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On the evolution of metal-bonded microgrinding tool topography due to wear

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Abstract

The key challenge in the analysis of the grinding process involves the characterization of tool topography due to a large degree of randomness in the grit shapes, sizes, orientation and distribution. The effect of random tool topography on the output characteristics is even more pronounced in microgrinding. During the process, the wear of bond and grits cause the exposure of the underlying grits of the multi-layered metal bonded microgrinding tools. Due to the random tool topography and its variation during grinding due to continuous wear and self-dressing makes the process analysis highly complex. This study proposes a model that characterizes the multi-layered metal bonded microgrinding tool topography and its evolution during the process caused due to wear. The effects of both grit and bond wear on topography evolution is investigated. The emergence of new grits due to bond wear during the tool-workpiece interaction has also been captured in the model. Individual grit life cycle has been analyzed and the number of protruding, active, dislodged and worn out grits at a given machining time is estimated. Statistical analysis of the protrusion height distribution is carried out which gives an insight into the effect of wear on the height distribution variation.

Keywords: Microgrinding; Tool topography; Wear; Grit dislodgement;

1. Introduction

Microgrinding is a widely used process for the superfinishing of miniature sized components in optical, electronics and medical industries. These applications have a stringent requirement for dimensional accuracy and surface finish. However, grinding tools offer a relatively higher degree of variability in the process due to the inherent randomness in their topography [1][2]. A typical microgrinding tool is either electroplated or metal bonded, with large number of random shaped and sized abrasives distributed onto the metal surface or within the bond
volume. Differences in the shapes, sizes and orientation of the grits renders each grit-workpiece interaction to be different that other [3]. The combined effect of all the random parameters make the process responses indeterministic which limit the applicability of this process where stringent control on dimensional accuracy and surface finish is required. Many researchers have tried to model and characterize the grinding tool topography for understanding of its effect on the process responses. Nassirpour and Wu modeled the grinding wheel as a stochastic isotropic surface by characterizing the grinding wheel in terms of active grit density and ratio of real to the apparent area of contact [4]. A few researchers modeled the grinding wheel as a two-dimensional random spatial field with each random variable representing the protrusion height of the grits [5,6]. As time progressed, advancements were made over these basic topographical models. Efforts were made to stochastically characterize the grinding wheel topographical features such as protrusion height, inter-grit spacing, the grit distribution on the tool surface etc. [7].

In order to effectively capture the effect of these random topographical features on the process output responses, attempts were made to correlate the random tool properties with that of the output responses such as surface roughness, forces etc. [8–10]. Any tool topography variation during grinding affects the finished surface characteristics in an unfavorable way. Grit pull-out, fracture or dulling of abrasive deteriorate the ground surface quality [11] resulting in the requirement if an unplanned tool change. Such unexpected tool replacements in between a process is uneconomical, time consuming and undesirable.

Under such circumstances, the multi-layered, metal bonded microgrinding tools prove to be highly advantageous [12]. These tools continuously evolve their topography due to the tool wear during micro-grinding. As the bond wears out, fresh grits are exposed which participate in the cutting process. This ‘self-dressing’ property of multi-layered microgrinding tools is extremely advantageous for the long life of the tool and production of a good surface finish on the workpiece [12]. However, the complexity of the topographical evolution of the multiple grit layers of the tool over the already existing complex grit arrangement makes mathematical modeling very difficult. Very few studies have been carried out to stochastically analyze the multi-layered tool topographical features [13,14].

It may be noted that not much significant work has been reported in the literature on the modeling of the topographical evolution of a multi-layered microgrinding tool due to wear. Hence, this paper presents a model to generate a microgrinding tool topography and
characterize it in terms of total grit count, protruding and active grit count and protrusion height distribution for a fresh microgrinding tool. The flow diagram in Fig. 1 illustrates the methodology adopted to predict the microgrinding tool topography after a given machining time.

![Flowchart illustrating the methodology adopted for predicting microgrinding tool topography](image)

**Fig. 1** Flowchart illustrating the methodology adopted for predicting microgrinding tool topography

Considering a constant rate of grit and bond wear, the variations in the tool topography is captured in detail. Statistical analysis of the protrusion height distribution variation with wear is carried out. Finally, the effect of the topography evolution on surface roughness is predicted. The study provides an insight into the different stages of the microgrinding tool topographical evolution during the process due to wear.
2. Generation and characterization of a fresh multi-layered microgrinding tool topography

2.1 Topography development for a fresh microgrinding tool

The development of a fresh microgrinding tool is carried out based on the mesh size of the abrasives and the concentration of the abrasives used by the manufacturer. Few assumptions that have been taken for the development of tool topography have been listed below:

