used the tool wear rate models that describe the rate of local volume loss on the tool contact face per unit area per unit time to predict the tool wear. Amongst them Takeyama and Murata model [10] given in equation (2), which considers abrasive and diffusive wear mechanisms and Usui's model [11] given in equation (3), which considers the adhesive wear mechanismis widely utilized.

$$\frac{\mathrm{dW}}{\mathrm{dt}} = \mathrm{G}(\mathrm{V},\mathrm{f}) + \mathrm{D}\exp\left(\frac{-\mathrm{E}}{\mathrm{RT}}\right) \qquad (2)$$

$$\frac{\mathrm{dW}}{\mathrm{dt}} = \mathrm{A}\sigma_{\mathrm{n}}\mathrm{V}_{\mathrm{S}}\exp\left(\frac{-\mathrm{B}}{\mathrm{T}}\right) \qquad (3)$$

where, $\mathrm{G}, \mathrm{D}, \mathrm{A}, \mathrm{B}$are constants,$\mathrm{dW}/\mathrm{dt}$ the wear rate (volume loss per unit contact area per unit time),V the cutting speed,f the feed rate, E the activation energy, R the gas constant and T the interface temperature, σ_{n} the normal stress and V_{S} the sliding velocity.

Usui et al. [9] used the adhesive tool wear rate model and reported that the flank wear rate (dVB/dT) increases with increasing feed, using analytical method and experimental validation. Their results showed that the proposed model can be used to predict both flank wear and crater wear as both follow similar wear mechanism. Xie et al. [12] utilized the Usui's abrasive tool wear rate model to predict the tool wear in turning operation using 2D finite element simulation. Attanasio et al. [13] performed the 3D finite element simulation to diffusive tool wear by incorporating the Takeyama and Murata model using Deform 3D software. Attanasio et al. [14] proposed a coupled abrasive-diffusive tool wear model to predict tool wear during the turning operation using uncoated carbide tools. Zanger et al. [15] proposed an additive tool wear rate model by combining the Usui model and Takeyama and Murata model to predict the tool wear during turning to Ti6Al4V alloy using uncoated carbide tools. Ozel et al. [16] employed the Usui tool wear model for predict the tool wear rate during micro-milling of Ti6Al4V alloy using uncoated and cBN coated micro-tools.From the literatures it is evident that the utilization of tool wear models to predict the tool wear rate during micro machining applications has been minimal. As the undeformed chip thickness becomes comparable with the cutting edge radius, the material deformation mechanism is influenced by size effect. Therefore, the tool experiences a nonlinear variation in cutting forces and specific cutting energy, which accelerates the tool wear. This necessitates the need of suitable theoretical model for the micro machining process incorporating the effects encountered in the size affected domain.

5. CONCLUSIONS

The present study focused mainly on the flank wear mechanism in the size affected domain during the micro turning of Ti-6Al-4V alloy using uncoated carbide tools. Results indicate that the tool wear during micro machining especially within the size affected domain is highly influenced by the ploughing mechanism. The flank wear was found to be increasing as the feed rate values decreases, within the size affected domain. However the higher nose radius and deflection of the workpiece as the diameter decreases may have significant influence on the results. The future scope of this workis to validate the efficiency of the tool wear models in predicting the tool wear in micro machining using finite element simulation.

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