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FORCE MODELING OF MICRO END GRINDING OF HARD AND BRITTLE MATERIALS

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ABSTRACT

Hard and brittle materials have broad application prospects in the defense, machinery and other fields, but hard machinability is crucial for its application. A promising processing method-micro end grinding (MEG), is put forward for machining microparts made of hard and brittle materials. Forces model of MEG is necessary to understand the effects of process, microgrinding wheel properties, material micro structure, etc, thereby allowing for process planning, optimization, and control. In this paper, a predictive model for MEG is developed by combined consideration of the undeformed chip thickness and the differences between up-grinding and down-grinding, and quantitatively predicts microgrinding forces. Experimental testing in a microgrinding configuration has been pursued to validate the predictive model by comparing measurements to analytical calculations. The analytical model is seen to capture the main trend of the experimental results, and many predictions are smaller than the experimental data of micro-grinding. The average deviations in normal direction and tangential direction are analyzed lastly.

KEYWORDS

Micro end grinding, force model, hard and brittle materials, undeformed chip thickness.

1. INTRODUCTION

Based on a study, in the fields of national defense, electronic etc, microproducts have become increasingly widespread in recent years [1]. Hard and brittle materials with good physical properties of high hardness, high uniform structure etc, are occupied with a larger proportion in microproducts yearly, but its hard machinability is crucial for its application [2]. According to a study, the existing processing technologies are easy to cause poor machined surface, and they can't machine complicated surfaces [3]. Study showed microgrinding is one of the most promising processing technologies in this field [4]. Forces model o microgrinding is necessary to understand the effects of process conditions, micro- grinding wheel properties, and material microstructure on the integrity of the parts produced, thereby allowing for process planning, optimization, and control. According to a study, many experts have studied the grinding force model, and research methods of grinding force models mainly include experimental data analysis, artificial intelligence method and analytical modeling method [5-7]. A researcher analyzed grinding forces by using the integral error distribution function to establish neural network model of grinding forces, and the model precision is verified as well. According to the grinding wheel surface morphology observation analysis, a researcher established the grit distribution density function with single convolution computation of abrasive grinding force model, and then force

model of the whole workpiece was obtained. Experimental data analysis is applied broadly, and shows directly relationships between grinding forces and grinding factors. However, the established model did not reflect the physical meaning of processing, and need vast experimental data. Therefore, the theoretical analysis suits the preliminary study of machining mechanism.

The previous researches mainly adopted peripheral grinding, and it can't machine complicated surfaces. In this paper, a promising machining method, micro end grind (MEG), is adopted to improve the existing problems. Firstly, the process of the machining method is theoretically analyzed. Then forces model is built based on the grinding process and the characteristics of up-grinding and down-grinding, and the values of some parameters in the model are determined by the experiments. At last, this paper analyzes experimental results, and verifies the predictive model by comparing measurements to analytical calculations.

2. FORCE MODELING OF MEG

2.1 Process of MEG

MEG process uses grains on the wheel face to remove the material, and it consists of up-grinding (angle from 0 to 90) and down-grinding (angle from 90 to 180), as is shown in Figure 1(a). The abrasives on outer rings contacting with unmachined artifacts

In MEG study, the grain radius and the grinding depth are in the same range of micron, and the grinding edge is supposed to the circular arc, rather than sharp like conventional machining [8]. Because of the depth of cut is invariable, the uncut chip thickness (h_m) is chosen to be the connection bridge between processing parameters and results in micro grinding of hard and brittle materials. Figure 2 shows that the cutting mode is changed with h_m. In Figure 2 (a), when the uncut chip thickness(h_m) becomes less than the brittle-ductile transition critical undeformed chip thickness (h_c) calculated by BIFANO model [9], the ductile cutting process follows the cutting model based on shearing and ploughing [9]. The ploughing process can be attributed to the size effect by the conclusion of K. Ramesh, and it will occupy a certain proportion in micro grinding process of ductile material, as well as in the plastic deformation removal process of hard and brittle material [10].

