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A REVIEW STUDY OF GRINDING WHEEL TOPOGRAPHY

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ABSTRACT

In this paper, we have covered grinding processes and their models, as well as the process factors and their effects, fundamental models, grinding applications, and grinding trends in the future. This paper reviews several researchers from various topographical model perspectives with a focus on the topography model, which includes 1D, 2D, and 3D models.

Keywords: Grinding process; Wheel topography; Modelling

1. INTRODUCTION

Grinding is a material removal process which is employed mainly as a finishing operation. The main purposes of grinding operation are to achieve desired dimensional, form and positional accuracy along with good surface finish and surface integrity. The main characteristics of grinding are as follows:

1. High negative rake angle of abrasive grits (average rake angle is −60°)
2. High grinding wheel speed to minimize the effect of high negative rake
3. Low depth of cut, consequently, low material removal rate
4. High specific grinding energy due to ploughing and rubbing
5. High temperature at the grinding zone as a result of high specific energy

Grinding has been used in manufacturing operations for than a century, and it can even be traced back to Neolithic times. It is mostly based on the size reduction principle. The scientific underpinning for the grinding process can be found in Alden and Guest's seminal work from 1914. Since then, "Grinding" has been described as "the machining process of removing material from a softer material using an abrasive grinding wheel rotating at a high speed."

In today's world, there are a variety of ways to carry out grinding processes, including computer-controlled feed drives and slide way motions, which aid in the production of complex shapes without the need for physical involvement.

The grinding process has progressed on a massive scale during the previous century, based on the wheel speed and feed rate and material removal rate i.e. boosted by 2 to 10 times. Not only that, but abrasive particles have evolved as a result of the introduction of ceramic abrasives as well as the creation of super abrasive CBN and Diamond abrasives, performance and productivity. Higher removal rates and improved surface integrity have been achieved thanks to the introduction of new grinding fluids and delivery systems.

High-velocity jets, factory-centralized delivery systems, shoe nozzles that use pure minerals and synthetic oils, and numerous new additives aimed at environmentally responsible manufacturing are all part of the progression. Grinding has become a vital technology in the development and production of innovative products and surfaces on a wide scale as a result of all of these innovations.

1.1. GRINDING

A grinding operation is a technique for removing undesirable material from a workpiece using strong abrasive particles. The small abrasive particles are shaped into the shape of a wheel in the present utilizing a suitable bond substance. The grinding wheel's abrasive granules serve as cutting tools. The rotating grinding wheel comes into contact with the workpiece surface during the grinding operation.

1.2. GRINDING PROCESS

Grinding process is a process of removing material by the application of abrasive particles which are bonded together by a suitable bonding material to produce superior surface finish. During the operation of grinding thousands of moving abrasive particles that are present on the grinding wheel comes in contact with the work piece that acts as a cutting tool and thus, making it a multi-point cutting tool, each particle cutting a tiny chip from the work piece. The tiny abrasive particles present on the grinding wheel also acts a self-sharpening tool.

1.3. SELF-SHARPENING

The self-sharpening action of the grinding wheel is an important feature in grinding. When a cutting tool becomes worn or damaged during the machining process, it must be replaced or re-sharpened. However, the wear of a single grit on the surface of a grinding wheel may not have a significant impact on the grinding wheel's performance. Such wear may increase the force on the worn grit, causing it to fracture and form new sharp cutting edges, or it may force the worn grit to drop off the wheel surface, allowing new grits in the lower layer of the wheel to engage in the grinding process. The self-sharpening action of the grinding wheel allows it to grind materials of similar hardness.In many aspects, the grinding process as a material removal process, such as the removal of materials in the form of chips, is similar to other cutting processes. The abrasive grits on the wheel surface, for starters, have irregular forms and are positioned randomly. Second, each grit or cutting edge in grinding has an extremely thin unformed cutting depth, down to the sub micrometer or nanometer level. In the grinding zone, the cutting chip may not form in every grit pass. Third, grinding has a substantially faster cutting speed than other machining techniques. It is normally ten times higher. Excessive grinding speed speeds up material removal, but it also raises the risk of high grinding temperatures.

