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Experimental Evaluation of a Chip Thickness Model Based on the Fracture Toughness of Abrasive and Work Material in Grinding of Alumina Ceramics

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Abstract: *Abrasive machining in general and grinding in particular are processes, which increase their importance with high demands on accuracy of surface finish. The chip thickness is an evaluating variable to describe the quality of ground surface as well as the performance of the overall grinding system. A significant characteristic that distinguishes ceramics from metals is their low fracture toughness, which also determines the material removal mechanism in the grinding of ceramics. An important prime requirement of an abrasive is its dynamic strength or fracture toughness which determines the fragmentation of the abrasive grain as it impacts the workpiece. In the present paper, a new chip thickness model has been formulated by incorporating the fracture toughness of abrasive and workpiece to assess the performance of super abrasive grinding of Alumina ceramics. The proposed model has been validated experimentally with the comparison of surface roughness obtained with the existing and proposed chip thickness models.*

Keywords: *Alumina ceramics, Alumina grinding, Chip thickness, Fracture toughness*

I. INTRODUCTION

Grinding processes relies on the significant effectiveness of transferring the laboratory based research results and available models to industrial practice where grinding setups and parameters are different. Thus there is a necessity to integrate the various heterogeneous models and information. Models form the basis for simulation of grinding process and create a precondition for high product quality by increasing the efficiency of the process [1]. The present work envisages the need for developing a chip thickness model based on the fracture toughness of wheel and work material.

The grinding technology has improved considerably in terms of grinding wheels with wear resistant abrasives and improved bonding systems together with higher process reliability due to improved process monitoring and control [2]. However grinding is a complex manufacturing process with a large number of characteristic quantities influencing each other, making the reproducibility critical and selection of process parameters attains significance. Hence there is a need to develop analytical on empirical models for the reliable prediction of dimensional accuracy and surface finish in grinding.

A chip thickness model plays a pivotal role in determining the boundary conditions necessary to maintain a certain quality level of the ground surfaces. The chip thickness models proposed by various authors are based on the speed ratio, depth of cut and equivalent diameter of wheel [1]. In order to consider the deformation due to elasticity of wheel and work material, a model proposed by Anne et al incorporated the modules of elasticities of grinding wheel and work piece in the existing chip thickness model [3]. But none of the models took the fracture toughness of abrasive and work material for calculation of chip thickness. The fracture toughness of work material determines the chip formation mode by ductile or brittle fracture, while the fracture toughness of abrasive determines the friability or tendency to fracture when placed under pressure. In the present chapter a new chip thickness model based on fracture toughness of abrasive and work material has been developed. The new model has been compared with existing model by using experimental data from the grinding of Alumina ceramics using surface roughness as an evaluating parameter.

II. LITERATURE REVIEW

The sequential removal of chips lead to the generation of the machined surface and nature of chips produced with varying degrees of plastic deformation will depends on the structure of the grinding wheel, quantities of motion and the geometric parameters. The various chip thickness models proposed by different authors have been consolidated by Tonshoff et al and these models are based on the speed ratio, depth of cut and equivalent diameter of wheel [1]. Shaw[4] and Malkin[5]have considered the grinding wheel topography in two-dimensional form by determining the grain count. The chip thickness model given by Malkin elaborates the various aspects of grinding process and various parameters related to it. The topography of the wheel and its kinematic interaction with workpiece was also described. Nakayama et al. developed the interrelationship between force and elastic deflection of thewheel [6]. Experiments were conducted to measure the deflection associated with the individual grain. It was shown that the deflection of the individual grain to be of the same order of magnitude as that of the undeformed chip thickness. Kun Li et al developed a model for number of cutting points and grinding forces per grit during ceramic grinding.

The grinding forces were found to be a power function of average cross sectional area of cutting edges or grit depth of cut [7]. The chip thickness model by Snoeys and Peters for determining the equivalent chip thickness was based on the equation of continuity .This characteristic quantity represents the sum of all individual chip thicknesses in contact area between grinding wheel and workpiece [8]. This simple model offers advantages in practical application as the characteristic quantities of the grinding wheel topography do not have to be determined. Saini et al. described the need of contact deflection in grinding. The various components of local contact deflections including that due to grain rotation and their combined influence on the ground surface from the point of view of industrial application was described [9]. As none of these models available in the literature take care of elastic deformation of grinding wheel and workpiece[1], a chip thickness model developed by Anne Venugopal[3] takes into account the modulus of elasticities of grinding wheel and work piece and the elastic modulus is incorporated in the existing basic chip thickness model to consider the elastic deformation.But one of the significant property of a work and an abrasive material (i.e) fracture toughness has not been considered into the above models and the incorporating the fracture toughness in the existing model would make a significant impact while estimating the chip thickness.