When h_m continues to increase, but is smaller than another

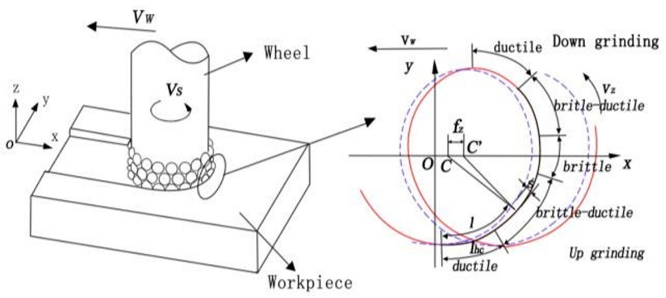
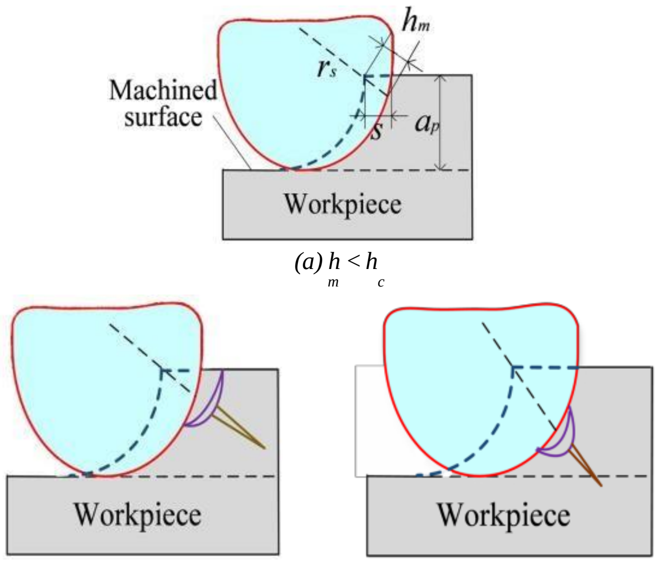


Figure 1: Simplifications for MEG process



(a) $h_m < h_c$ (b) $h_c < h_m < h_d$ (c) $h_m > h_d$

Figure 2: Change in cutting mode.

critical undeformed chip thickness (h_d) which is determined by experiments, due to instability, grinding material produces cracks, but cracks don't extend to the location under the depth of cut, as is shown in Figure 2(b). In this process, plastic deformation and brittle fracture all can be found in the machining process. When hm keeps increasing to be larger than hd, cracks can extend to the position below machined surface, brittle fracture removal becomes major manner in Figure 2(c), grinding material will be fractured rapidly and fallen off, and cracks are stayed on the machined surface.

2.2 Force Modeling of MEG

The analysis is based on the followed hypothesis: the grain is assumed as spherical, and distributed uniformly on the wheel surface; the abrasive wear, the eccentricity of the wheel and the material elastic recovery are ignored; the wheel end face is parallel to the workpiece.

According to above analysis and hypothesis, the force model is expressed as Equation (1):

$$F = \int_0^{h_{m-max}} [(1-r)k_f + r(k_c + k_p)]l\,dh_m \quad (1)$$

Where k_f, k_c, k_p is fracture force, cutting force and ploughing force in specific cutting arc respectively, and the forces are determined by the measured cutting force. h_{m-max} is the max uncut chip thickness, l is the length of contact arc in up-grinding or down-grinding and is related to h_m.

r is the ratio of the ductile process and (1-r) is the ratio of the brittle process. r is given by Equation (2):

$$r = \begin{cases} 1 & (h_m < h_c) \quad \text{Ductile} \\ \dfrac{h_d - h_m}{h_d - h_c} & (h_c < h_m < h_d) \quad \text{Ductile-brittle} \\ 0 & (h_d < h_m) \quad \text{Brittle} \end{cases} \quad (2)$$

Consequently, the normal force (F_N) and the tangential force (F_T) can be expressed:

$$F_N = \int_0^{h_{m-max}} [(1-r)k_{fN} + r(k_{cN} + k_{pN})]l\,dh_m \quad (3)$$

$$F_T = \int_0^{h_{m-max}} [(1-r)k_{fT} + r(k_{cT} + k_{pT})]l\,dh_m \quad (4)$$

Different stages of the grinding process are expressed in Figure 1(b). Because of the whole grinding process is made up of up-grinding and down- grinding, the whole grinding force(F) is followed as in (5):

$$F_{total} = F_{up} + F_{down} \quad (5)$$

Where F_{up} is the grinding force in up-grinding process, F_{down} is the grinding force in down-grinding process. And the force model are expressed as Equations (6) and (7):

$$F_{up} = \int_0^{h_{m-max}} [(1-r)k_f + r(k_c + \mu k_p)]l\,dh_m \quad (6)$$

$$F_{down} = \int_0^{h_{m-max}} [(1-r)k_f + r(k_c + \mu k_p)]l\,dh_m \quad (7)$$

2.3 Important Parameters in Model

Figure 2(a) also shows the geometry model of single grain. According to a researcher, the model of uncut chip thickness (hm) can be expressed as Equation (8), the relationship between the depth of cut (ap), grain radius (rs), and instantaneous cutting thickness (s) are considered.

