Grinding force model for Inconel 718 with CBN and conventional wheels

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Abstract
Grinding force plays crucial role in choosing grinding parameters since it can be used for predicting power, wheel wear, surface roughness, temperature etc. In this paper a force model was developed to predict average grinding force for Inconel 718 with electroplated CBN. Two methods, namely mechanistic and oblique cutting approaches were employed and results were compared with the experiments. There was a good agreement between predicted force in both approaches and experiment data although mechanistic approach gave a better prediction than mechanics of cutting approach. Furthermore, performance of CBN and aluminum oxide wheels was studied by comparing grinding force and force coefficients. Results showed that grinding with CBN wheel led to lower force and force coefficients.

Keywords
Grinding; Electroplated CBN wheel; Aluminum oxide wheel; Force model; Inconel 718

1. Introduction

Abrasive machining is one of the oldest machining processes which accounts for about 25% of the total expenditure of machining operations in the industry [1]. Grinding force directly affects surface integrity of the part, grinding power and wear of the wheel. As a result, prediction of the grinding force is a crucial factor in grinding and many researchers have tried to investigate the effect of process conditions on grinding force through modelling with the objective of optimizing the process. In one of such studies, Yao et al. [2] experimentally studied grinding force and temperature of Aermet 100 steel in surface grinding for various wheel types and concluded that CBN wheel had smaller friction force coefficient compared to white aluminium and single alumina wheels. Sun et al. [3] developed a new force model for grinding of brittle and hard materials however they used indentation experiment to evaluate their model. In another work, Jian et al. [4] developed some probability functions to predict surface roughness of the workpiece. They assumed spherical grits which is not the case in reality, plus their model cannot be used for electroplated CBN wheels where there is only one layer of grits. In order to shed more light on chip formation mechanism in grinding processes single grain scratching test have been applied although the results of this approach cannot be applied for grinding where the interaction of grits with the workpiece is more complicated. Rasim et al. [5] studied the influence of 3D grain shape on the chip formation process by single grain scratching test. They concluded that some angles of grits like apex angle, opening angle, rake and wedge angles can change the length of three deformation phase i.e. elastic deformation (rubbing) plastic deformation (ploughing) and plastic deformation with chip formation (cutting). Transchel et al. [6] investigated influence of the clearance angle ranging from -1 to +7 degree on the cutting and ploughing forces of hexa-octahedron shaped diamond grains by using single grain test and concluded that a small negative rake angle can increase the plowing and cutting forces profoundly. Aslan and Budak [7] developed a semi analytical force model using micro milling analogy for conventional grinding wheels and showed that simulated forces were in good agreement with experiments having less than 14% discrepancy.

In this work, a force model using milling analogy has been adopted to electroplated CBN wheels to predict grinding forces for Inconel 718 work material. In addition, performance of aluminum oxide and CBN wheels has been investigated by comparing forces and force coefficients. Two methods i.e. Mechanistic and oblique cutting approaches are first introduced in section 2, experimental setup and procedure are explained in the section 3 and finally results are compared and performances of the two wheels are discussed in the section 4.

2. Force model and solution

Assuming grinding wheel acts similar to a milling tool where each grain removes material from the workpiece, the milling analogy can be applied for grinding process. Axial force can be neglected here and force components can be projected in x (cutting direction) and y (normal direction) directions as given in eq.1 where F_t and F_n are tangential and normal forces and φ is instantaneous immersion angle. Minus/plus signs are for up/down grinding, respectively.

$$F_x = -F_t \cos(\varphi) \mp F_n \sin(\varphi) \quad , \; F_y = F_t \sin(\varphi) \mp F_n \cos(\varphi) \tag{1}$$

