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Digital Modeling of Grinding Wheel Structure

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Abstract

Grinding is the finishing operation where the component is made to the desired dimensions with specified tolerances on grinding machine using suitable grinding wheel. Generally, the structure of grinding wheel is characterized by the density of randomly shaped abrasive particles, of certain size range, held firmly by the bond in a certain volumetric proportion. The structure of wheel directly influences the outcomes of grinding process where the randomly oriented abrasives on wheel surface interact with work while removing the material and generating finish on its surface. Besides this, the wheel structure also defines the topography on wheel surface at different depths which is thus responsible for imparting finish on ground surface. In order to understand and analyze the wheel work interaction and the grinding process outcomes with any chosen wheel, it is important to develop a model of wheel that can represent its real physical structure in 3 D. The present work aims at modeling and analysis of three dimensional structure of grinding wheel based on the specification of wheel. In this method, the grits are represented by different geometries such as sphere, ellipsoid, frustum and truncated pyramid of sizes distributed normally around the average grit size. Based on the volumetric composition of grit, bond and porosity, the 3D geometrical structure of a grinding wheel is modelled and simulated in COMSOL using MATLAB interface. From this model or with this model, various parameters such as surface grit density and average distance between grits can be derived. The effectiveness of this model is demonstrated by comparing the derived results with the results published in the literature.

Keywords: Grinding wheel structure model, grits, bond, porosity, wheel topography.

1. INTRODUCTION

In grinding process, the grinding wheel interacts with the work surface and produces the required finish on the surface. A grinding wheel comprises of abrasive particles held firmly by the bond with certain porosity. The microscopic interaction of the wheel constituents with work surface at the grinding zone can be categorized into four types: abrasive/work, chip/bond, chip/work and bond/work interactions. These interactions are responsible for various mechanisms like cutting, ploughing, rubbing and sliding. During grinding, the grit loses its sharpness resulting in wear flats due to grit wear, micro and macro-fracture of grits, and total-break out of grains. The loss in grinding efficiency is not only affected by the above phenomenon but is also affected by the deviation in the form of grinding wheel such as profile and roundness. In order to rejuvenate the wheel and restore the desired sharpness and form, it is subjected to periodical dressing using a single point or multi point diamond dresser, which essentially causes either bond fracture to expose fresh grits or grit fracture to generate micro cutting edges on worn out grits.

Analysis of grinding or dressing process requires the modeling of wheel structure or topography at the first place. As the structure of wheel combined with the kinematics of grinding influences the performance of wheel in terms of material removal rate, surface finish, grinding forces and wheel wear, the model of grinding wheel, showing the complex structure of grinding wheel, with random shaped grits of different size, distributed randomly in bond material with certain amount of porosity, can aid in predicting the performance of wheel in grinding. Therefore, the modeling of wheel structure is important for analyzing the outcome of grinding. In order to obtain a realistic model of grinding wheel, the grits, bond and porosity need to be arranged volumetrically in a suitable manner in three dimensional space based on the wheel specification. Earlier attempts on modeling of wheel topography considered symmetrical shape of grits like spheres and ellipsoid with which the grinding wheel could not be modeled more precisely or exactly. Further, the earlier attempts did not include the porosity of wheel while modeling the structure of wheel. In this work, the overall structure of grinding wheel is modeled in 3D from which the parameters such as the number of grains per unit area and average grain distance can be derived by analyzing a cross section area of the modeled wheel structure. This model can also be used to predict the section profile and the surface topography on a specific grinding wheel.

2. LITERATURE REVIEW

Existing literature on modeling of the physical structure of wheel are mostly related to the topography of grinding wheel. Earlier models on wheel topography were limited to 1D and 2D with limited focus on the nature of topography generated by dressing process [2, 3, 4, 8]. Further, these attempts were mostly empirical based on extensive data and could not predict wheel surface topography. A few attempts were made on stochastic modelling of wheel surface profile [5, 8]. An attempt was made to employ 3D modelling for predicting the grit protrusion height, static number of cutting edges, inter-grain spacing, and the exposed area of the grains [7]. In another attempt, the model was developed to predict the stochastic distribution of grain size, grain spacing and protrusion height, uncut chip thickness, contact length and the kinematic grain count [11]. 3D models were developed by assuming grits shape as sphere [6] and ellipsoid [9]. All these models used certain empirically derived parameters for predicting the topography on grinding wheel surface. Apart from these models, a few attempts were made to model the real physical structure of grinding wheel [10, 12, 13]. However, the implementation of these models are not fully realized for downstream application for analyzing dressing and grinding process. In this work, efforts are made to model the real wheel structure by

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considering various shapes and sizes of grit as well as porosity, which can be subjected to analyze the wheel wear and topography variation in grinding and dressing operations. This model finds particular application in analyzing the non-contact process of laser dressing of grinding wheels where the interaction of high intensity pulsed laser beam with wheel material leading to ablation of grits and bond can be studied and analyzed to predict the wheel topography and its subsequent behavior in grinding.