$$h_m = M_d\, a[2s(\frac{2a_p}{r_s})^{1/2}(1-\frac{2a_p}{r_s})^{1/2} - \frac{2s^2}{r_s}] \quad (8)$$

M_d describes the effects when grinding come into micro scale. Becasue of other parameters are constant in one process, the instantaneous cutting distance(s) plays an important role to the derivation of h_m. In Figure 1(b), grain movement is composed of rectilinear movement and rotation around wheel axis. Grain trajectory relative to X axis is not symmetrical, so instantaneous cutting distances are different between up-grinding and down-grinding. The commonly used method now is Martellotti's model however, its precision is poor [11]. This paper improves the model by unfolding and simplifying by Taylor's formulation. Equations (9) and (10) are expressed as followed:

$$s_{up} = f_z\sin\theta - [m_1/(2\pi R)]f_z^2\cos 2\theta + [m_1/(2\pi R)]f_z^2\cos\theta \quad (9)$$

$$s_{down} = f_z\sin\theta - 2[m_2/(\pi R)]f_z^2\cos 2\theta + 2[m_2/(\pi R)]f_z^2\cos\theta \quad (10)$$

Where f_z is feed rate of single grain, R is wheel radius, m_1, m_2 is the magnification factors in up- grinding and down-grinding.

In this section, the grinding force equation has two advantages from the aforementioned deduction and analysis:

(a) The model can describe the characteristics of micro machining, including ploughing effect, cutting rounded radius, etc.

(b) Some parameters of the model are determined through experiments. Hence, the mode based on both the grinding theory and experiments, is more precise. This can lay a good foundation for the next step research of mechanism.

3. EXPERIMENTAL MODEL VALID

The micro-grinding experiments were performed using a miniaturized machine tool without coolants, and sample material is optical glass. The main purposes to determine the value of parameters value and validate the proposed model of microgrinding. In these experiments, to measure the forces created by microgrinding, a Kistler 9256-C2 MiniDyn is adopted. The data of grinding forces is gathered (Sampling rate is 25000 Hz), transmitted and stored in DynoWare analysis software, and then managed by virtual digital filter in the software.

3.1 Determination of Parameter Values

Through regression analysis, the parameter values can be calculated in Table 1.

parameter	m_1	m_2	h_c (μm)	h_d (μm)	M_d
Value	1.2	1.1	0.17	0.93	1.05
parameter	k_f (N/m)		k_c (N/m)	k_p (N/m)	
Normal	40.12		25.68	24.97	
Tangential	26.1		17.12	16.32	

3.2 Comparisons between Experiment Data and Predictions

The predictive grinding forces and experimental data under different grinding parameters are also shown in Figure 3. It is observed that the predicted microgrinding forces show good agreement with the experimental data, and many predictions are smaller than the experimental data of MEG. The errors in these comparisons may come from the following: (i) the effect of the wheel wear, (ii) the blocking of the wheel, (iii) the effect of grains on inner rings. The adding cutting edge radius by the wheel wear will increase contact arc length of the grain and workpiece. Some chips when created are trapped within the space between grits, and they participate in the grinding process. Moreover, the abrasives on inner rings plow the machined surface. All these will cause the increase of grinding forces.

In addition, across wheel speed, the depth of cut, workpiece speed and grain radius, the average deviation between the measured forces and predictions is 13%, 19%, 13%, 8% in tangential direction, and 24%, 25%, 23%, 11% in normal direction respectively. The deviations in normal direction are larger than them in tangential direction. In microgrinding, material elastic recovery has a significant impact on processing process. It will add undeformed chip thickness, and negative rake angle become smaller. Therefore, Fn heightens faster than Ft. Meanwhile, the undeformed thickness affected by the order from strong to weak is the depth of cut, wheel speed, workpiece speed and grain radius. Hence, the above phenomenon is done.