- The grits are assumed to be spherical.
- The sizes of the grits are assumed to follow the normal probability distribution function. Normal distribution is based on central limit theorem which establishes that under certain conditions, when multiple independent entities are put together, their combined characteristics convolute towards a normal probability distribution function. Thus, during the grit sieving process, independent factors, such as the sieve shaking process and the grit sizes present in the given sample of the grit number are completely random. Thus, the final grit sizes tend to follow a truncated normal distribution within the selected upper and lower sieve sizes.
- The grits are allocated random positions following uniform probability distribution within the bond volume. The uniform probability distribution function assigns equal probability to all the locations for grit allocation in the bond volume, which is a reasonable assumption for capturing the phenomenon of grit distribution.

The grits in a grinding tool come in a variety of shapes. Polycrystalline diamonds come in various irregular geometries, whereas the monocrystalline diamond grits have a cubic or cub-octahedron shape [6]. The inclusion of the random shape of the grits adds additional random factors such as varied orientations, rake angles, interacting plane of the grits, sharpness of the grit etc. [15]. The work done by Liu et al. proposes a methodology wherein the spherical shaped abrasives are converted into irregular hexahedrons to model realistic grinding wheel topography [3]. This makes the analytical modeling of the process, especially the modeling of the grit-workpiece interaction very complex. Moreover, during grinding, grits are known to offer a high negative rake angle which can be best reproduced in the modeling by assuming the grits to be of spherical shape [6]. Many researchers have used spherical shaped grits to model the grinding wheel topography [16–19].
The topography is generated for a pin type metal bonded microgrinding tool. The schematic of tool geometry and wall grinding process is shown in Fig.2. The initial topography for an unused microgrinding tool has been created by distributing random sized grits \(d_i\) (following normal probability distribution function) into the available bond volume along the length as well as thickness of the tool. Thus, in a pin type microgrinding tool, the available bond volume for the distribution of the grit has been sampled into radial \(S_r\), angular \(S_\theta\) and axial \(S_z\) direction.

The placement of each grit has been carried out by allocating random positions to the grits inside the bond volume, followed by checking the grit overlap [20]. During wall microgrinding, the tip length of the tool \(L_w\) is in contact with the workpiece material (Fig. 2(b,c)). Hence, the sample space for grit distribution is within the bond volume along the tip length (see Fig. 2(c)) which has been formulated in Eq. (1-3) [13].

![Fig. 2](image)

**Fig. 2** (a) SEM image of a metal-bonded microgrinding tool; schematic of (b) tool-workpiece interaction during wall grinding (c) tool geometry

\[
S_r = \left\{ r \mid 0 < r < \frac{D_w}{2} + 0.4d_i \right\} 
\]

\[
S_\theta = \left\{ \theta \mid 0 < \theta < 2\pi \right\} 
\]
\[ S_z = \{ z \mid 0 < z < L_w \} \]  

The number of grits \((N_a)\) which need to be distributed in the sample space is estimated based on the concentration number \((C)\) and the tool dimensions as shown in Eq. (4-6) [13].

\[
V_i = \frac{\pi}{6} d_i^3
\]  

\[
E[V_a] = \frac{CL_m \pi \left( \frac{D^2_w - D^2_c}{4} \right)}{400}
\]  

\[
E[N_a] = \frac{E[V_a]}{E[V]}
\]

The distribution of the estimated number of grits \((E[N_a])\) within the sample space is carried out such that each grit is allocated a random location based on uniform probability distribution function. The overlap of the chosen grit location with other grits is checked and a fresh location is allocated in case of an overlap [20]. The simulation is carried out for all the grits. Fig. 2(c) shows the cylindrical sample space in radial \((S_r)\), angular \((S_\theta)\) and axial direction \((S_z)\) and random distribution of grits in the metal bond surrounding the tool core.

2.2 Characterization of fresh tool topography

The characterization of the topography of a fresh microgrinding tool is carried out in terms of the identification of the protruding grits, active grits, grit depth embedded inside the workpiece material for a given depth of cut. Fig. 3 shows a schematic of a metal bonded microgrinding tool during the process of wall grinding at a low depth of cut, without any bond-workpiece contact.
It can be seen in Fig. 3 that the protruding grits have their tips located outside the boundary of the bond thickness. This condition of identification of the protruding grits and their protrusion height ($h_i$) from the bond surface is expressed in Eq. (7-8).

$$R_i + \frac{d}{2} > T_b + \frac{D}{2}$$  \hspace{1cm} (7)

$$h_i = \left( R_i + \frac{d}{2} \right) - \left( \frac{D}{2} + T_b \right)$$  \hspace{1cm} (8)