3. FRAMEWORK FOR DIGITAL MODELING OF GRINDING WHEEL STRUCTURE

In the previous literature [4, 5, 6, 7], wheel topography was modeled stochastically by randomizing spherical grits locations from a regular cubic structure. Figure 1 shows the framework developed in this work to model 3 D structure of wheel.

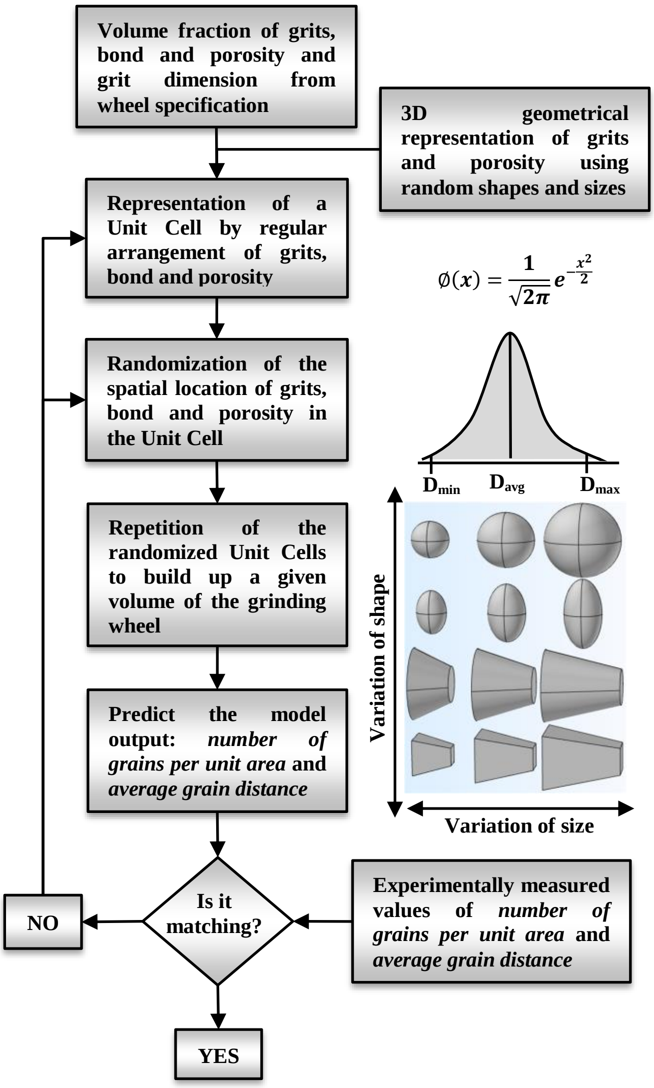


Fig. 1. Framework for digital modeling of grinding wheel structure

From the specification of a grinding wheel such as grit number (*M*), structure number (*S*) and grade number (*n*), the average grit dimension (Dg) in mm and the volume fractions of grit (V_g), bond (V_b) and porosity (V_p) are determined using the following empirical equations 1, 2 and 3 based on the reference [1]:

$$D_g = 15.2/M \quad (1)$$

$$V_g = 2(32 - S)/100 \quad (2)$$

$$V_p = [2(99.5 - 2n) - 100V_g]/300 \quad (3)$$

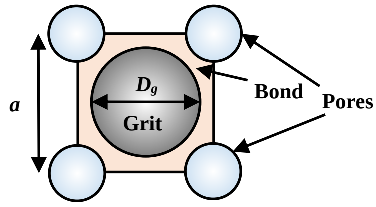


Fig. 2. Simple cubic unit cell containing grit, bond and porosity

3 D geometric representation of grits and porosity in a simple cubic cell is shown in figure 2, from which the size of unit cell (*a*) and spherical pore (D_p) are determined using below equations.

$$a = D_g\,[\pi/(6V_g)]^{1/3} \quad (4)$$

$$D_p = a\,[(6V_p)/\pi]^{1/3} \quad (5)$$

The grit shapes are modeled as ellipsoid, frustum and truncated pyramid with their dimensions as fractions of the average grit size (D_g) and volume equal to the base sphere with diameter as D_g. Table 1 covers the geometrical parameters for modeling these grit shapes. The shapes of grits were selected randomly by associating lower weightages to highly symmetric shapes. Generally the size of grits exhibit normal distribution between a maximum and minimum dimension. For a given grit number (M), the extreme dimensions were obtained from literature [4].

$$D_{min} \le D \le D_{max}$$

$$D = K\,D_g \quad (6)$$

where *K* is the shape factor given by,

$$K = (D_{min}/D_g) + R_n\,[(D_{max} - D_{min})/D_g]\ \forall\ R_n \in N(0, 1)$$

In order to maintain the same volume fraction of grit in a given volume of wheel material, the grit sizes are varied around the mean grit dimension in a pairwise manner in consecutive unit cells as given below and shown in figure 3 (a).