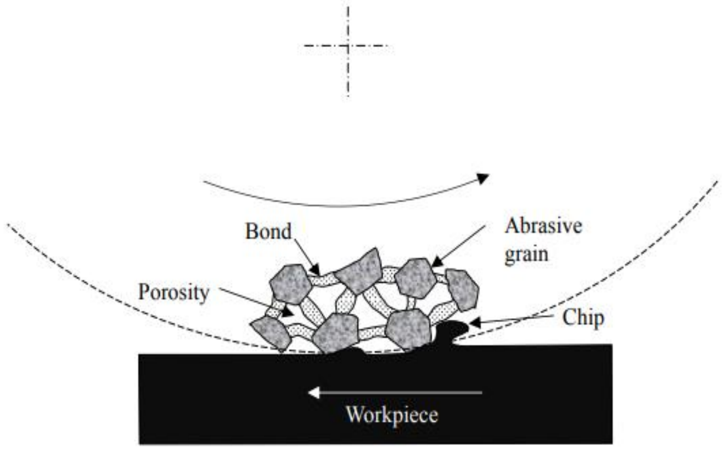


Fig.1 Illustration of grinding wheel components and chip formation

1.4. ADVANTAGES OF GRINDING PROCESS OVER OTHERS**

- Grinding process uses tiny abrasive particles and hence has a larger number of cutting edges.
- The chips produced are of magnitude almost two orders smaller than the magnitude of chips obtained in other processes.
- It produces better quality products with higher tolerances.
- Hard and brittle surfaces can also be machined with comparable ease.

2. PARAMETERS OF GRINDING

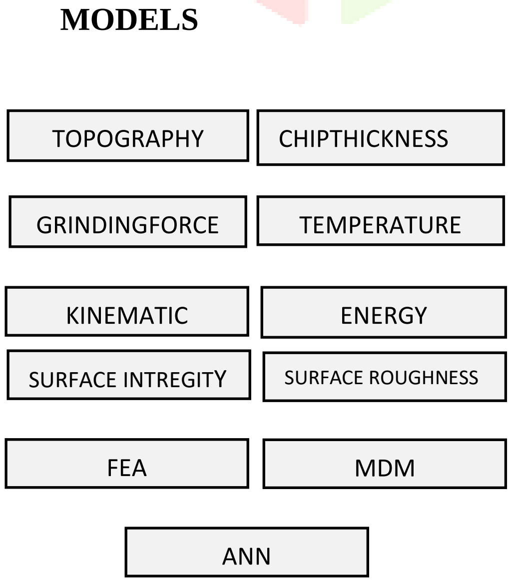
The underlying complications and complexities of the grinding process have been an avenue for research and discussions in order to comprehend the subtleties of the process.

The present paper elaborates the dependencies of different parameters like grain size, grain type, type of bond, mode of grinding, depth of cut, feed, wheel wear, coolants, on the surface finish of the product**.** These parameters effect the process as a whole as well as the output. The surface finish is affected by the grinding wheel speed, grinding wheel grade, depth of cut, grinding wheel material, and feed rate, which in turn influences the component's productivity. Some of the parameters are discussed below in the paper.

Grinding wheel selection is one of the most basic parameters in the grinding process. They are selected such as the number of active grains are maximised also the wheels that can be dressed to perform better. ***Grain type*** used in the wheel plays a very crucial role in the grinding process with grain materials ranging from diamonds, being the most popular to most extensively used materials like aluminium oxide and silicon carbide. With the development of super abrasives like Cubic Boron Nitrite (CBN) machining of very hard and brittle materials like Ceramics, or super alloys have also become possible. ***Bonding type*** such as vitrified bonds, rubber bonds, shellac bonds are chosen for good surface finishes and better material removal. CVD (chemical vapour deposition) abrasives also known as bondless diamond grinding wheels are available nowadays. ***Depth of Cut*** affect the process in the following manner lesser depth of cut, results in small and discontinuous chips resulting in a rough finish and micro cracks, while increasing depth of cut improves the surface finish. Higher ***Feed Rates*** are appropriate for high grinding wheel speed while the lower feed rates are appropriate for lesser depth of cut and a good surface finish. ***Surface Finish*** almost all of the grinding energy converts to heat energy the accumulation of heat causes various types of thermal damage on the work piece as well as the wheel which in turn worsens the surface finish. ***Temperature*** grinding process has high specific energy and thus results in higher heat generation which depends on the interacting forces as well as the plastic deformation mechanism, the table speed, grinning wheel speed or the speed of the work piece in grinding.