Analytically derived average cutting forces can be obtained as (detailed calculation can be found in [8]):

$$\overline{F_x} = \left\{\frac{Nfa}{8\pi}\left[K_{tc}\cos(2\varphi) - K_{nc}(2\varphi - \sin(2\varphi))\right]\right\}_{\varphi_{st}}^{\varphi_{ex}} \;, \tag{2}$$

$$\overline{F_y} = \left\{\frac{Nfa}{8\pi}\left[K_{tc}(2\varphi - \sin(2\varphi)) + K_{nc}\cos(2\varphi)\right]\right\}_{\varphi_{st}}^{\varphi_{ex}}$$

K_{tc} and $K_{nc}$are cutting force coefficients in tangential and normal directions, respectively, *a* is width of cut, *N* is number of active grains which are defined as number of cutting points around any line on the wheel periphery which participate in chip formation process[1] (analogous to cutting teeth in milling). It can be identified by simulation of micro-interaction of grains with workpiece and setting a critical condition for penetration depth [4]. A MATLAB code was developed to simulate the interaction in this study to identify the number of active grits. *f* is feed per revolution per active grain.

2.1. Mechanistic approach

In mechanistic approach in order to obtain force coefficients, instead of calculation of cutting variables such as shear angle, shear stress etc., a set of grinding tests are conducted at same wheel speed, axial and radial depth of cut but different feed rates. Results are used to identify force coefficients from eq. 2. So the coefficients are obtained experimentally [8]. Once the force coefficients are known, it is possible to predict grinding forces at any arbitrary condition in the range of experimental data.

2.2. Prediction of force coefficients (Oblique cutting model)

In addition to mechanistic approach to identify force coefficients, they can also be identified analytically when mechanics of oblique cutting is taken into account [8]. Analytical equation for force coefficients is given as [8]:

$$K_{tc} = \frac{\tau_s}{\sin\varphi_n}\frac{\cos(\beta_n-\alpha_n)+\tan i\tan\eta\sin\beta_n}{\sqrt{cos^2(\varphi_n+\beta_n-\alpha_n)+tan^2\eta\, sin^2\beta_n}} \quad , \; K_{nc} = \frac{\tau_s}{\sin\varphi_n\cos i}\frac{\sin(\beta_n-\alpha_n)}{\sqrt{cos^2(\varphi_n+\beta_n-\alpha_n)+tan^2\eta\, sin^2\beta_n}} \tag{3}$$

where τ_s is shear stress, φ_n is shear angle, β_n is friction angle, α_n is rake angle, η is chip flow angle and i is oblique angle. In order to obtain force coefficients from eq. 3, three important variables i.e. shear stress (τ_s), shear angle (φ_n) and friction angle (β_n) should be known. Chip flow angle (η) can be taken as equal to oblique angle (i) based on Stabler's empirical rule. Oblique and rake angles are obtained by investigation of grit properties which will be described in the next section. In this study, shear stress was obtained by using Johnson-Cook model [7]:

$$\tau = \frac{1}{\sqrt{3}}\left[A + B\left(\frac{\gamma}{\sqrt{3}}\right)^n\right]\left[1 + C.\ln\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)\right]\left[1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \quad (4)$$

Table 1 shows the constants of Johnson-Cook equation for Inconel 718 which was taken from [9].

Table 1 Constants of Johnson-Cook equation for inconel 718.

A (Mpa)	B	C	m	n
1485	904	0.015	1.689	0.77

Shear strain (γ) and shear strain rate ($\dot{\gamma}$) are given as [8]:

$$\gamma = \frac{\cos(\alpha_n)}{\sin(\varphi_n)\cos(\varphi_n-\alpha_n)} \quad (5) \qquad \dot{\gamma} = \frac{V\cos(\alpha_n)}{d\cos(\varphi_n-\alpha_n)} \quad (6)$$

Where V is cutting speed and d is the shear zone thickness which can be approximated to 0.15 of shear plane length (l) where [8]:

$$l = \frac{h}{\sin(\varphi_n)} \quad (7)$$

where h is undeformed chip thickness which is in order of few micron [10]. d was approximated as 1 micron in this study. During the analysis, it has been observed that thickness of shear plane did not affect the shear stress significantly. This fact was also reported in [11].