III. MODELING OF CHIP THICKNESS

The existing chip thickness model proposed by Malkin[5] is a well-known equation for estimating the maximum chip thickness. The equation is as follows

$$h_m = \left[\frac{4}{c.r} \frac{V_w}{V_s} \left(\frac{a_e}{d_e} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \qquad (1)$$

where r is the chip width to thickness ratio, c is the number of active grits per unit area, V_w is the work velocity V_s is the wheel velocity, $a_e$is the work engagement and d_e is the equivalent wheel diameter. The value of 'r' is difficult to determine and is assumed in the range of 10-20[10]. In this work 'r' was assumed to be equal to 10. The number of active grits per unit area 'c' derived by Xu et al [11] is as follows

$$c = \frac{4f}{\left[d_g{}^2 \left(\frac{4\pi}{3v} \right)^{\frac{2}{3}} \right]} \qquad (2)$$

v= volume fraction of diamond in grinding wheel and f is the fraction of diamond particles involved in active grinding. As the grinding wheel used in this study has a density of 75, v = 0.18. For calculating the number of active grits per unit area , it is assumed that only one half of diamond particles are engaged in cutting [11]or f = 0.5. The equivalent spherical diameter of diamond grit (dg) is given [5] as

$$d_g = 15.2.M^{-1} \qquad (3)$$

where M is the mesh number used in the grading sieve.

A significant characteristic that distinguishes ceramics from metals is their low fracture toughness, which also determines the material removal mechanism in the grinding of ceramics. A chip formation model proposed by Subramanian suggests that materials of high strength and fracture toughness would exhibit greater plastic deformation during grinding [12]. On the other hand low fracture toughness materials would produce large degree of discontinuous brittle fractured chips. Thus the change in maximum chip thicknessis directly proportional to the fracture toughness of the work material.

An important prime requirement of an abrasive is its dynamic strength or fracture toughness which determines the fragmentation of the abrasive grain as it impacts the workpiece. High toughness implies that an abrasive grain is less likely to fracture each time it engages the workpiece. On the other hand a more friable (less tough) abrasive would regenerate sharp cutting edges (self-sharpen) as the grain dulls by attrition. Hence more friable abrasive would promote significant undeformed chip thickness than the less friable abrasive, thus making an indirect proportionally with the maximum chip thickness.

Combining the above effects, the maximum chip thickness can be expressed as

$$h_m \propto \frac{F_1}{F_2} \qquad (4)$$

Where F_1 is the fracture toughness of the work material and F_2 is the fracture toughness of abrasive. The fracture toughness of work material (Alumina) is 3.5µpam$^{1/2.}$The fracture toughness of the diamond abrasive is 9.5 µpam$^{1/2}$.Thus the existing chip thickness model is modified by incorporating the fracture toughness of work and abrasive material and is expressed as

$$\bar{h}_m = \left[\frac{F_1}{F_2} \right]^n \left[\frac{4}{c.r} \frac{V_w}{V_s} \left(\frac{a_e}{d_e} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \qquad (5)$$

an is the exponent which accounts for the linear & non-linear deflections of the workpiece and grinding wheel. To validate the proposed model is surface roughness model written in terms of chip thickness [5] has been used and is given as

$$R_a = \frac{h_m^{\,2}}{a_e}\left[\frac{q}{q+1}\right]^2 \qquad (6)$$

where R_a is centre line average value of surface roughness and q is the ratio of wheel speed to work speed = V_S / $V_{W.}$

IV. EXPERIMENTAL EVALUATION

The estimation of maximum chip thickness is done by carrying out the experiments according to the grinding conditions given in the table 1 and measuring the resulting tangential force. The exponent (n) is calculated with these tangential force values and the proposed model is validated using surface roughness as a parameter of evaluation.