$D_1 = K_1\,Dg$ and $D_1' = (2 - K_1^3)^{1/3}\,D_g$

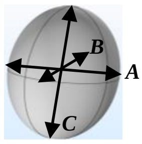
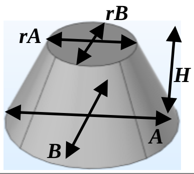
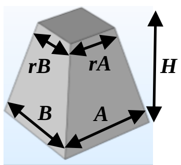
$D_2 = K_2\,Dg$ and $D_2' = (2 - K_2^3)^{1/3}\,D_g$ and so on, where K_1, K_2, etc. are the random shape factors.

The grits location were randomized from the uniform structure by giving random displacements to grit centers within each unit cell as shown in figure 3(b). For example to randomize a grit in the nth unit cell in x –direction, the final X - coordinate is given by,

$$X = [(2n - 1).a]/2 + R_n\,\Delta x \quad (7)$$

where R_n is the random fraction and Δx is the separation between grit and porosity in a unit cell. Similarly the final Y and Z coordinates were derived. The equations from 1 to 7 were employed to write MATLAB scripts to generate the 3 D structure model of the wheel as discussed in the next section.

Table 1. Selection of different grit shapes

S. No.	Grit Shape	Parameters
1. Ellipsoid		$A = K\,D_g$, $B = D_g/K$ $C = D_g$ $K \geq D_g/a$
2. Frustum		$A = K_1\,D_g$, $B = K_2\,D_g$ $H = D_g$ $r = [[8/(K_1K_2) - 3]^{1/2} - 1\,]/2$ $K_1K_2 \geq 0.67$ *for* $r \leq 1$
3. Truncated pyramid		$A = K_1\,D_g$, $B = K_2\,D_g$ $H = D_g$ $r = [[2\pi/(K_1K_2) - 3]^{1/2} - 1\,]/2$ $K_1K_2 \geq \pi/6$ *for* $r \leq 1$

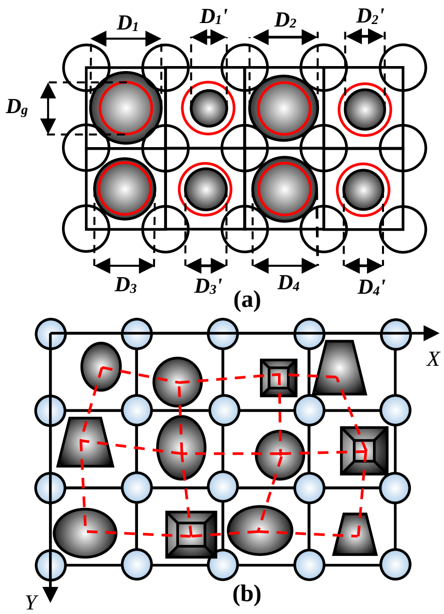


Fig 3. a) Pairwise variation of grit sizes about the mean grit dimension in consecutive unit cells. b) Randomized location of grits within unit cells

4. IMPLEMENTATION AND VALIDATION OF THE DIGITAL MODEL OF GRINDING WHEEL STRUCTURE

The wheel structure was generated using the package COMSOL Multiphysics® 5.2 with MATLAB® which provides the platform to write MATLAB scripts to generate 3 D geometries in MATLAB and then import it in the geometry module at COMSOL GUI. Post processing of the geometry was done at COMSOL end by cutting different planes through it and analyzing these cross sections. Grinding wheels with same volumetric composition of grit and bond but different grit sizes were selected from the literature [13]. The 3 D wheel structure generated was analyzed in COMSOL desktop by cutting it by random planes. The digital model was generated using Intel(R) Core(TM) i5 processor (CPU@3.30 GHz) and generation time was 420.498 s, 67.725 s and 32.813 s for wheel volumes of 0.5 mm × 0.5 mm × 0.2 mm of grit sizes 46 μm, 91 μm and 181 μm respectively. The generated 3 D wheel structures were post processed at COMSOL end and are shown along with their cross section images in figure 4.

