Ductile Regime Machining of Alumina Using Cross Peripheral Grinding: Mathematical Modelling and Experimental Validation

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Abstract

Owing to the high mechanical strength, excellent corrosion and wear resistance, ceramic materials have widespread application in optical, biomedical and aerospace field. But it is a challenge to make damage free and precise ceramic parts due to the high hardness and low fracture toughness of ceramics with conventional methods of machining. Cross peripheral grinding (CPG) is an advanced method of machining which can be used for the precise machining of brittle ceramics. In CPG, a rotating hollow diamond core tool with diamond grits impregnated or electroplated at the lateral and end face of the bottom portion promotes grinding action for material removal. In this study,CPG is carried out for the machining of alumina and the process is done in theductile regime. An expression for predicting the critical depth of cut to carryout machining of alumina in ductile regime is derived. The critical depth of cut is used to develop a theoretical cutting force model considering the ductile mode of material removal. The developed model correlates the total cutting force with the active diamond grits, depth of cut, Young's modulus, fracture toughness and the model is experimentally validated. It is found that the cutting force predicted by the mathematical model is in close agreement with that obtained from experiments and the cutting force prediction can be performed with a mean error of 8% with the developed model. To find the effects of machining parameters, experiments are carried out and their effects on cutting force are studied using thedesign of experiments. A regression model is developed to correlate the machining parameters and the cutting force. Analysis of variance is performed and the significant parameters which affect cutting force are found out.

Keywords:Cross Peripheral Grinding, Critical Depth of Cut, Tool Feed, Active Diamond Grits

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1. INTRODUCTION

Advanced ceramics are attractive for many applications owing to their superior properties such as resistance to chemical degradation, low density, wear resistance and high strength at elevated temperatures. Due to this sufficient mechanical strength and outstanding thermostability, they find application in aerospace, optical and biochemical field. But it is a challenge to make damage free precision ceramic parts with conventional methods of machining due to their low fracture toughness and high hardness. In this scenario, Cross Peripheral Grinding (CPG) can be suggested using which precision machining can be done. Cross peripheral grinding (CPG) is an advanced method of machining which can be used for the precise machining of brittle ceramics. In CPG, a rotating hollow diamond core tool with diamond grits impregnated or electroplated at the lateral and end face of the bottom portion which promotes the grinding action for material removal.

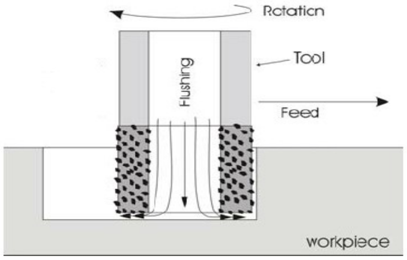

Fig. 1. Illustration of CPG

The key factor which affects the quality of subsurface/surface of the machined workpiece is the cutting force. Higher cutting forces induce chipping and subsurface cracks and hence the cutting force play an important role in the service life. Another important factor to be considered is the cutting depth which distinguishes between the brittle mode and ductile mode of machining. It should be understood that the mode of material removal that takes place in thebrittle and ductile region are different. In the ductile region, the interference volume between the grits of diamond and the workpiece gives the material removal volume whereas in the brittle region the propagation of cracks decides the material removal volume.

Several researchers have conducted studies on ceramic grinding and their machining in ductile regime. Xinghi et. al. [1] conducted studies on ultrasonic vibration assisted side grinding of zirconia ceramics. They predicted a mathematical model for the total grinding force and validated it experimentally. From their studies, it was found that the vibration frequency has no significant effect on cutting force. Ramesh et. al [2] studied the effects of high speed grinding on advanced ceramics and it was found that the grinding force value decreased with an increase in the rotational speed of the grinding wheel. Lawn et. al. [3] reviewed the principles and practical applications of indentation fracture and studied how surface removal is taking place in brittle materials. Bifano et. al. [4] conducted studies on ductile regime grinding and found that all brittle materials will undergo plastic flow if the depth of machining is small enough. Mohsen et. al. [5] investigated the effects of lubrication in grinding of alumina ceramic and they found that the use of lubrication can significantly affect the cutting force.