3. MODELS

Any model is basically an abstract representation of a process which serves to link causes and effects. A model thus establishes a relationship between input and output quantities in order to describe both the dynamic and static performance of each individual process and modelling is the simplified formulation of the process conditions. There are two types of modelling: Physical modelling and Empirical modelling. A physical model is created using a mathematical formulation of the qualitative model, and it is formed from basic physical principles with specific aims in mind. Relevant physical processes are chosen based on process knowledge and experience, and a physical model is created. An empirical model, on the other hand, is built on the basis of measurable values gained through grinding experiments. This paper also discusses briefly some of the basic models to the recently developed such as topography model, chip thickness model, grinding force model, grinding energy models, temperature models, surface integrity models, surface roughness models, kinematic models, Finite Element Models, Molecular Dynamic Models, Artificial Neural Networking Models.



Topography Models as the name suggests takes the topography of the wheel in to consideration that is it describes the structure of the grinding wheel while taking the geometric parameters in to account. *Chip thickness models* represents the chip formation and solely examines the machine tool's set-up parameters and geometric dimensions. *Grinding Force Model* explains how parameters such as the distance between cutting edges, the material of the work piece, and the above-mentioned models are related to distinct grinding forces such as shear and normal forces. *Temperature Model* scan thus be used to characterise the temperature distribution within the work piece, and no model with reliable predictions has been created to yet. *Surface Integrity Models* characterise the impacts of grinding on the work piece material beneath the work surface, both mechanically and thermally. In *Grinding Force,* the grinding power (=tangential force x cutting speed) is equal to the mechanical power utilised as an input in grinding. While the energy generated during chip manufacturing is turned into different forms of energy. *Surface Roughness Models* examines the surface roughness which is a crucial attribute because it determines the work piece's quality and are primarily defined by microstructure of the grinding wheel. There is an obvious link between surface roughness models and the topography models outlined previously.

4. GRINDING WHEEL TOPOGRAPHY MODELS

Although the grinding process has been known for thousands of years, it was not studied properly until the middle of the 1940s. In the years since, a lot of research has been done in this area. Grinding activities are becoming increasingly important in today's world. Many industrialized countries have grinding operations as an essential economic component. In modelling of grinding, the topography of the grinding wheel must be considered during operations. Understanding the cutting-edge geometry, which is stochastically distributed and orientated on the grinding wheel and understanding the mechanism of chip generation leads to gain a better grasp of the grinding procedure.

To obtain a topography model for a grinding wheel, there are two main approaches: utilizing scanned surface topography data from an actual grinding wheel, or modelling the topography of the ground.

GRINDING WHEEL MODELS

The grinding wheel topography models are categorized in three parts:

One-dimension (1D) model, two dimensions (2D) model and three-dimension (3D) model.

"1D" model refer to a model that is incapable of providing topographical features of the wheel surface. In other words, characteristics such as surface roughness and the number of exposed cutting edges on the wheel surface define the wheel surface.

In "2D" models, rather than using empirical descriptions, grains are characterized mathematically. As a result, the grain size has decreased. The distribution, position, protrusion height, and dressing impact are all evaluated.

In "3D" models, not only the grain position and shape are described as 3D objects but also to characterize the wheel, the 3D surface is simulated or measured.

4.1. One Dimensional topography models

To specify grinding wheel properties such as wheel surface roughness and the number of cutting edges, one-dimensional topography models were created. According to Peklenik each given abrasive grain may have numerous cutting edges.

Later, Verkerk et al. reported that due to negligible chip clearance needed for chip formation, the cutting edges of the same grain or adjacent grain could be considered as a single cutting edge. Chip creation is not possible due to a lack of chip clearance. These conclusions were utilized as a guideline for the classification of the abrasive grains.

They are divided into two types: static and kinematic cutting edges.

The number of static cutting edges is the summation of all the cutting edges. Whereas the number of kinematic cutting edges is the sum of only the cutting edges that are responsible for chip formation. Kinematic cutting edges are also known as active cutting edges.