It can be obtained from the Figure 3 is that grinding force changing with the processing parameters. Under the condition of wheel speed from 8000r/min to 36000r/min, both of the normal force and tangential force decrease. When the depth of cut increases, the variations of grinding forces are proportional to it. When workpiece velocity adds, grinding force increases. The feed per tooth grows with workpiece speed augment, at the same time the undeformed chip thickness grows. Besides, the grinding force is inversely proportional to the grain size. With smaller grain size, the ratio of undeformed chip thickness and particle radius becomes bigger. But this causes grinding force increased. But the influence is little.

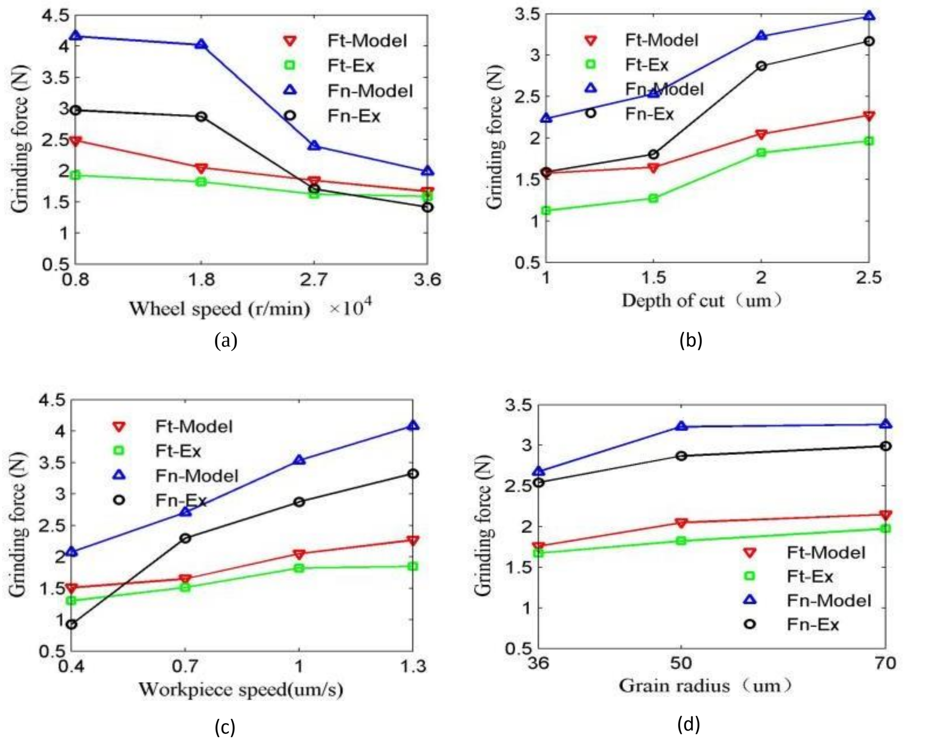


Figure 3: Effects of grinding parameters on grinding forces. (a) Effects of wheel speed (vw=100μm/s, ap= 2μm, #270). (b) Effects of depth of cut (vw= 100μm/s, n=18000r/min, #270). (c) Effects of wrokpiece speed (vw=100μm/s, n=18000r/min, #270). (d) Effects of grain size (ap=2μm, n=18000r/min, vw=100μm /s).

4. CONCLUSION

To resolve the existing problems in micro machining, this paper adopts another way of processing—Micro End Grinding. Firstly, the machining mechanism of MEG is introduced, and then, the grinding force model is built based on above analyze. Through regression analysis, the values of parameters can be calculated. And then, Experimental testing has been pursued to validate the predictive model by comparing measurements to analytical calculations. The conclusions are as follows.

MEG process is composed of up grinding and down grinding. Meanwhile, it is divided into three phases based on the relationship of instantaneous undeformed chip thickness and two critical state points, which are ductile, ductile/brittle complex and brittle stages respectively.

The grinding force model is built by considering three phases in machining process, the characteristics of micro machining, and the characteristics of up- grinding and down-grinding. Some parameters of the model are determined through experiments. The model based on both the grinding theory and experiments, will lay a good foundation for further research.

The analytical model is seen to capture the main trend of the experimental results, and the experimental data are larger than many predictions of micro-grinding, and the error analysis are carried out. Otherwise, the average deviations in normal direction are larger than them in tangential direction.

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