Out of the protruding grits, those grits which interact with the workpiece with a significant depth of cut, known as ‘critical depth’ are classified as the ‘active grits’. The grits with depth of cut lower than the critical depth of cut are considered as the ‘ploughing grits’. In the subsequent generation of the surface, only the interaction of active grits that perform the cutting action is considered. The identification of the active and ploughing grits is based on a coordinate system whose origin is defined as the point of contact of the highest protruding grit of the tool with the workpiece surface. The depth of cut for the tool ($doc$) is given from this defined origin. The identification of the active grits is based upon the depth of penetration of the grits into the workpiece surface as shown in Fig. 3. The condition for the identification of
active grits and grit portion inside the bond material is formulated in the following Eq. (9) and Eq. (10) respectively.

\[ h_m - h_i < doc \]  \hspace{1cm} (9)

\[ d_b = d_i - h_i \]  \hspace{1cm} (10)

For the depth of cut values which are significant enough to enable bond-workpiece interaction, progressive bond wear takes place which results in the exposure of fresh underlying grits. The protrusion heights of the active grits also increase which may ultimately lead to their dislodgement due to insufficient bond holding force. Thus, bond wear results in significant variation of the tool topography in terms of the number of active grits, protruding grits, grits getting dislodged, mean protrusion height etc. This phenomenon of tool topography variation due to the combined effect of grit and bond wear is analyzed in the subsequent section.

3. Analysis of tool topography evolution with time due to wear

Depending on the depth of cut, the analysis is carried out for two cases; case 1 where there is no bond-workpiece interaction due to insufficient depth of cut and case 2 where the depth of cut is high enough to enable bond-workpiece interaction.

3.1 No bond-workpiece interaction

When the depth of cut is sufficiently low, there is no bond and workpiece contact as shown in Fig. 3. In such a case, the topography variation is affected only by the wear of grits. In this model, steady-state wear of grit is considered with a constant grit wear rate \( \dot{h} \). The grit wear rate is considered as a function of specific cutting energy \( U \), grit hardness \( H_o \), process parameters such as depth of cut \( doc \) and feed rate \( V_w \), number of effective grits \( N_{eff} \) and tool diameter \( D_w \) as formulated in Eq. 11 [21].

\[ \dot{h} = \psi \left( \frac{U}{\pi H_o N_{eff} D_w^2} \right) doc dV_w \]  \hspace{1cm} (11)

The factors which affect the wear rate such as grit diameter, effective depth of cut, specific cutting energy are unique for each grit. The effect of chemical interactions between the workpiece and the grit on grit wear [22] is neglected. Thus, for each pass, such variable factors
affecting the wear rate have been considered and due revision in the wear rate has been done in the simulation for the next grinding pass.

For any grit, maximum wear (Δ\(l_i\)) takes place till the grit height reaches the workpiece surface as shown in Fig. 3. Considering the constant grit wear rate, time (\(t_i\)) taken for Δ\(l_i\) wear (defined in Eq. (12)) to take place is defined in Eq. (13).

\[
\Delta l_i = \text{doc} - (h_m - h_i) \tag{12}
\]

\[
t_i = \frac{\Delta l_i}{h} \tag{13}
\]

During grinding, the reduction in protrusion height of a grit depends on the grit wear rate and the time of grit contact with the workpiece surface. During wall grinding, grit contact is maintained only for a part of the tool rotation. For grinding a channel length of \(L\) mm with feed rate (\(V_w\)) \(\mu\)m/s, time taken (\(t_s\)) is expressed as:

\[
t_s = \frac{L}{1000V_w} \tag{14}
\]

Contact length of a grit in one rotation (\(l_k\)) is defined as [23]:

\[
l_k = \sqrt{a_e D_w} \tag{15}
\]

where \(a_e\) is defined as the depth of cut of the individual grit.

Total sliding length (\(l_{ks}\)) of the grit in contact with the workpiece surface during channel grinding can be expressed mathematically as:

\[
l_{ks} = \sqrt{a_e D_w} \frac{N}{60} \frac{1000L}{V_w} \tag{16}
\]

For the given sliding length, time of grit contact (\(t_{gc}\)) can be expressed as:

\[
t_{gc} = \frac{l_{ks}}{V_s} \tag{17}
\]

where \(V_s\) is the grit linear velocity.
Grit protrusion height reduction ($\Delta h_i$) for the above calculated grit contact time is expressed as:

$$\Delta h_i = \begin{cases} h_{t_{gc}}, & t_{gc} < t_i \\ \Delta l_i, & t_{gc} > t_i \end{cases}$$  \hspace{1cm} (18)

Final grit size ($d_{i,tm}$) after a given machining time is estimated as:

$$d_{i,tm} = d_i + \left( h_i - \Delta h_i \right)$$  \hspace{1cm} (19)

The above analysis gives an estimate of the tool topography after a given machining time in terms of the number of protruding grits, number of active grits and the variation of mean protrusion height of the grits as wear progresses.