Some of the 1D models are described below:

4.1.1. Tonshoff model (Basic topographic model)

Tonshoff [29] conducted a review of topographical models widespread in Europe in 1992, for research on grinding process. The majority of these models were centred on the creation of empirical formulas that specify the static and kinematic number of cutting edges for a particular grinding wheel. As a function of the predicted kinematic cutting-edge density there are four aspects to consider: the cutting-edge shape (SF), the speed ratio

(SR), depth of cut (DC) and grain size (GS). The basic formula of the kinematic cutting-edge density was given by [29]:

$$N_{kin} = (\mathrm{SF})(\mathrm{SR})(\mathrm{DC})(\mathrm{GS}) \qquad (1)$$

The static grain density was measured experimentally using profilometry and the stylus method, among other approaches. Tonshoff [29] proposed basic models in Equations (2) and (3), which describe the static and kinematic cutting edges respectively, to compare different grinding wheel topographical models developed before 1992.

$$\mathrm{Nst} = \mathrm{Cst}\, z^{A_3} \qquad (2)$$

$$N_{kin} = A_{gw}\left(\frac{a}{q^2 d_{eq}}\right)^{\frac{A_2}{2}} \qquad (3)$$

In Equations (2) and (3), N_{kin} and Nst represent the number of static and kinematic cutting edges, respectively, Cst is the volumetric static cutting-edge density (grain per unit volume), a represents the depth of cut, is the equivalent d_{eq} grain diameter, q represents the speed ratio, is the A_{gw} cutting edge shape constant, and A1 and A2 are empirical constants.

4.1.2. Fractal theory and Warren Liao model

Mandelbrot [31] developed the fractal theory in 1975. Fractals are self-similar patterns that form an object. Objects are self-similar if they look the same from close and far. The object generated by the fractal theory can be divided into parts, each of which is a copy of the object. Figure 3.1 depicts a fractal object known as a "Sierpinski triangle." Self-similar triangles are arranged to form a triangular object in the figure.

The fractal dimension denotes pattern details. The fractal dimension for self-similarity objects of N parts scaled by size r_p from the whole is defined by[30]:

$$D = \frac{\log(N)}{\log\left(\frac{1}{r_p}\right)} \qquad (4)$$

Because the abrasive grains have identical shape, the fractal theory has been employed to characterize a ground work piece, paper-ground and grinding wheel topographies [32-34]. The fractal dimension was used by

Warren [35] to describe a diamond grinding process for grinding wheel profiles, the fractal dimension was found for different scale length.

The profile shape is controlled by the length. When the scale length is reduced, more of the profile detail is added and the profile length increases as more detail is added. Warren [35] employed the following equation for fractal dimension.

$$D = 1 - \frac{\log(L_p)}{\log(r_p)} \qquad (5)$$

Where L_p is the total profile length, $r_p$is scale length

Hence, Warren [35] give a conclusion that for the assessment of surface roughness of grinding wheel, the shorter the scale, length the finer will be the wheel.

4.1.3. Hou and Komanduri model

Hou and Komanduri [36] proposed a stochastic topography model for grinding wheels in 2003. The model calculated the number of grains of a particular size and their probability within the grinding wheel volume. This model shows a plot of mean grain diameter d_{g_mean} against grain size $d_g$acquired from the grinding wheel marking system, from which the best-fit relation was derived [36].

Using the following equation, Hou and Komanduri [36] calculated the average number of grains per unit length N_l on the grinding wheel's surface:

$$N_l = \frac{10}{d_{mean}} V_g^{1/3} \qquad (6)$$

The volume fraction of abrasive grains is shown in the preceding equation. As a result, the average number of grains N_a per unit area is given by [36]:

$$N_a = (N_l)^2 = \left(\frac{10}{d_{mean}} V_g^{1/3}\right)^2 \qquad (7)$$

Hou and Komanduri [36] assumed a regular distribution of abrasive grain size on the grinding wheel surface. The following equation expresses the normal distribution function formally

$$P(x) = \frac{1}{\sqrt{2\pi}} e^{(-0.5x^2)} \qquad (8)$$

4.1.4. Koshy et al. model (1)

A topography model of a freshly dressed resin/metal bonded diamond grinding wheel was created by Koshy et al [37]. The mathematical model developed estimates the planer grain density, the percentage area due to abrasives on the wheel surface, and the abrasive protrusion height distribution.