In the present study, a model is proposed to predict the cutting force considering brittle fracture mechanisms and plastic flow. An expression for predicting the critical depth of cut to carryout machining of alumina in ductile regime is developed. The model derived relates the final cutting force and the input variables. Finally, pilot experiments are carried out to verify the model.To find the effects of machining parameters,experiments

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are carried out and their effects on cutting force are studied using thedesign of experiments and a regression model is obtained.

2 MATERIAL REMOVAL MECHANISM

The material removal in cross peripheral grinding involves two distinct phases, first one is the removal which takes place in the ductile region where the materials are removed through plastic flow and the other one is the material removal which takes place in the brittle region where the material removal takes place according to the indentation fracture mechanism. This distinction of material removal into ductile removal and brittle removal is based on critical cutting depth.

2.1 Critical Cutting Depth

It is seen that during the machining of brittle materials upto a particular depth of cut or undeformed chip thickness, the machining or the material removal takes place by the plastic flow. When this depth value increases beyond a particular depth value, there will be formation of cracks. Hence the depth at which the transition of machining from ductile to brittle mode takes place is known as critical cutting depth. Considering the CPG of ceramics, the value of undeformed chip thickness a_g gradually increases from zero to maximum. And there is a critical cutting depth a_{gc} beyond which cracks begin to appear.

2.2 Ductile Mode Material Removal

In theductilemode, material removal takes place by plastic flow as shown in Fig. 2

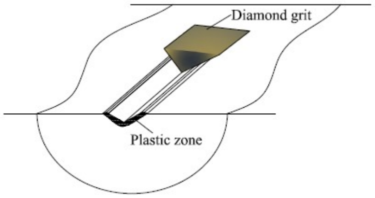

Fig. 2. Material removal by plastic flow

In this method, plastic flow takes place by the shearing action. In this mode of grinding maximum depth of cut provided is below the critical cutting depth and the cutting force is below the critical cutting force. In other words, only light normal load and very small contact is taking place. The material removal volume depends on the penetration depth of diamond grits on the workpiece surface and there will be no signs of crack formation. Thus the surface quality of machining is greater in ductile mode machining compared to brittle mode machining..

2.3 Brittle Mode Material Removal

In thebrittlemode, material removal takes place by the propagation of cracks as seen in the indentation fracture mechanism. During unloading the lateral cracks are generated and hence these cracks cause fragmentation of the affected region or the plastic zone and they get chipped off. This cracks the bond between atoms and hence then material removal is made easy. More material removal takes place in brittle mode as the applied force is more and also the depth of indentation is high.But chance for failure of the workpiece is high as there is the formation of median cracks which causes strength degradation

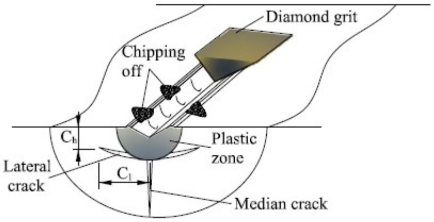

Fig. 3. Brittle fracture material removal

3 MODELLING

Cross Peripheral Grinding is a complicated process with numerous diamond grits. To simplify modeling procedure, a single diamond grit is analyzed first and the final model is obtained by summing the effects of active diamond grits. In order to develop the cutting force model the following assumptions are made:

1) The diamond grits considered are assumed to be rigid octahedrons which are of thesame size as shown in the Fig. 4 and every four adjacent triangles present have a common vertex which form a pyramid. While one pyramid is buried within the metal bond the other one of the octahedral particle actively takes part in cutting.

2)The angle which is present between two opposite edges of a diamond grit α=90°(shown in Fig. 4) and the wear which is taking place to the diamond grit are not considered. The edge lengths of the diamond grit are assumed to be same.