**3.2 Bond-Workpiece interaction**

Under significant depth of cut values, bond-workpiece interaction may occur as shown in Fig. 4.

![Fig. 4 Schematic of tool-workpiece interaction during wall grinding with bond-workpiece interaction](image)

This results in bond wear to take place which causes exposure of fresh underlying grits. This phenomenon is called as ‘self-dressing’ of grinding tools. In this model, volumetric bond wear ($\Delta b$) is assumed to be following Archard’s wear law as expressed below [24]:
\[ \Delta b = kFL \]  

where \( k \) is the Archard’s constant assumed to be \( 10^{-4} \text{mm}^3/\text{N-mm} \), \( F \) is the normal force and \( L \) is the sliding contact length between the bond material and the workpiece surface. The bond wear rate \( (\dot{b}) \) is calculated as:

\[ b = \frac{\Delta b}{t_m} \]  

where \( t_m \) is the machining time.

Due to the exposure of underlying grit layers, each grit has a different time of exposure to the workpiece surface depending on its location within the bond volume and the bond wear rate. As seen in Fig. 7., the contact time of each grit is different as bond thickness reduces from \( T_b \) to \( T_{bf} \).

![Identification of active and inactive grits](image)

**Fig. 5 Identification of active and inactive grits**

The protruding grits (Type I) are the first ones to interact with the workpiece surface whose time of contact can be mentioned as ‘zero’ i.e. at the beginning of machining. Type II grits are those which come in contact with the workpiece surface after reduction of a certain amount of bond thickness. Type III grits are which never come in contact with the workpiece surface for a given depth of cut due to their inner lying position in the radial direction. These grits are identified as the ‘inactive grits’. For the remaining active grits, the time instance of their contact with the workpiece surface is expressed in Eq. (22):
The bond thickness at the instance of grit exposure \((T_{b,i})\) is different for each grit depending on its radial location in the bond volume as shown in Fig. 5. The bond thickness at the instance of grit exposure is identified for each grit. It is formulated in terms of grit size and radial grit location as in Eq. (23):

\[
T_{b,i} = \begin{cases} 
T_b & \left( R_i + \frac{d_i}{2} > T_b + \frac{D_c}{2} \right) \\
\left( R_i + \frac{d_i}{2} \right) - \frac{D_c}{2} & \left( T_{b,f} + \frac{D_c}{2} \right) < \left( R_i + \frac{d_i}{2} \right) < T_b + \frac{D_c}{2}
\end{cases}
\]  

(23)

The maximum extent of wear of the active grits is the instant when the grit starts rubbing against the workpiece surface. Thus, maximum wear possible \((\Delta h_{i,\text{max}})\) for any \(i^{th}\) grit is defined as:

\[
\Delta h_{i,\text{max}} = (R_i + d_i/2) - (T_{b,f} + \frac{D_c}{2})
\]  

(24)

### 3.3 Estimation of grit dislodgement

The grits which become active during machining either get dislodged in the process or they dull out to the extent till their tip just rubs the workpiece surface. The other case may be that the grit gets dislodged in the process without getting completely worn out for the given depth of cut. For the generation of tool topography during wear, every grit is checked for their dislodgement during the given machining time. For the identification of the dislodgement of grits, two criteria have been considered as follows.
3.3.1 Grit dislodgement due to insufficient bond thickness

Most of the previous researches have proposed the dislodgement criteria as the instance at which the grit portion embedded inside the bond material is less than 30% of the total grit size at that instance [25].

![Schematic showing the dislodgement for grits at different locations](image)

A set of equations (Eq. 25 (a-d)) derived from the analysis of Fig. 6 is solved to determine the time of grit dislodgement from the start of machining.

\[
\begin{align*}
    d_{b,fl} & = 0.3d_{i,fl} \\ 
    T_{b,fl} & = T_{b,i} - \left(d_b - d_{k,\beta}\right) \\ 
    \dot{t}_{g,m} & = d_b - d_{b,\beta} \\ 
    \Delta h_{fl,T_{g,m}} & = d_i - d_{\beta}
\end{align*}
\]

The solution of the equations gives the values for the grit working life before dislodgement \((t_{g,m})\), grit size at dislodgement \((d_{i,fl})\) and the grit depth inside the bond at the time of dislodgement \((d_{b,fl})\). Once the working life of the grit has been estimated, the instance of its dislodgement from the beginning of machining \((t_{g,fl})\) can be calculated as:

\[
t_{g,fl} = t_{\text{contact}} + t_{g,m}
\]