The grains were assumed to be spherical in shape with a radius distribution that conforms to a symmetric truncated normal distribution. The following equation [37] describes the probability density function of grain radiusr_g.

$$f_R(r_g) = \frac{A_4}{\sigma_r\sqrt{2\pi}} e^{\left[-0.5\left(\frac{r_g-\bar{r}_g}{\sigma_r}\right)^2\right]} \qquad , r_{g_1} \le r_g \le r_{g_2}$$

Where $\bar{r}_g$the average of the grain radius, A4 isan empirical constant and $\sigma_r$is the standard deviation of the grain radius [37].

$$\sigma_r = \frac{r_{g_2} - r_{g_1}}{6} \qquad (9)$$

4.2. Two-dimensional topography models

4.2.1. Koshy et al. model (2)

Koshy et al. [38] extended their 1D model [37] to 2D in 1997, presenting a stochastic simulation of metal/resin-bonded diamond grinding wheels. Diamond abrasive grains were distributed stochastically in a volume of a cube of side. The grain size was assumed to be normal and distributed symmetrically around the mean grain diameterσ_d . Equation provided the standard deviation of grain diameter [38].

$$\sigma_d = \frac{d_{g\_max} - d_{g\_min}}{6} \qquad (10)$$

As the model was based on the topography of a resin/metal bonded diamond grinding wheel, it was assumed that the dressing operation affects the bond material rather than the abrasive grains. Under the right conditions, some dressing techniques, such as electrochemical [39], electrical discharge [40], and rotary wire brush [41], can dress the diamond wheel with little or no damage to the diamond abrasives.

The bond material around the diamond abrasives is gradually removed during the dressing process. As a result, the abrasive protrusion heights are increased. Eventually, abrasives that are not deeply embedded in the bond material are unable to withstand the dressing load and are dislodged from the bond material.

4.2.2. Chen and Rowe model

Chen and Rowe [25] developed a model that accounted for the dressing process. The topography model is influenced by grinding wheel characteristics, dressing diamond shape, and dressing conditions. Figure A depicts the relationship between the input and output parameters of the dressing process.

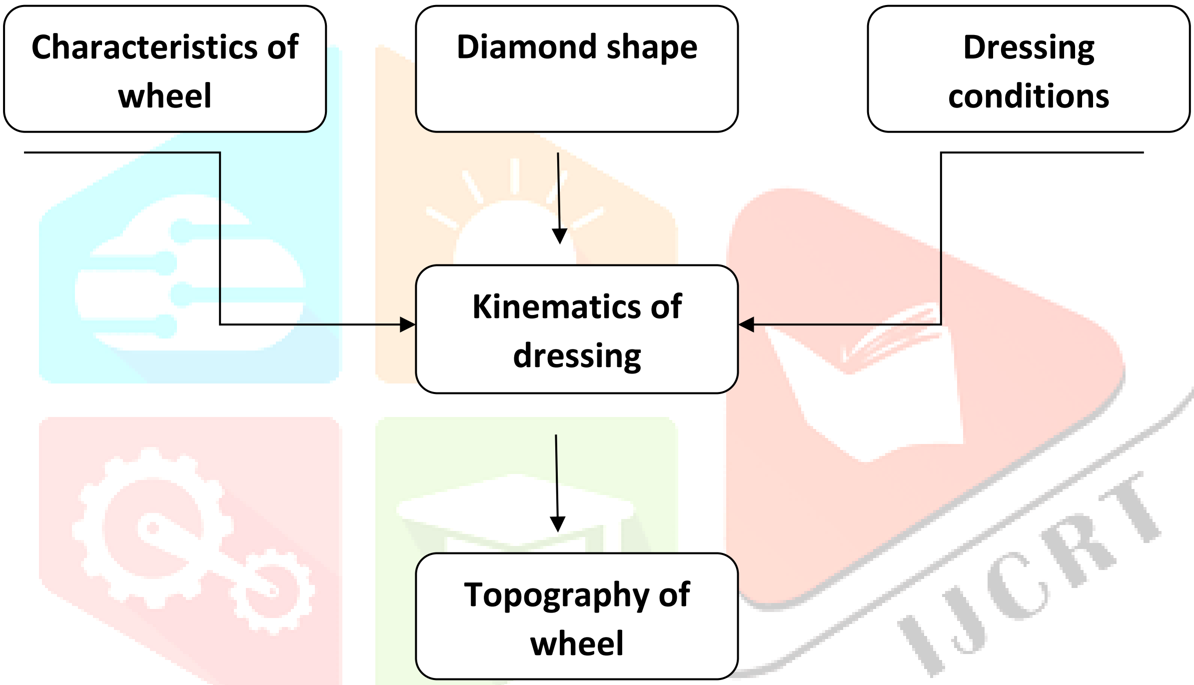


Fig. A Relationships in a dressing process [25]