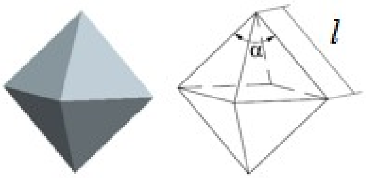

Fig. 4. Single diamond grit

Figure below shows the diamond grit in motion

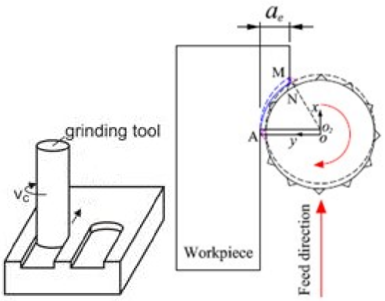

Fig. 5. Diamond grit in motion

Depending on the critical cutting depth, the cutting takes place in two phases. When thedepth of cut (a_g) is less than critical cutting depth (a_{gc}) the material removal takes place in theductile zone and when the depth of cut exceeds the critical value, material removal takes place in the brittle zone. Considering one-quarter rotation of diamond grit, material removal takes place both in theductile zone and brittle zone. Consider the ductile zone (Fig. 6) [1]. The material removal volume in this zone can be assumed to be a triangular pyramid of length h, base side length b and base area Bas shown in Fig. 7(a).

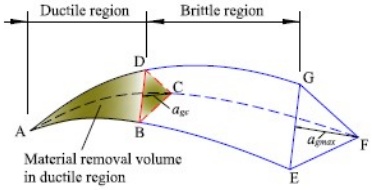

Fig. 6. Ductile region and brittle region in CPG

Hence the volume of material removed in the ductile zone is given by

$$V_1 = \frac{1}{3} a_{gc} . b . h (1)$$

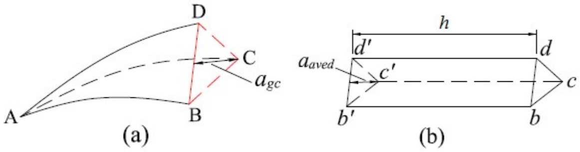

Fig. 7. Illustration of material removal volume

But in the case of a triangular pyramid the depth of cut varies from zero to a_{gc} and hence calculation of average cutting force is difficult, so this volume is compared with the volume of atriangular prism of same length h, base area B and anaverage depth of cut a_{avg} (Fig.7(b)). The base area is given by Equ. (2) and the volume of the prism is given by Equ. (3). Equating the two volumes the relation between a_{gc} and a_{avg} can be obtained as in Equ. (4)

$$B = \frac{1}{2} . 2 . a_{avg} . \tan 45 . a_{avg} (2)$$

$$V_2 = Bh \ (3)$$

$$a_{avg} = \frac{1}{\sqrt{3}} a_{gc} (4)$$

The relationship between the cutting depth of single diamond grit a_g and the cutting force F_d[3] can be presented as

$$a_g = \left(\frac{F_d}{2.H.tan\left(\frac{\propto}{2}\right)\sqrt{(2+tan^2\frac{\propto}{2}}} \right)^{\frac{1}{2}} \qquad (5)$$

where H is the hardness value. Hardness value [4] can be represented in terms of Young's modulus and depth of cut as

$$H = \left(\frac{0.15.E.K_c^2}{a_g} \right)^{\frac{1}{3}} \qquad (6)$$

Substituting equations (6) and (4) in (5), we get:

$$F_d = \left(\frac{a_{gc}}{\sqrt{3}}\right)^{\frac{5}{3}} . (0.15 . E . K_c^2)^{\frac{1}{3}} . 2 . tan\frac{\propto}{2} . \sqrt{2 + tan^2\frac{\propto}{2}} \ (7)$$

where K_c is the fracture toughness. The total cutting force(F_{dt}) in the ductile regionis obtained by multiplying the Equ. (7) with active number of grits N

$$F_{dt} = N . \left(\frac{a_{gc}}{\sqrt{3}}\right)^{\frac{5}{3}} . (0.15 . E . K_c^2)^{\frac{1}{3}} . 2 . tan\frac{\propto}{2} . \sqrt{2 + tan^2\frac{\propto}{2}} (8)$$