3.3.2 Grit dislodgement due to thermomechanical stresses

It has been observed that in the early stage of grinding, grit dislodgement is a dominant phenomenon, because initially, a relatively smaller number of grits participate in the cutting phenomenon, thereby increasing the load shared by each grit. Thus, in order to identify the
grits which, get dislodged during the process due to high load impact, Paris Fatigue Law is used. Paris fatigue law is applied in microgrinding to define the relationship between grit loads and the accumulated damage incurred to the grits. Grit dislodgement is quantitatively estimated using the process parameters, thermal properties and grinding wheel topographical features. Table 1 shows the thermo-mechanical properties of different components (diamond grit, metal bond and the steel shank) of the microgrinding tool.

This methodology was developed by Yu et al. which is adopted in the current simulation for the identification of grit dislodgement in the microgrinding process [21]. Following steps are undertaken to estimate the lifecycle of a grit before getting dislodged due to thermomechanical stresses under a given set of process parameters:

1. Estimation of the grinding power
2. Partitioning of the grinding power to thermal loads on the cutting grits
3. Evaluation of thermomechanical stresses on the cutting grits
4. Estimation of the grit fatigue life

Table 1: Thermo-mechanical properties of the microgrinding tool and workpiece material

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hardened steel core</th>
<th>Bronze bond</th>
<th>Diamond grit</th>
<th>Zirconia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio ($\mu$)</td>
<td>0.29</td>
<td>0.34</td>
<td>0.22</td>
<td>0.27</td>
</tr>
<tr>
<td>Young’s Modulus ($E$), GPa</td>
<td>205</td>
<td>95</td>
<td>1050</td>
<td>175</td>
</tr>
<tr>
<td>Thermal Conductivity ($k$), W/mK</td>
<td>22</td>
<td>189</td>
<td>1000</td>
<td>1.5</td>
</tr>
<tr>
<td>Density ($\rho$), kg/m$^3$</td>
<td>~7500</td>
<td>7400</td>
<td>3510</td>
<td>6000</td>
</tr>
<tr>
<td>Specific heat capacity ($c_p$), J/kg.K</td>
<td>456</td>
<td>380</td>
<td>630</td>
<td>420</td>
</tr>
<tr>
<td>Modulus of rigidity ($G$), GPa</td>
<td>80</td>
<td>30</td>
<td>440</td>
<td>70</td>
</tr>
<tr>
<td>Fracture toughness ($k_c$), MPa.m$^{1/2}$</td>
<td>-</td>
<td>57</td>
<td>13</td>
<td>4.5</td>
</tr>
<tr>
<td>Hardness ($H$), MPa</td>
<td>693</td>
<td>1430</td>
<td>45 GPa</td>
<td>9500</td>
</tr>
<tr>
<td>Coefficient of thermal expansion ($K_L$)</td>
<td>12E-06</td>
<td>~17E-06</td>
<td>7E-06</td>
<td>~8E-06</td>
</tr>
</tbody>
</table>

Total power ($P$) generated in the microgrinding process is a combination of the power consumed in ploughing ($P_{pl}$) and chip formation ($P_{ch}$) which is expressed as below [26]:

$$P = P_{ch} + P_{pl} = ab_s V_w U_{ch} + F_{pl} V_s$$  \hspace{1cm} (27)

where, $a$ is the depth of cut, $b_s$ is the wheel width, $V_s$ is the grinding wheel speed and $F_{pl}$ is the ploughing force component.
Specific energy ($U_{ch}$) required for chip formation is estimated from the tangential cutting force ($F_t$) and the microgrinding process parameters as expressed in Eq. (28)[27]. The tangential cutting forces are obtained from the microgrinding experiments.

$$U_{ch} = \frac{F_t}{b_s a \left( \frac{V_s}{V_w} \right)} \tag{28}$$

The total grinding power consumed is expected to get dissipated as thermal energy into the tool-workpiece system. The heat flux generated is conducted both into the workpiece and the microgrinding tool. Thus, an energy partition ratio is calculated which defines the ratio of the total heat flux going into the grinding tool and the workpiece. Due to the heat flux flowing into the active grit ($Q_g$), the temperature rise ($T_g$) in single grit is expressed as [21]:

$$T_g = Q_g \frac{\rho_g}{\rho_s} \frac{1}{\sqrt{V_s}} \tag{29}$$

Referring to Eq. (27), the total power consumed during the material removal is considered to arise from the tangential forces acting on the active grits. Since normal stress does not induce interface bond-grit failure, only shear stresses are considered for estimating the grit dislodgement. The shear stress ($\tau_{mech}$) induced by mechanical load is expressed as [21]:

$$\tau_{mech} = \frac{F_t}{N_{eff} \alpha_g d^2 g} \tag{30}$$

In grinding process, thermal stresses are larger than the cutting/mechanical stresses for a single grit. The thermal stresses ($\tau_{thermal}$) are calculated by considering the grit, the bond layer and the core material of the microgrinding tool as a three-layer structure [21].