Table 1 Grinding conditions

Factors	Values		
Mesh number	100		
Wheel Speed (m/s)	21.6		
Feed (m/min)	10	15	20
Depth of cut (µm	10	20	30

IV.I Evaluation of the exponent (n)

The value of 'n' is calculated by solving the energy balance equation which is stating that energy given by the grinding wheel is equal to the amount of energy required to remove the material. It can be written as
F_t. V_s= specific energy x volume of material removed / unit time (7)
where F_t is the tangential force on the grinding wheel.

Volume of material removed /unit time = No. of chips produced / unit time xVolume of each chip
= ($c.b_S.V_S$). V_C (8)

where V_C is volume of each undeformed chip produced and $b_s$is the grinding wheel width .Assuming a chip with triangular cross section, V_C can be approximated , analogous to that of a triangular pyramid **,** as one third times the product of maximum cross sectional area (r . h_m^2 / 2) and length l_c from the following formula (Malkin, S., 1989)

$$V_c = \frac{r.\bar{h}_m^{\,2}}{6}\left(\sqrt{a_e.d_e}\right)\left(\because l_c = \sqrt{a_e.d_e}\right) \qquad (9)$$

.The value of specific energy is taken as 15 J/mm^3 for the present study which is carried out at faster material removal rate (Hwang et al., 1999) during which specific energy is minimum.
By substituting above equations (8) & (9) in (7), we get

$$F_t.V_s = 25.cb_s.V_s\bar{h}_m^{\,2}\sqrt{a_e.d_e} \qquad (10)$$

$$F_t.V_s = 25.cb_s.V_s.\left[\left(\frac{F_1}{F_2}\right)^n h_m\right]^2\sqrt{a_e.d_e}\ , \qquad \left(\because \bar{h}_m = \left(\frac{F_1}{F_2}\right)^n h_m\right) \qquad (11)$$

The tangential force is measured using a strain gauge dynamometer and value of n is calculated. During this study diamond wheel of D1A1 100/120 BNC 20 C75 has been used. The work materialis Alumina ground at a speed of 21.59 m/sec without any lubricant. The values of 'n' were calculated for different values of feed and depth of cut and results are tabulated in Table 2. The new chip thickness model has been formulated by taking the average value of 'n' which was found to be 0.357.

Table 2 Values of exponent (n) at various grinding conditions

V_w (m/min)	a_e (μm)	F_t (N/mm)	n
10	10	7.95	0.276
15	10	10.33	0.32
20	10	11.72	0.333
10	20	10.65	0.344
15	20	15.54	0.351
20	20	16.2	0.383
10	30	14.4	0.39
15	30	17.5	0.404
20	30	19.3	0.41
		Average	0.357

IV.II Validation of the proposed model

In order to validate the new chip thickness model , the surface roughness (R_a) of all ground specimens were measured and deviation of the measured roughness value (R_a) with the surface roughness computed using existing model (R_{a1}) and surface roughness computed using new model (R_{a2}) has been shown in Figure 1.