The above equation gives the relation between critical cutting depth and cutting force. From the properties of alumina, the critical depth value can be obtained as 0.3µm. A feed value of .018 mm/min is given so as to machine alumina in the ductile zone. Now the material removal from cutting depth zero to a_{max} is considered. Here also the material removal volume can be assumed as a triangular prism with aheight of base $a_{max}$and proceeding as in the above case, relation between maximum cutting depth and theaverage value of cutting depth can be obtained as inEqu. (9). Substituting the equations (9) and (6) on (4) the total cutting force by a single grit can be obtained as

$$a_{avg} = \frac{1}{\sqrt{3}} a_{max} (9)$$

$$F_n = \left(\frac{a_{max}}{\sqrt{3}}\right)^{\frac{5}{3}} . (0.15 . E . K_c^2)^{\frac{1}{3}} . 2 . tan\frac{\propto}{2} . \sqrt{2 + tan^2\frac{\propto}{2}} (10)$$

Hence the total cutting force when the depth of cut increases from zero to a_{max} is given by

$$F = N . \left(\frac{a_{max}}{\sqrt{3}}\right)^{\frac{5}{3}} . (0.15 . E . K_c^2)^{\frac{1}{3}} . 2 . tan\frac{\propto}{2} . \sqrt{2 + tan^2\frac{\propto}{2}} \qquad (11)$$

The above force model gives the total cutting force in one revolution and N is the number of active diamond grits which is$N = \rho_{grit} . 2\pi R . D$ (12)

Where ρ_{grit} is the grit density, R is the radius of tool and D is the depth of cut in the vertical direction.Model for predicting the cutting force in the ductile region is given by equation (8)

3.1 Experimental Verification

The experimental setupexplained in section 4.1 is used for the verification of the model. From the properties of alumina given in table 3 the critical depth of cut is obtained as 0.3µm. A feed of .018 mm/min helps to carry out machining in theductile zone. The experimental and model force values are compared as shown in table 1.

Table 1 Comparison of Experimental and Cutting Force values

Spindle speed (Rpm)	Vertical Depth of Cut (mm)	Cutting Force (N)	
		Experimental	Model
1500	0.4	1.1	0.91
	0.6	1.22	1.37
	0.8	1.42	1.82

It is seen that the cutting force predicted by model agrees well with the force value obtained from experiments with a relative mean error of 8.78%.

4 EFFECT OF PROCESS PARAMETERS

4.1 Experimental setup

Cross peripheral grinding experiments are conducted on CNC Vertical Machining Center (Agni BM45 TC24 4-axis VMC). The setup consists of a numerical control machining system, a cutting force data acquisition system, and a coolant system. The maximum spindle speed of the machine is 6000rpm and a feed rate of 1 to 10,000 mm/min can be provided. The diamond metal bonded tool is provided by Excel Impex (Kerala, India), its diameter is 6mm. Cutting fluid is used during CPG as acoolant. The flood cooling method is adopted. The cutting force data is acquired using Kistler 9257B dynamometer and then processed with the aid of Dynoware software.The machining setup and the slots machined are shown in Fig. 8.

4.2 Design of experiments

The workpiece material is alumina ceramics. The material properties [5] are given in the Table 3. The process parameters varied during machining are shown in Table 2. The dimension of alumina ceramic plate taken is 15x10x1 cm. Box-Behnken Design (BBD) was selected to generate the experimental runs. Box-Behnken designs are a class of rotatable second order designs based on three level incomplete factorial designs. The advantage of BBD is that it has no combinations for which all factors are at their highest or lowest levels and hence avoiding the experiments which are to be performed under extreme conditions.


