PROCEEDINGS OF THE FOURTH INTERNATIONAL CONFERENCE ON METAL CUTTING NON-CONVENTIONAL MACHINING AND THEIR AUTOMATION

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FOREWORD

The fourth international conference on metal cutting, non — conventional machining and their automation (IMCC) is jointly organized by Beijing Institute of Technology and Hong Kong Polytechnic and to be held in Beijing, China from 25 April to 27 April 1989. About 200 papers by the scholars from various countries and regions such as China, Hong Kong, UK, Japan, USA, Australia, Canada, Italy, USSR, Sweden, Singapore, etc. have been received. Accepted papers presented in the conference are included in the conference proceedings. The content of the papers can be categorized into five aspects: (1) cutting; (2)grinding; (3)tool system and tool design; (4) non — conventional machining; (5)automation. The proceedings is published by the Beijing Institute of Technology Press.

The academic exchange of IMCC began in 1983. The three former events were held in Guangzhou, Wuhan and Nanjing, China respectively. Representatives and papers increased at each occasion and this 4th IMCC has the greatest number of participants. This can be regarded as an indication of the increasing importance of this international academic exchange and we hope that future activities of the IMCC will prosper.

We would like to extend our thanks to all scholars for their participation and to the authorities of Beijing Institute of Technology and Hong Kong Polytechnic for their unreserved support.

Prof. Yu Qixun

Dr. W. S. Lau

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ON MECHANICS OF CIRCULAR GROOVE CUTTING

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ABSTRACT

A cutting model for circular groove cutting is established theoretically in this paper. Based on this model, the theoretical cutting force formula and the cutting equation are derived. Meanwhile the theoretical formula presented in this paper is verified experimentally, and results show that theoretical predictions agree well with experimental results.

INTRODUCTION

Much work on the mechanics of orthogonal and oblique cutting s been done in the past. But a much smaller volume of work has en concerned with the mechanics of form groove cutting. One of rm groove cuttings is circular groove cutting. It is often countered in practice. However it is very hard to study the chanics of circular groove cutting because of difficulties in thematics and mechanics. W.K.Luk had analyzed indirectly the chanics of circular groove cutting[1]. But some of the theorecal predictions, especially when the effective rake angle of e tool is not equal to zero, do not give satisfactory agreement th experiments. Therefore it is necessary to take further steps study the mechanics of circular groove cutting.

THEORETICAL ANALYSIS

1 Cutting model for full depth cuts

As shown in Fig. 1, the radius of the ol r is usually much greater than the cut chip thickness T. So it may be asmed that plane strain conditions will be ceptable and the chip flow will take ace in planes parallel to the symmetrical ane of the tool which may be called chip

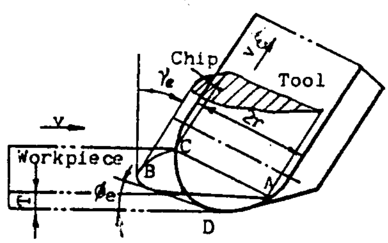

Fig.1 Cutting model

ow plane. In chip flow planes the effective rake angle γ_e and fective shear angle ϕ_e can be defined. It will also be assumed at in each chip flow plane along the cutting edge ADC the marial being cut will be sheared in the same direction. The cirlar groove cutting process in Fig. 1 may therefore be considered a piling up of much orthogonal cuttings with the same effective ear angle ϕ_e and effective rake angle γ_e, but with different cut chip thickness along the cutting edge ADC. Thus it can be en that the shape of shear plane ABCDA is a part of an elliptic cylinder with the directrix ADC and generatrix BD. Assuming that an ideally plastic material is taken into account, then the shear stress in the shear plane can be found to be equal to the yield shear stress of the material τ_s, while the normal stress in the shear plane σ_n can also be found to be equal to τ_s from the equilibrium of element close to the shear plane.

2.2 Area of the shear plane

Let us see Fig. 2, equation of the shear plane is given by,

$$\begin{cases} x = r\cos\theta \\ y = r\sec\gamma_e\cos(\phi_e-\gamma_e)\sin\theta \end{cases} \qquad (1)$$