$$\tau_{thermal} = \chi G ((1 + V_g) \alpha_g - (1 + V_s) \alpha_s) T_g \tag{31}$$

In the above equation, $G$ is the equivalent shear modulus of the system, $\nu_g$ is the poisson’s ratio of the grits, $\nu_s$ is the poisson’s ratio of the base (shank), $\alpha_g$ is the coefficient of thermal expansion of grits and $\alpha_s$ is the coefficient of thermal expansion of base (shank). $\chi$ is a geometric factor that is obtained from FEA modelling. (mention $\alpha$ factors) To obtain this factor, a FEA model is designed using Abaqus/ CAE 6.11-1. The diamond grit, bronze bond and hardened steel core of the microgrinding tool are modeled as a sandwich structure. The average grit size is considered as 20 µm for the given mesh size of the tool, the bond thickness as 200 µm as per the tool’s specifications and the length of complete model is considered as 350 µm. The element
type is taken as CPE4T. It is a four-node plane strain thermally coupled quadrilateral, bilinear displacement and temperature element. This simulation is done for different temperatures (100°C to 900°C). For all the temperature values, analytical model for shear stress is calibrated against FEA model. The effective value of geometric factor ($\chi$) is calculated by taking mean of all the geometric factors calculated at different temperatures. Fig. 7 (a) and (b) show the FEA model and the shear stress distribution after simulation at 300°C.

![Fig. 7](a) FEA model for thermal analysis (better to put a schematic and show BCs) (b) shear stress distribution (indicate 3 regions)

From Fig. 7, it can be concluded that maximum shear stress is generated at the interface of grit and bond. The initiation point for damage is the interface and it grows until failure. This analytical model for shear stress is calibrated against FEA model and geometrical factor ($\chi$) is calculated to be about 0.63.

Initially it is assumed that there is some crack already present in the microgrinding tool due to some inherent manufacturing defects. Due to mechanical and thermal stresses, the crack length is expected to gradually increase to an extent till the grit gets dislodged from the bond surface. This critical crack size at which the grit dislodgement takes place is dependent on the fracture toughness of the material. The mean-time to failure of individual grit ($N_f$) is controlled by process parameters and thermal loads as well as the initial defect state $h_i$ (dictated by the processing condition of the diamond grinding wheel) and the final defect state $h_f$ (dictated by the interfacial fracture toughness) [21].
\[ N_f = \frac{2^{\frac{2-m}{2}}}{(2-m)c(\beta \sqrt{\Delta \sigma + \Delta \tau})^m} \]  

(32)

After calculating the lifecycle of each grit, the grits which get dislodged during a given machining time (either due to insufficient bond thickness or thermo-mechanical stresses) are removed from the tool topography. The remaining intact grits which get worn out in during the grinding process, are analysed further to determine the tool topography as discussed in the following Section 3.4.

### 3.4 Final tool topography

After the identification of the grit lifecycle i.e. the time of grinding that a grit can withstand before getting dislodged, the grits which get dislodged are identified and are removed from further analysis. For the remaining intact active grits, the reduction in protrusion height \( \Delta h_i \) and the final grit size \( d_{i,tm} \) after the machining time \( t_m \) can be calculated as:

\[
\Delta h_i = \begin{cases} 
\hat{h}_{g,m}, & t_{g,m} < t_i \\
\Delta l_i, & t_{g,m} \geq t_i 
\end{cases}
\]  

(33)

\[ d_{i,tm} = d_i - \Delta h_i \]  

(34)

The final protrusion height of the grits is the function of the grit wear and bond wear which can be expressed as below:

\[ h_{i,final} = h_{i,initial} - \Delta h_i + \Delta T_{b,m} \]  

(35)

where, \( \Delta T_{b,m} \) is the bond thickness reduction in the machining time \( t_m \) and \( h_{i,initial} \) is the initial protrusion height of the grit.