Workpiece temperature was measured experimentally in a separate experiment by embedding thermocouple into the workpiece and average value of 100 degree centigrade was observed during the tests. Friction angle can be experimentally obtained as follow [8]:

$$\beta_n = \tan^{-1}\frac{F_y}{F_x} + \alpha_n \quad (8)$$

A few grinding tests were done at different feed rates and friction angle was calculated from eq. 5 after subtracting the ploughing forces. It varied from 32.5 to 35.3 degree an average value of 33.9 degree was used here. Shear angle can be estimated by using Merchant equation which has been derived for orthogonal cutting condition based on minimum energy principal [8]:

$$\varphi_n = \frac{\pi}{4} - \frac{(\beta_n-\alpha_n)}{2} \quad (9)$$

A straightforward approach to identify the shear stress, friction and shear angles is using orthogonal database in which those values are defined experimentally for each pair of workpiece-tool at corresponding rake angle. Due to varying and high negative rake angle of the grain and very small undeformed chip thickness in grinding process, it is difficult and time consuming to conduct orthogonal cutting tests. Accordingly, in this work eq. 4 to 9 was used instead. The total average force is obtained by summing up the force for all active grits.

3. Experimental setup and procedure

Fig. 1.a shows setup of the experiment. The tests are done on Chevalier-Smart-H/B818 type Grinding CNC. An electroplated CBN wheel is used to cut the Inconel 718 workpiece (hardness of 45 HRC). Coolant (5% oil) was used to reduce the temperature and tool wear in this work. The first set of experiments was done at depth of cut of 40μm at four feed rates varying from 0.0025 to 0.01 mm/rev to identify the force coefficients for mechanistic approach and the friction angle needed in oblique cutting model. Fig 1.b shows the force results. A linear regression was used to obtain ploughing force as well [8]. Tests were conducted at other depth of cut, i.e. 20 μm

and 60 µm at different feed rates to compare the predicted force with experimental data. Moreover, grinding tests were conducted by using an aluminum oxide wheel to investigate performance of both wheels.

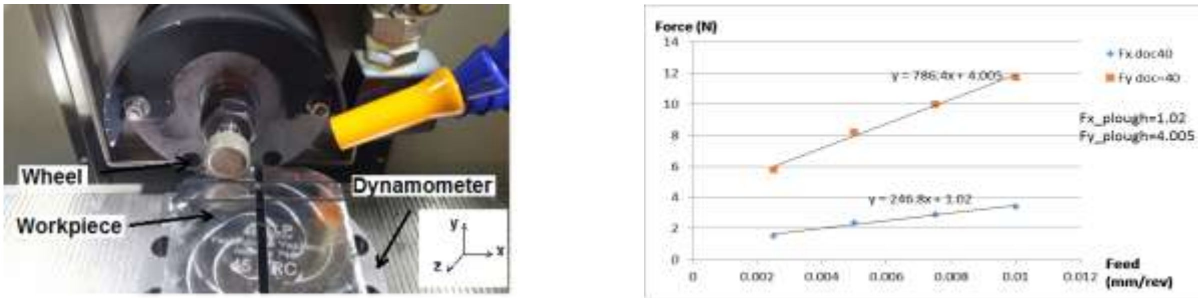

Figure 1 a) Experimental setup and b) grinding force (N) at different feed rate (mm/rev) depth of cut 40µm, wheel speed 40 m/s, CBN wheel.

The grit geometric properties used in the oblique method were determined with a usurf Nanofocus device which can zoom into the material and it was able to scan it with light to create 2D and 3D shapes of the individual grits on the tool. Fig. 2.a shows a sample result providing the 3D shape of grits. Fig. 2.b shows the results of analysing the rake and oblique angles of more than 100 grits in order to use the average value in force coefficient equations.