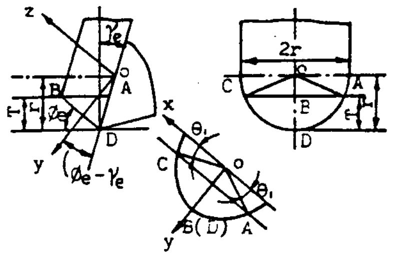

Fig.2 The geometry of shear plane

It can be seen from Fig. 2 that the area of shear plane A_s is equal to that of the elliptic cylinder expressed by equation (1) sectioned by the surface of workpiece AB and tool rake face AD. According to the geometry in Fig. 2, we have

$$\text{equation of AB:} \quad f(y) = y\cot\phi_e - (r-T)\csc\phi_e \qquad (2)$$

$$\text{equation of AD:} \quad g(y) = -y\tan(\phi_e-\gamma_e) \qquad (3)$$

Thus the area of shear plane A_s can be given by

$$A_s = 2\int_{\theta_1}^{\pi/2}\left[f(y)-g(y)\right]\sqrt{\dot{x}^2(\theta)+\dot{y}^2(\theta)}\, d\theta \qquad (4)$$

Substituting equation (1), (2) and (3) into (4), we obtain

$$A_s = I_1 + I_2 \qquad (5)$$

in which

$$I_1 = 2abr^2\int_{\theta_1}^{\pi/2}\sqrt{1-(1-a^2)\cos^2\theta}\,\sin\theta\, d\theta \qquad (6)$$

$$I_2 = -2ar(r-T)\csc\phi_e\int_{\theta_1}^{\pi/2}\sqrt{1-\left(1-\frac{1}{a^2}\right)\sin^2\theta}\, d\theta \qquad (7)$$

and

$$\begin{cases} a = \sec\gamma_e\cos(\phi_e-\gamma_e) \\ b = \cot\phi_e + \tan(\phi_e-\gamma_e) \\ \theta_1 = \arcsin\left(\frac{r-T}{r}\right) \end{cases} \qquad (8)$$

Integration of (6) gives

$$I_1 = \begin{cases} \frac{ab}{\sqrt{1-a^2}}\left[\sqrt{c(r^2-c)} + r^2\arcsin\left(\frac{\sqrt{c}}{r}\right)\right] & a<1 \\ 2br\sqrt{T(2r-T)} & a=1 \\ \frac{ab}{\sqrt{a^2-1}}\left[\sqrt{-c(r^2-c)} + r^2\ln\left(\frac{\sqrt{-c}+\sqrt{r^2-c}}{r}\right)\right] & a>1 \end{cases} \qquad (9)$$

where

$$c = T(2r-T)(1-a^2) \qquad (10)$$

The integral expressed by equation (7), I_2, belongs to the second type of elliptic integration. In order to calculate it, we expand the function to be integrated into the power series and take the first two terms of the series as its approximant. Thus

$$I_2 \doteq -2ar(r-T)\csc\phi_e\int_{\theta_1}^{\pi/2}\left[1-\frac{1}{2}\left(1-\frac{1}{a^2}\right)\sin^2\theta\right]d\theta$$

$$= \frac{r-T}{2ar\sin\phi_e}\left[(a^2-1)(r-T)\sqrt{T(2r-T)} - r^2(1+3a^2)\arccos\left(\frac{r-T}{r}\right)\right] \qquad (11)$$

2.3 Cutting force and cutting equation

Fig. 3 shows the cutting forces of circular groove cutting.

Since the shear stresses in the shear plane are in the same direction, the shear force in the shear plane can be given by

$$F_s=\tau_s A_s=\tau_s(I_1+I_2) \qquad (12)$$

The direction of the normal stresses in the shear plane varies with different θ. In order to calculate the component F_n, let us consider a small element, $d\theta$, which makes an angle of θ with x axis (referring to Fig. 3). Assuming that the normal force acting on this element equals dF_{sn}, it may be resolved into the component dF_n and the component dF_x. The total component F_x in the x direction is equal to zero because of geometric symmetry. Another component F_n can thus be calculated as follows

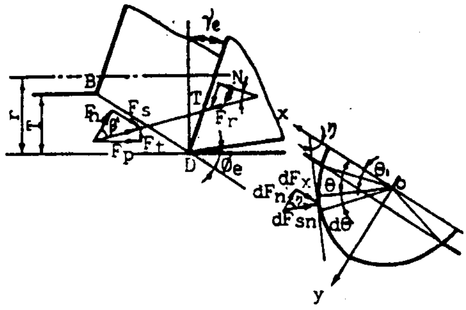

Fig.3 Force diagram

$$F_n=2\int_{\theta_1}^{\pi/2} dF_n=2\tau_s\int_{\theta_1}^{\pi/2}\left[f(y)-g(y)\right]\sqrt{\dot{x}^2(\theta)+\dot{y}^2(\theta)}\,\cos\eta\, d\theta \qquad (13)$$