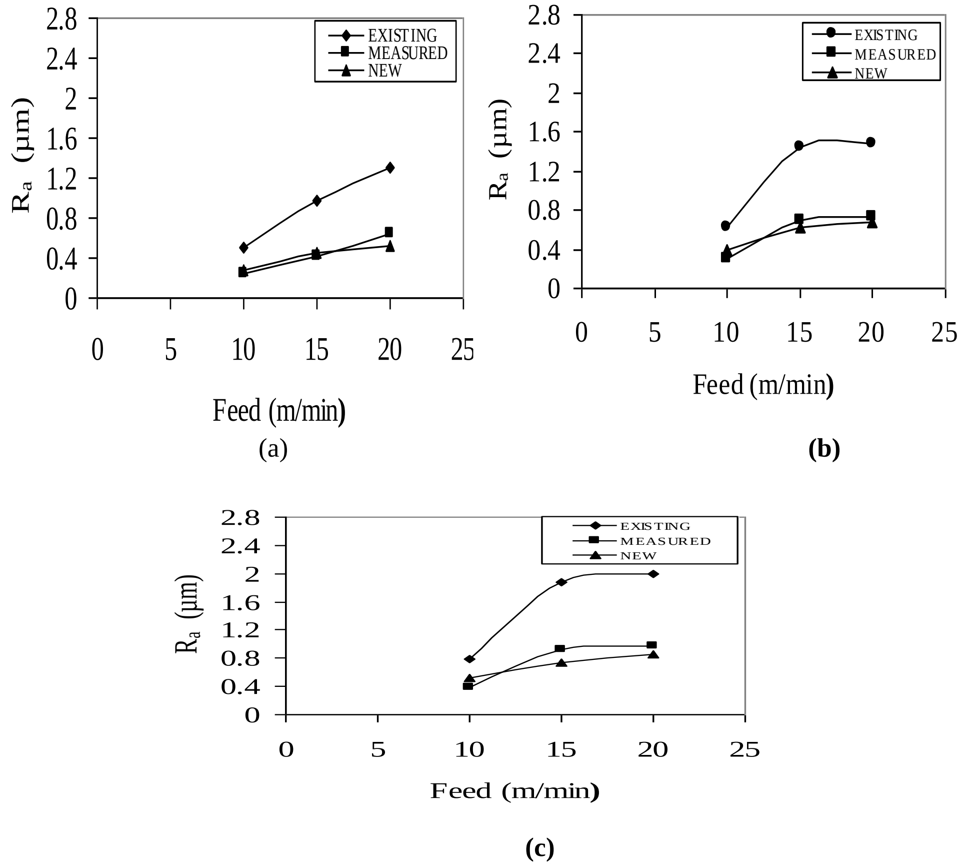

Figure 1. Variation of surface roughness with grinding variables at depth of grinding of (a) a_e=10 μm, (b) a_e=20 μm and (c) a_e=30 μm

V. RESULTS AND DISCUSSION

The existing chip thickness models have taken the main influencing quantities into consideration and among these are speed ratio, working engagement and equivalent diameter. But none of these models considered one of the significant characteristics of the fracture toughness of work and abrasive material which determines the material removal mechanism in the grinding of brittle materials.

In the present work, the fracture toughness of work material and abrasive have been incorporated in the existing chip thickness model and deviation of the maximum chip thickness estimated by new model with the existing model is shown in Table 3. The surface roughness values measured experimentally were compared with the surface roughness values calculated using the existing and the proposed model.

Table 3. Values of Surface roughness by using the existing and newchip thickness models

Chip thickness using existing model (h_m) (□m)	**Chip thickness using modified model ($\bar{h}_m$) (□m)**	**Surface roughness using existing model (R_{a_1}) (□m)**	**Surface roughness using modified model (R_{a_2}) (□m)**	**Surface roughness measured in experimental investigations (R_a) (□m)**	**Deviation of R_a with respect to R_{a_1} (%)**	**Deviation of R_a with respect to R_{a_2} (%)**
2.285	1.599	0.513	0.252	0.285	44.44	11.57
3.157	2.21	0.981	0.419	0.452	53.92	7.32
3.648	2.553	1.309	0.642	0.521	60.19	18.84
2.514	1.76	0.622	0.305	0.393	36.81	22.39
3.819	2.674	1.436	0.704	0.621	56.75	11.78
3.884	2.718	1.485	0.728	0.682	54.07	6.31
2.832	1.982	0.789	0.387	0.521	50.95	25.71
4.359	3.051	1.871	0.917	0.732	60.87	20.17
4.501	3.151	1.995	0.978	0.854	57.19	12.67

It can be observed from the Fig.1 that the surface roughness values computed by the new chip thickness model are closer to the actual values as compared with that of the existing model. The maximum percentage variation between the surface roughness predicted with existing model and measured value is 61% and the maximum percentage variation between the surface roughness predicted with the modified chip thickness model and measured value is 26%. Hence the proposed model shown in the following equation proves to provide an accurate estimation of the maximum chip thickness which is influenced by wheel, work, machine characteristics and operating conditions.

$$\bar{h}_m = \left[\frac{F_1}{F_2}\right]^{0.357} \left[\frac{4}{c.r}\frac{V_w}{V_s}\left(\frac{a_e}{d_e}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}} \qquad (12)$$

VI. CONCLUSIONS

The proposed chip thickness model lays an emphasis on incorporating a decisive material property of the fracture toughness of work piece and abrasive which were neglected in the basic model. The validation of the chip thickness model has been carried out by measuring the surface roughness experimentally and calculating the subsequent deviation of the surface roughness values computed from the existing and proposed model with the actual value. Hence the proposed model strengthens the representation of evaluating the competitiveness of the grinding system which is influenced by the surface quality of the specimen ground.

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