(a) (b)

Fig. 8. (a) Machining setup (b) Machined slots

Table 2 List of Process Parameters

Parameters	Unit	Level 1	Level 2	Level 3
Speed	rpm	500	1500	2500
Feed	mm/min	2	4	6
Depth of cut(DoC)	mm	0.4	0.6	0.8

Table 3 Material Properties

Density	3.81 kg/m^3
Elastic Modulus	326 GPa
Hardness	12.76 GPa
Fracture toughness	3.97 MPam$^{0.5}$

5 RESULTS AND DISCUSSIONS

The factors selected for study are feed rate, spindle speed and depth of cut. 15 experimental runs are carried out based on Box-Behnken design. For the analysis of the experimental data MINITAB version 17 software was used.

5.1 Effect of Process Parameters on Cutting Force

Main effects plot is used to explain the effect of process parameters on the response. For obtaining main effects plot, the average of responses obtained for each level of the factor is used.

From the Cutting force vs Speed graph, it is seen that the cutting force value decreases as the spindle speed increases. But analyzing the cutting force vs feed and cutting force vs depth of cut graphs, it is seen that the cutting force value increases with increase in feed and depth of cut values. This may be because the number of active diamond grits increases with an increase in feed and depth of cut. Hence the mean cutting force also increases.

5.2 ANOVA for Cutting Force

Analysis of variance is used to determine the significant factors and its contribution to response. Table 4 shows the ANOVA for cutting force. The regression model generated using Minitab is given by,F= 61.1 - 0.0282 Speed + 23.76 Feed + 111.9 x DoC - 0.000008 Speed x Speed - 2.453 Feed x Feed+ 0.00395 Speed x Feed. Backward elimination method is used to get the regression model. It is seen that the main effects of depth of cut, speed and feed, squared effects of feed and speed and the interaction effects of speed and feed are significant. This can be confirmed from the F-values given in Table 3. From the P-value of lack-of-fit, it can be confirmed that the lack of fit is insignificant.

6 CONCLUSIONS

In this study machining of alumina is carried out using the cross peripheral grinding technique. A mathematical model correlating critical depth of cut with active number of diamond grits, Young's modulus, fracture toughness and cutting force in the ductile regime is developed and the same is validated by experiments. It is seen that the experimental cutting force values are in close agreement with the developed force values with a relative mean error of 8.78%. The effect of process parameters on the cutting force is analyzed using the design of experiments and a second order regression modal is obtained. It is seen that with an increase in feed and depth of cut, the cutting force value increases and with increase in spindle speed the cutting force value decreases. From the analysis of variance, it is seen that speed is the most significant factor affecting the cutting force followed by the depth of cut and feed.

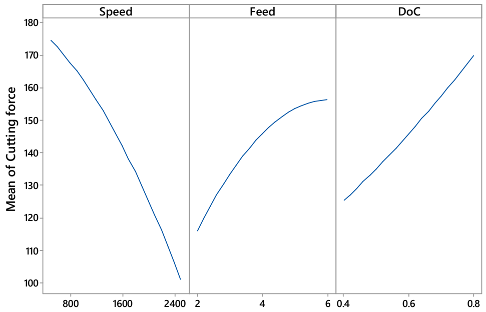

Fig. 9. Main effects plot for cutting force

Table 4 ANOVA for cutting force

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	18906.5	3151.1	62.76	0.000
Speed	1	10850.1	10850.1	216.09	0.000
Feed	1	3239.3	3239.3	64.51	0.000
DoC	1	4004.2	4004.2	79.75	0.000
Speed*Speed	1	245.3	245.3	4.89	0.058
Feed*Feed	1	357.6	357.6	7.12	0.028
Speed*Feed	1	249.3	249.3	4.97	0.056
Lack-of-Fit	6	346.6	58.1	2.19	0.346
Pure Error	2	53.1	26.5		
Total	14	19308.2			

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