The grinding wheel characteristics are represented by the grain size, packing density of the grains in the grinding wheel, and other parameters. Chen and Rowe [25] assumed that the grinding wheel is made up of spherical grains with diameters of dg and that the grinding wheel is made up of evenly sized and randomly distributed throughout the volume of the wheel .The grain is initially constructed with a simple cubic unit cell (SC) and are randomly rearranged. Each individual grain is located in the grinding wheel by the following matrix [25]:

$$[G_{i,j,k}] = \begin{bmatrix} G_{i,j,k}^{x} \\ G_{i,j,k}^{y} \\ G_{i,j,k}^{z} \end{bmatrix} = \begin{bmatrix} G_{0,0,0}^{x} + i\Delta x + R_x \\ G_{0,0,0}^{y} + j\Delta y + R_y \\ G_{0,0,0}^{z} + k\Delta z + R_z \end{bmatrix} \qquad (11)$$

Where the average spacing in x, y and z directions is equal, i.e. Δx = Δy = Δz = L, as the spatial probability is assumed to be uniform. The total volume of grains in one SC cell is calculated by [25]:

$$V_{g,SC}^{cub} = \frac{1}{6}\pi d_g^3 \qquad (12)$$

The grain packing density V_g determined by Equation, is the ratio of the total volume of the grains in one cell to the whole volume of the cell [25]

$$V_{g} = \frac{V_{g,SC}^{cub}}{V_{cell}^{cub}} = \frac{\pi d_g^3}{6L^3} \qquad (13)$$

$$L = \left(\frac{\pi d_g^3}{6V_g}\right)^{\frac{1}{3}} \qquad (14)$$

$$V_g = 2(32 - S\,) \qquad (15)$$

Where S is the structure number of the grinding wheel and L is the inter grain spacing.

4.3. Three dimensional topography models

In 3D grinding wheel topography models the grinding wheel working surface is either empirically or statistically defined in detail to be used in simulation of the effect of the grinding wheel topography, or to generate a simulated ground surface of the work piece.Type equation here.

4.3.1. Hegeman model

Hegeman [45] proposed a three-dimensional topography model based on the assumption that grains are ellipsoidal in shape. The ellipsoidal grain size and orientation are varied at random. In the wheel global coordinate system, the grain shape function is [45]:

$$z^{gr}(x,y) = r_g^z \sqrt{1 - \left(\frac{x - x_g^c}{r_g^x}\right)^2 - \left(\frac{y - y_g^c}{r_g^y}\right)^2} \qquad (16)$$

Where (x_g^c,y_g^c, z_g^c = 0) is the location of the grain center andr_g^x,r_g^y, r_g^z and are the grain axis radii in x, y and z directions, respectively.

By creating a non-smooth surface on the grains, Hegeman [45] introduced a dressing function to his model. Hegeman [45] constructed a stochastic periodic function, Equation, to simulate the smooth ellipsoidal surfaces generated by Equation dressing's effect

$$z^{fr}(x,y) = \cos(\widehat{\omega}_x x + \hat{\alpha}_x) + \cos\left(\widehat{\omega}_y y + \hat{\alpha}_y\right) \qquad (17)$$

Where $\widehat{\omega}_x \hat{\alpha}_x \widehat{\omega}_y \hat{\alpha}_y$ and are all random numbers Figure depicts the results of Hageman's topography model simulation without dressing. The wheel surface can be found at z = 0. This model requires some experimentally determined parameters, which are listed in Table given below

The wheel parameters required in Hegeman model:

Wheel parameter	Symbol	Experimental technique
Grain density per unit area	C_A	Scanning electron microscopy
Grain base radius	$r_g^x = r_g^y$	Confocal scanning optical microscopy
Grain protrusion height	r_g^z	Confocal scanning optical microscopy