The above methodology gives an estimate of the microgrinding tool topographical features in terms of total grit count, active grits, protruding grits, the number of grits getting dislodged and the mean protrusion height of the intact grits with time. It is to be noted that due to continuous bond wear under a high depth of cut during grinding, bond thickness continuously reduces which weakens the bond holding forces for many grits. Thus, higher rates of grit dislodgement are expected during this phase of microgrinding.
4. Results and Discussion

4.1. Experimental validation

4.1.2 Static grit density

Static grit density is defined as the number of grits per unit surface area at a given cross-section in the grinding tool. Analysis of static grit density accounts for the grit packing efficiency as well as the grit wear and pull-out that might take place during the grinding process. Thus, it is a significant parameter for the analysis of a microgrinding tool topography before and after the process. Static grit density of the unused tool is calculated for mesh size of #220 and #1200. Fig. 8 shows the comparison of results for static grit density calculation for different cross-sections at different distances from the center of the tool core. Could you show a snapshot of your simulation with #220 and #1200 and show at which cross-section you are presenting this data (RKS)

![Fig. 8 Comparison of analytical static grit density with simulation results for a microgrinding tool of mesh size (a) #220 (b) #220 from literature [13] (c) #1200 (d) #1200 from literature [13]](image)
From Fig. 8, it is observed that both the tool topographical characteristics: number of grits and static grit density are successfully captured by the simulation.

4.1.2 Validation of tool topography after grinding

Validation of the model is carried out from the microgrinding experiments carried out by Feng et al [28]. The diamond microgrinding tool considered for validation has an outer diameter ($D_w$) of 850 µm, the mesh size of 150 and the concentration of 100. Simulations were carried out for slots of 6.5 mm × 0.85 mm × 20 µm at the experimental parameters summarised in Table 1. The tool topography after each channel was compared against the experimental results of micro grinding of MgO partially stabilized Zirconia [28]. Grit wear rate calculated from Eq. (11) depends on the specific energy for chip formation ($U_{ch}$) which in turn is a function of cutting speed and tangential cutting forces. The experimentally recorded cutting forces in the literature are used to evaluate $U_{ch}$ [28]. Thus, the grit wear rate takes into consideration the material properties of the workpiece as well as the effect of the process parameters.

<table>
<thead>
<tr>
<th>Table 1 Microgrinding process parameters [28]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental parameters</td>
</tr>
<tr>
<td>Rotational speed (rpm)</td>
</tr>
<tr>
<td>Feed-rate (mm/min)</td>
</tr>
<tr>
<td>Number of passes</td>
</tr>
<tr>
<td>Depth of cut for each pass (µm)</td>
</tr>
<tr>
<td>Channel length (mm)</td>
</tr>
<tr>
<td>Total channel depth (µm)</td>
</tr>
</tbody>
</table>

The experimental and predicted values of active grits and dislodged grits follow a similar pattern initially. However, a heavy grit dislodgement is predicted between 36 < $t_m$ < 40 min in the simulated results. This lowers the predicted active grit count significantly in the same time range (Fig. 9).
Even though the fall out of the grits lowers the predicted active grit count, similar trend of steady rise in the active grit count is observed for both the predicted and simulated results in the intermediate machining duration. The heavy dislodgement predicted is possibly due to the difference in the values of bond wear rate considered in the model and experiment. It may happen that experimentally the bond wear rate is low and the bond strength is high enough to expose the grits while not resulting in dislodge of the grits.

The pattern of the grit dislodgement is further examined to understand the tool wear mechanism (Fig. 10). It is observed that the model predicted heavy grit dislodgement in the beginning and in the end of the machining. The intermediate slots ($46 < t_m < 96$ minutes) show a consistent trend indicating a steady tool wear stage [29]. The initial higher grit dislodgement rate has been reported by previous studies as well [28,30]. It is mainly a reflection of the initial transient state of the grinding wheel where all the weakly bonded grits experience pull out due to sudden load impact. In the middle stage of machining ($45 < t_m < 96$ min), a regular pattern of grit dislodgement is predicted as the bond wears out. Finally, at the end of tool life, the bond thickness is reduced to a significantly low value which is no longer able to hold the remaining grits which experience sudden heavy fallout. A similar pattern of tool wear is reflected by the analysis of the active and protruding grit wear as shown in Fig. 10. It is observed that initial tool wear causes a rapid increase in the number of active grits. After heavy grit dislodgment between 36-40 minutes, the active/protruding grit count falls rapidly and becomes consistent in the intermediate tool wear stage. The rapid fall in the grit count after 96 minutes signifies the last stage of tool wear.

![Fig. 9 Analysis of tool wear mechanism](image-url)
reaching the end of tool life.

![Diagram showing grit count pattern](image)

**Fig. 10** Active, protruding and dislodged grit count pattern

### 4.2 Analysis of tool topography evolution on the basis of model predictions

The simulations for tool topography evolution were carried out for a diamond microgrinding tool having specifications summarized in Table 2.