in which, the angle η can be determined by equation of shear plane (1). According to geometric sense of the derivative we have

$$\frac{dy}{dx}=\tan(\pi-\eta)=-\tan\eta \qquad (14)$$

substituting (1) into (14), and using trigonometric formula, we obtain

$$\cos\eta=1/\sqrt{1+a^2\cot^2\theta} \qquad (15)$$

Upon the substitution of (2), (3), (8) and (15) in (13), we thus obtain

$$F_n=2\tau_s\int_{\theta_1}^{\pi/2}\left[abr^2\sin^2\theta-r(r-T)\csc\phi_e\sin\theta\right]d\theta=\tau_s A_s' \qquad (16)$$

in which

$$A_s'=abr^2\arccos\left(\frac{r-T}{r}\right)+(ab-2\csc\phi_e)(r-T)\sqrt{T(2r-T)} \qquad (17)$$

In reference to Fig. 3, the resultant force F_r, power force F_p and thrust force F_t of circular groove cutting can thus be obtained as

$$\begin{cases} F_r=F_n/\sin(\phi_e+\beta-\gamma_e) \\ F_p=F_r\cos(\beta-\gamma_e) \\ F_t=F_r\sin(\beta-\gamma_e) \end{cases} \qquad (18)$$

where β is the friction angle.

The so-called cutting equation, in which the relationship between the three angle parameters ϕ_e, β and γ_e is represented, can be also obtained from the geometry in Fig. 3 as

$$\phi_e=\frac{\pi}{2}-\beta+\gamma_e-\beta' \qquad (19)$$

where β' may be determined according to the mechanical conditions in the shear plane, that is

$$\beta'=\arctan\left(\frac{F_s}{F_n}\right)=\arctan\left(\frac{A_s}{A_s'}\right) \qquad (20)$$

It may be observed from (20) that $\beta'>\frac{\pi}{4}$ since $A_s'<A_s$. Obviously the shear angle of circular groove cutting according to the equation (19) will be smaller than corresponding that of orthogonal cutting according to Lee—Shaffer's cutting equation [2]. When $A_s'=A_s$, which implies that the shape of shear plane will change from an elliptic cylinder into a plane, we then have $\beta'=\frac{\pi}{4}$, and the equation (19) becomes consistent with Lee-Shaffer's equation, thus the circular groove cutting changes into orthogo-

nal cutting. So the circular groove cutting could be considered as the extension of orthogonal cutting in this sense.

2.4 Non-full depth cuts

By non-full depth cuts is meant that the circular form tool is making uncut chip thickness t on an existing circular groove having the same radius r as the tool, as shown in Fig. 4. It may be assumed that little difference in cutting mechanism exists between the full and non-full depth cuts except the change of real area of cut. All above analyses for full depth cuts are so valid for non-full depth cuts.

In fact, referring to Fig. 4, the non-full depth cuts can be regarded as the difference between two full depth cuts with respectively the uncut chip thickness T and T-t. After other cutting conditions are determined, it may be assumed that the cutting forces of full depth circular groove cuts may be expressed as the function of the uncut chip thickness T, i.e.

$$\begin{cases} F_p=F_p(T) \\ F_t=F_t(T) \end{cases} \qquad (21)$$

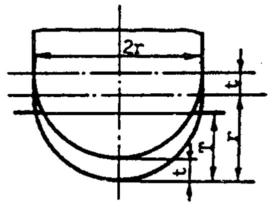

Fig.4 Non-full depth cuts

Thus the cutting forces of non-full depth circular groove cuts with the uncut chip thickness t can be written by

$$\begin{cases} F_p=F_p(T)-F_p(T-t) \\ F_t=F_t(T)-F_t(T-t) \end{cases} \qquad (22)$$

In which, the function $F_p(T)$ and $F_t(T)$ are all the same as corresponding those in (18), only regarding T as a variable.

3 COMPARISON WITH EXPERIMENT

The experiments were run on a vertical milling machine. The cutting tools (H.S.S.) used in tests were ground by means of a special radius grinding fixture. The radius of the circular form tools was measured accurately by means of a toolmaker's microscope. The cutting tool was fitted to the stationary taper hole of the spindle by a special fixture. The workpiece(LY12 Al-alloy) was clamped on a piezoelectrical dynamometer which was in turn secured to the table. All the cutting tests were performed by feeding the workpiece past the stationary tool at a speed of 0.015 m/s. The data of cutting forces were sampled and processed by use of a computer aided test system.