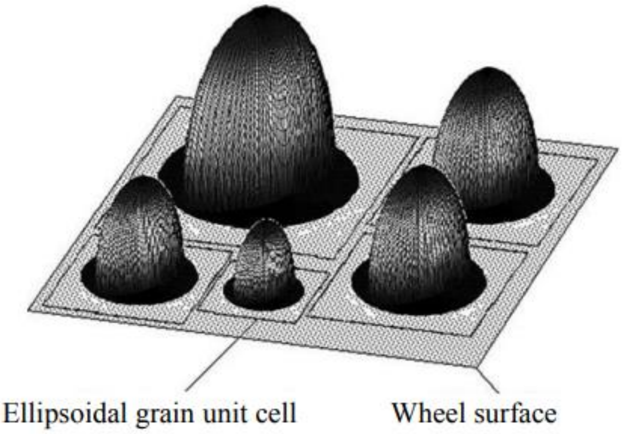


Figure: Schematic of Hegeman model approximation of the grinding wheel topography [30]

4.3.2. Doman model (A framework for general 3D model)

Doman et al. [30] used a survey of grinding wheel topography models prior to 2005 to build a framework for a general 3D topography model. As shown in Figure, Doman et al. [30] summarized the grinding topography model in a general modelling approach. The framework is divided into two major components. The first step is to model the undressed grinding wheel topography, and the second step is to apply the dressing process to generate the final grinding wheel topography model.