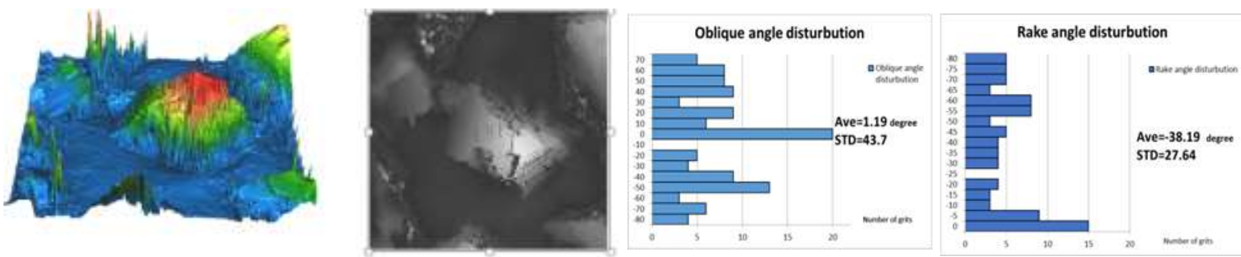

Figure 2 a)Individual grit scans, CBN wheel b) Oblique and rake angles distribution of CBN grits

4. Results and discussion

Table 2 shows the results of the first set of the experiments indicating that the force coefficients are high compared with milling or even micro milling operations.

Table 2 a) Cutting coefficients and friction angle obtained by grinding experiment, 40 µm depth of cut, CBN wheel b) Conventional wheel, depth of cut 20 µm

Feed (mm/rev)	**K_{tc}** (N/mm^2)	**K_{nc}** (N/mm^2)	β_n
0.0025	43593	120860	32.58
0.005	55760	143050	35.39
0.0075	52696	136640	33.74
0.01	49671	131871	34

a

Feed (mm/rev)	**K_{tc}** (N/mm^2)	**K_{nc}** (N/mm^2)	β_n
0.0025	65853	252290	39.59
0.005	39404	159590	40.35
0.0075	42883	139080	37.02
0.01	49262	126980	32.89

b

High force coefficients in grinding have been reported by other researchers using different approaches [1-2]. In grinding operations chip formation is done in micro scale which raise the concept of ‘’size effect’’ which have been reported in other micro machining operations providing one possible reason of such a high cutting force [12-13]. Poor cutter geometry is another reason that can explain such high force coefficients. In grinding grains with different shapes and high negative rake angle, even -60 degree, are randomly distributed. Negative rake angle decrease the shear angle which results in higher shear stress and higher force. Nevertheless, these high force coefficients can be used for predicting the grinding force at different grinding conditions. Furthermore, the cutting coefficients obtained by eq. 3 (oblique cutting model) were also used to predict the forces. Fig. 3 shows the force comparison obtaining by experiments and both models at different feed rates (mm/rev).

a b

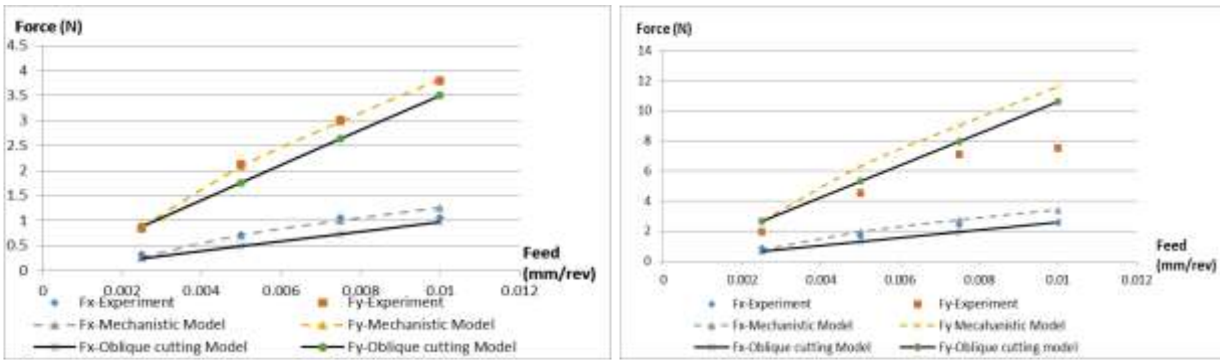

Figure 3 a) Comparison between experimental data, mechanistic and oblique cutting model, at different feed rate. wheel speed of 40 m/s, depth of cut of 20 µm, CBN wheel b) depth of cut of 60 µm