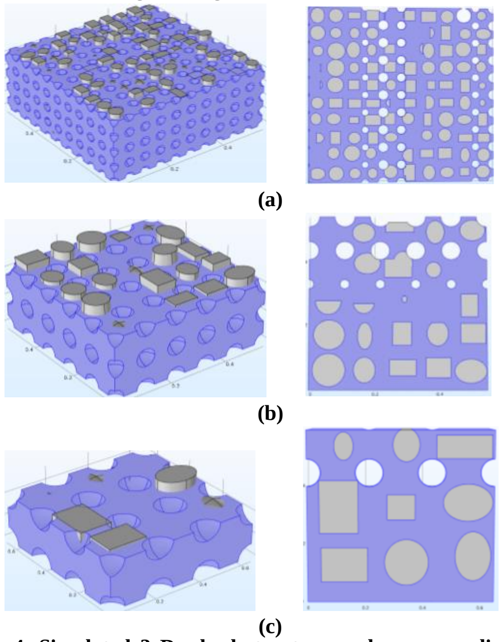
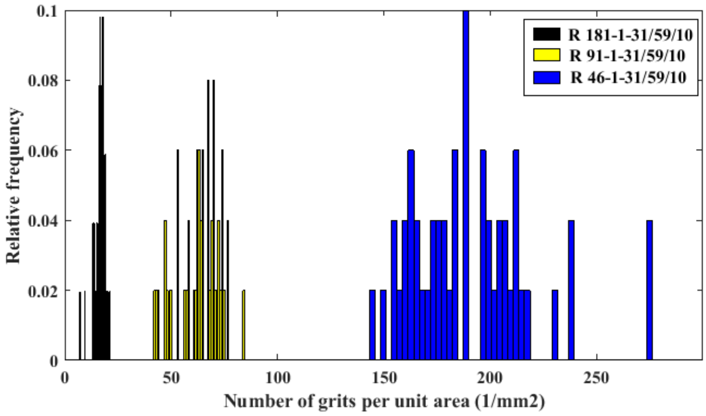


Fig. 4. Simulated 3 D wheel structure and corresponding section images. (a) D_g = 46 μm, (b) D_g = 91 μm and (c) D_g = 181 μm with V_g, V_b and V_p as 0.31, 0.59 and 0. 10 respectively.

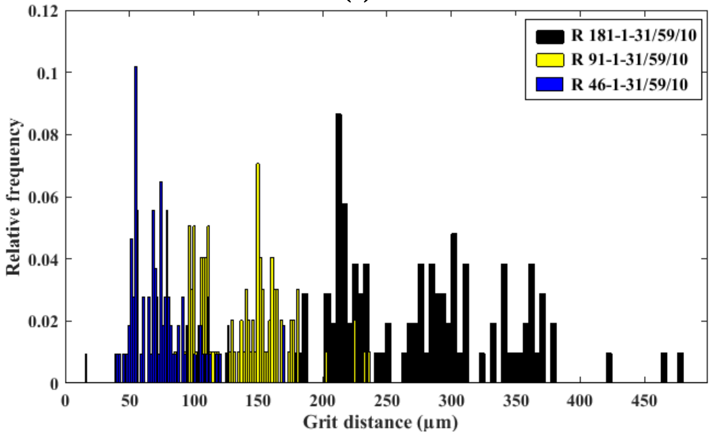
The number of grits per unit area and the average grit distance were derived from the section images and compared with the published data [13] as shown in Table 2 and their relative frequency distributions are plotted in figure 5. The percentage errors in the grit densities are 3.8%, 4.1% and 14.3% and the average grit distances exhibit errors of 1.3%, 7.9%, and 8.7% with their corresponding wheels of 46 μm, 91 μm and 108 μm grit sizes respectively. This indicates a closer agreement with the real wheel. This model can be extended to derive 2 D and 3 D wheel profiles at different depths of wheel. In case of highly porous wheel like vitrified wheels, overlap may occur between grits and pores in the unit cell, which can be minimized by improving the algorithm for randomization of grit. Also for wheels with grit volume fraction more than 0.52, the design of unit cell need to be changed from simple cubic to body centered cubic cell which can accommodate a maximum of 0.68 grit volume fraction.

Table 2. Comparison of modeled surface grain density and average grit distance with published results [13]

Grinding wheel nomenclature	Number of grains per unit area [1/mm^2]		
	Modeled structure from literature [13]	Structure from digital model	Real structure
R 46-1-31/59/10	211	191	184
R 91-1-31/59/10	87	71	74
R 181-1-31/59/10	24	18	21
	Average grain distance (μm)		
R 46-1-31/59/10	72	75	76
R 91-1-31/59/10	128	136	126
R 181-1-31/59/10	276	220	241



(a)



(b)

Fig. 5. Frequency distribution of (a) surface grit density (1/mm^2) (b) grit distance (μm)

5. CONCLUSION

Grinding wheel structure was predicted using the structure model developed in this work and the results matched closely with the real wheel structure data obtained from published literature. The digital model takes wheel specification as input and can simulate wheel structure in 3 D. The model can be extended to develop surface topography of grinding wheels. This can also be used for simulating the variation in wheel topography during dressing and grinding process. Further improvements can be made by including complex shapes of grits. The model may be limited in simulating wheels with very high porosity relative to the grit as the grits may overlap with pores in the unit cell.

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