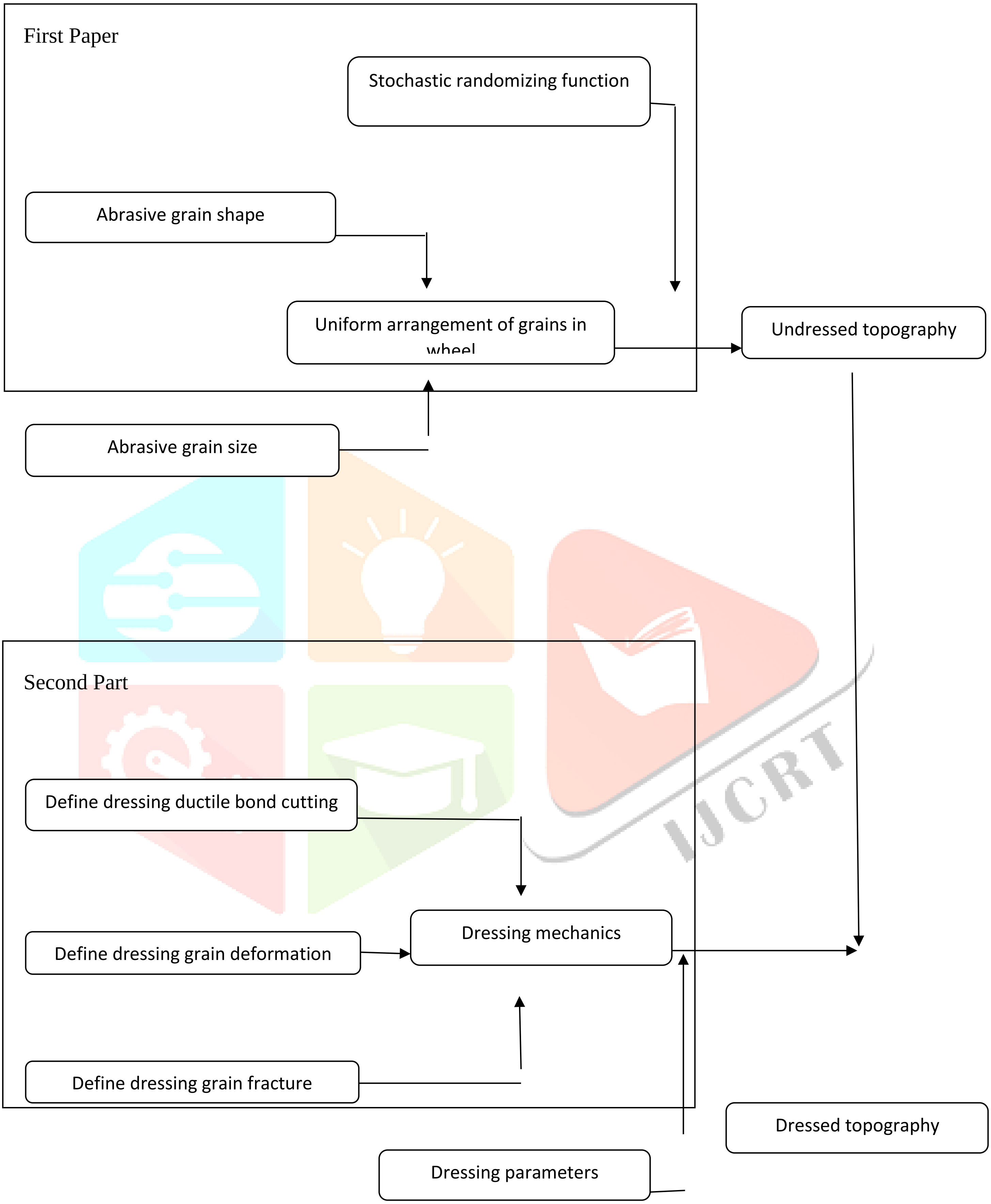


Figure: General 3D physical topography model approach [30]

The grains are randomly shaped, sized, and located in the first part of the framework. The abrasive grain shape, which is typically spherical, size, and location are all uniformly set. As a result, the stochastic randomizing function is used to randomize the size and location of the grains. The finished model is now ready for the dressing process.

The dressing technique is the second component of the framework model, and it is the result of three major mechanisms. Grain fracture, ductilebond cutting, and grain deformation are the mechanisms involved. Dressing parameters such as dressing tool shape, dressing depth, and dressing lead influence all of these mechanisms.

5. CONCLUSION

In this paper, we have discussed the basics of grinding processes and also the various parameters affecting the process. Further we have studied the various models taking into consideration the various input and output parameters. The output parameters mentioned are surface finish, chip thickness, MDM, Energy, while the input parameters are depth of cut, feed rate, bonding type, etc. Furthermore we highlighted the practical advantages of the grinding process.

Moving on to the modelling, we have illustrated various physical and empirical models such as topography models, chip thickness model, kinematic model etc.

Topography model has been discussed in detail and describes the structure of the grinding wheel while taking the geometric parameters into account . The models are categorized in three parts 1D model, 2D model and 3D model. In 1D model, surface roughness and the number of exposed cutting edges define the wheel surface, in 2D model grains are defined mathematically and the distribution, position, protrusion height are all evaluated while in the 3D model, the 3D surface is simulated or measured.

Starting with the Tonshoff model , it was centred on the creation of empirical formulas that specify the static and kinematic number of cutting edges for a particular grinding wheel. Fractal theory developed by Mandelbrot depicts a fractal object and the fractal dimension denotes pattern details . following Mandelbrot warren used the fractal dimension to describe diamond grinding process for grinding wheel profiles. Other 1D models such as Hou and Komanduri model, Koshy et al model, have been mentioned. Moving on to the 2D model the extension of the Koshy et al model , Chen and Rowe model have been accounted for the dressing process . further the 3D model include Hegeman model, and the Doman model.

These models elaborately explains wheel surface properties and the factors affecting the topography of the wheel.

6. FUTURE TRENDS

The current mega trends such as resource efficiency individualisation ergonomics and industry 4.0 are changing the appearance of the grinding machines technology. Grinding process is also affected by the availability of new technologies such as sensors, actuators and the control or machine intelligence.

Insight Significance of the Grinding machine in the industry Grinding machines are important in a variety of industries, most companies have thought of many ways why grinders are so indispensable. Sharpening and whetting of tools after their manufacture making it serviceable again is one of the many reasons. Grinding machines are an important part of industries today for they allow companies to extract minerals, reduce the particulate size of materials, and create materials mechanically with high precision and at a low cost. Future of the Grinding Machine The abrasive machining is a century-old technology; it continues to play an important role in industry. The extremely small scale of chips produced and the self-sharpening of grinding wheels are key advantages of abrasive machining and should be taken advantage of in future efforts to develop abrasive machining technologies. The most recent developments in abrasive machining are reviewed pointing out problems to be solved for their practical applications in the near future technologies. Technologies for making abrasive grinding wheels, high-precision machining, Heavy-duty machining Implementation of intelligent abrasive machining, Use of computer simulation to understand abrasive processes, environmental aspects of abrasive processes. It is concluded that promising abrasive technologies of the future should include: grinding wheels with ultrafine grits, molecular dynamics surface integrity assessment techniques, high-speed abrasive machining with CBN, autonomous machining system implementing

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