As the error percentages expressed, the discrepancies in the predicted forces by the oblique cutting model, are higher than that of the predicted forces by the mechanistic model. The advantage of the mechanics of cutting model is that it requires fewer experiments, but it involves the need of measurement procedure. One may find the measurement techniques of grinding wheels time consuming so the mechanistic model may thrive slightly more comparing to other cutting methods such as milling or turning where the cutter geometry is known and the cutting force can be predicted analytically.

Experimental investigation was also carried out on the same workpiece and same parameters used for the CBN wheel in this work but white aluminum oxide. The aim was to compare the performances of conventional and CBN wheels when used on an Inconel 718 workpiece. For the tests which have the depth of cut larger than 20 µm, the need for spark-out was observed, hence the data of the 20µm depth of cut experiments were used to calculate the force coefficients. Even with this depth of cut at higher feed rate (0.01 mm/rev) the spark out was observed. This was the case in Fig.3b. Experimental force comparison has been shown for both wheels in Fig. 4.

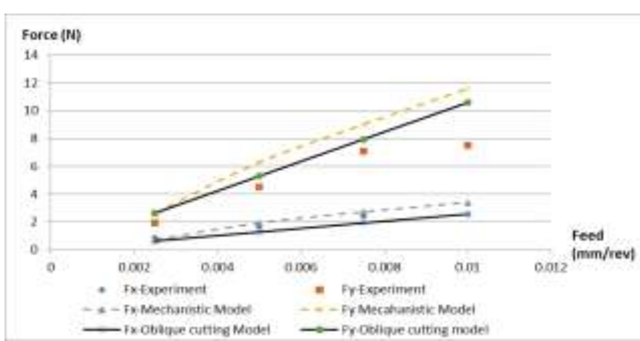

Figure 4 Comparison of force for CBN and aluminium oxide (conventional) wheel, at different feed rate and wheel speed of 40 m/s, depth of cut of 20 µm

As it can be seen from the figure, grinding force for conventional wheel is considerably higher than CBN wheel. After subtracting ploughing force, same procedure described in section two, was applied for the conventional wheel in order to obtain force coefficients and friction angle. Table 2.b shows the results, indicating higher force coefficient in y direction and higher friction angle compared to CBN wheel. Higher grinding force for conventional wheel compared to CBN wheel, is attributed to higher ploughing force and cutting force for conventional wheel. The ploughing forces coefficients for conventional wheel in x and y directions were obtained as 0.21 N/mm and 0.37 N/mm, respectively, while for CBN wheel they were 0.05 N/mm and 0.3 N/mm respectively. Force coefficients in normal direction, and consequently cutting force has also increased for conventional wheel. This is more distinguished for small depth of cuts. At higher depth of cut, force coefficients in x direction for conventional wheel are slightly higher than for the CBN wheel which may be due to thermal softening effect. Increasing the force coefficients in y direction could be due to increasing the friction angle.

5. Conclusion

Grinding process is one of the most complicated machining processes due to stochastic nature of the wheel and micro scale chip formation process. In this paper, milling analogy was employed and a force model with two different methods i.e. mechanistic approach and oblique cutting model was adopted to predict the cutting force in finishing grinding of Inconel 718 with an electroplated CBN wheel. Performance of CBN tool was compared to aluminium oxide wheel as well. Results showed that there was a good agreement between predicted force and experiments results for both approaches, however mechanistic approach gives more accurate prediction than the other one. Furthermore, grinding with CBN wheel produced smaller force compared to the conventional wheel. This was due to higher ploughing force and friction angle in grinding with conventional wheel. Rapid wear of conventional wheel was also observed during the tests, while CBN wheel showed much more persistence to wear.

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