In accordance with a number of experimental results [3,4,5], the cutting force F_p and F_t are usually a linear function of the uncut chip thickness T. for circular groove cutting it can so be written as

$$\begin{cases} F_p=K_{1p}+K_{2p}T \\ F_t=K_{1t}+K_{2t}T \end{cases} \qquad (23)$$

where K_{1p}, K_{2p}, K_{1t} and K_{2t} are constants. According to the analysis in reference [4] the intercept forces K_{1p} and K_{1t} represent tool edge forces which do not contribute to the chip formation process, and so they should be ignored in the analysis. Thus we have

$$\tan(\beta-\gamma_e)=\frac{F_t}{F_p}=\frac{K_{2t}}{K_{2p}} \qquad (24)$$

and using (16), (18) and together with (23), we have

$$\tau_s = K_{2p}\frac{T\sin(\phi_e+\beta-\gamma_e)}{A'_s\cos(\beta-\gamma_e)} \tag{25}$$

By means of (24) and (25), the friction angle β and shear stress τ_s can experimentally be determined.

3.1 Full depth circular groove cuts

Seven circular form tools with rake angles from 0° to 24°, radii 1.98 mm to 3.63 mm and 6° normal clearance angles were tested for a range of uncut chip thickness which was set with the help of a dial gauge.

Some experimental data the auther obtained for full depth circular groove cuts are shown in Table 1. It can be seen that the effective shear angle ϕ_e increases with the effective rake angle γ_e, as we know in orthogonal cutting. But ϕ_e decreases slightly with the increase of tool radius r according to the three tools with 0° rake angle.

Table 1 Full depth cuts data

γ_e deg.	r mm	K_{2t} N/mm	K_{2p} N/mm	ϕ_e deg.	β deg.	τ_s N/mm²
0	1.98	1567	2174	9.3	35.8	216
0	2.43	1605	2191	9.1	36.2	193
0	3.63	1766	2361	8.7	36.8	164
10	3.46	1193	2093	15.1	39.7	233
15	2.36	748	1613	17.3	39.9	228
20	3.35	724	1747	20.1	42.5	236
24	3.42	512	1526	24.4	42.5	240

Fig. 5 shows the theoretical values of the cutting forces for the tool with $\gamma_e=15°$ and r=2.36 mm, which is one of the tests, in comparison with experimental data. And the theoretical predictions of the shear angle according to the cutting equation (19) are also compared with experimental data in Fig. 6. From the figures it can be seen that the theoretical values are better consistent with experimental results.

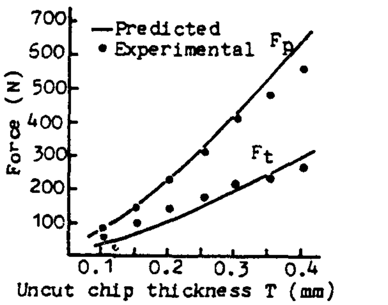

Fig.5 Predicted and experimental cutting forces $\gamma_e=15°$, r=2.36mm, v=0.015m/s

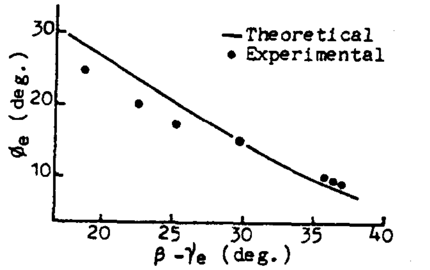

Fig.6 Comparison of theoretical and experimental shear angles γ_e=0°-24°, r=1.98-3.63mm T=0.2mm, v=0.015m/s

3.2 Non-full depth circular groove cuts

The way in which the tests were run is keeping the uncut chip thickness t constant and varying the groove depth T. The effects of cutting conditions on the shear angle for non-full depth circular groove cuts are given in Table 2. The data in Table 2 show that the variation of shear angle with cutting conditions is the same as that of the above full depth cuts, explainning that there does exist little difference in cutting mechanism between these two types of cut. However the shear angles for non-full depth cuts are a little smaller than corresponding those for full depth cuts, which illustrates the fact that the specific cutting force changes with different cutting geometry.

Table 2 Non-full depth cuts data

γ_e deg.	r mm	T mm	t mm	ϕ_e deg.
0	1.98	0.98	0.2	8.8
0	2.43	1.23	0.2	8.5
0	3.63	1	0.2	8.3
10	3.46	1	0.2	13.2
15	2.36	1.46	0.15	16.8
20	3.35	1	0.2	19.3
24	3.42	1	0.2	23.5

The cutting force variation for the tool with $\gamma_e=15°$, r=2.36