<table>
<thead>
<tr>
<th>Tool characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter (μm)</td>
<td>300</td>
</tr>
<tr>
<td>Core diameter (μm)</td>
<td>220</td>
</tr>
<tr>
<td>Tip length (μm)</td>
<td>500</td>
</tr>
<tr>
<td>Grit mesh size</td>
<td>D37</td>
</tr>
<tr>
<td>Concentration number</td>
<td>145</td>
</tr>
</tbody>
</table>

**Table 2 Microgrinding tool specifications**

Topography evolution was estimated after the completion of each channel length of 10 mm till the end of tool life. The microgrinding process parameters used for the surface generation are summarized in Table 3.
Table 3 Microgrinding process parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed (rpm)</td>
<td>24000</td>
</tr>
<tr>
<td>Feed rate (µm/s)</td>
<td>30</td>
</tr>
<tr>
<td>Depth of cut (µm)</td>
<td>15</td>
</tr>
</tbody>
</table>

Fig. 11 shows the simulated tool topography before and after machining.

4.2.1 Estimation of tool topography evolution in terms of grit count

The tool topography after machining is characterized in terms of the identification of protruding, active and dislodged grit count. The initial depth of cut given is 15 µm. The maximum protrusion height of the highest protruding grit in the simulated tool topography is 22.06 µm. The point of contact of the highest protruding grit is taken as the origin from where the depth of cut is given. Since the depth of cut is less than the maximum protrusion height (22 µm), initially there is no bond-workpiece interaction which leads the analysis to fall under Case 1 as elaborated in Section 3.1. Under this condition, the multilayered metal bonded tool acts as a single-layered tool where only the outermost protruding grit layer interacts with the workpiece. The topography changes due to the effect of grit wear only. Due to the progressive wear of grits with time, the protrusion height of the grits reduces which result in a reduction of the number of active grits as shown in Fig. 12. As the wear progresses, for the given depth of cut, a stage reaches when there are no active grits for significant material removal. In the model, this stage is identified as an instance when the tool requires dressing. An alternate method to utilize the remaining protruding grits is to set a fresh origin as the point of contact of the highest grit.
protruding grit at that stage with the workpiece surface and then give the depth of cut from that point.

Due to the setting of fresh origin and depth of cut, a greater number of grits start interacting with the workpiece surface which results in an increase in the active grit count after the dressing stage as seen in Fig. 12 at \( t=61 \) min. More simulations are carried out after giving a fresh depth of cut from the new defined origin. The progressive wear is captured as before, till the tool reaches a stage where no more significant number of protruding grits are left. At this stage the bond material starts getting eroded out. This exposes the fresh underlying grits. From Fig. 12, it can be observed that the active grit count is fairly stable in the bond wear zone even though continuous grit dislodgement is taking place. The bond wear affects the topography in two ways. On one hand, it exposes the inner layers of grits and on the other hand, it causes dislodgement of the grits due to a continuous reduction in its thickness (see Fig. 11). The dislodgement of the grits causes lowering of the protruding and active grit count at some instants. A significant point to be noted here is that, at this stage, the protruding and active grit counts are same as whatever grits are protruding out are interacting with the workpiece material.

In a nutshell, it can be said that, initially at low depths of cut, the microgrinding tool behaves as a single layered tool and wear effect is reflected in the continuous reduction of the active
grit count. However, at later stage, the inner layers of grits lying within the bond material start getting active and the net active grit count which is dependent on both the dislodgement rate of the grits and the exposed grits becomes quite stable. The effect of the exposure of grits is reflected more clearly in the analysis of the variation of mean protrusion height and protrusion height distribution with wear as discussed in the following section 4.2.2.

**4.2.2 Tool topography evolution in terms of protrusion height variation**

The qualitative analysis of the microgrinding tools was done by taking SEM images before and after grinding. The SEM images clearly showed the phenomenon of increase in protrusion height due to the exposure of underlying grits as seen in Fig. 13. The emergence of fresh underlying grits occurs due to the wear of the outer layers and the metallic bond. This self-sharpening characteristic of the metal bonded tools provides them a greater grinding life.

**Fig. 13** *SEM image of a multilayered microgrinding tool showing grit dislodgement and exposure of new grits by bond erosion*

Due to the emergence of fresh underlying grits during grinding, the mean protrusion height gets affected. Thus, the mean of the protrusion heights of all the protruding grits is calculated after each run and plotted against time as shown in Fig. 14. The low initial depths given to the tool do not result in the engagement of the bond material with the workpiece surface. Thus, till the non-engagement of the bond and workpiece, the variation in the mean protrusion height is the sole effect of the grit wear. The progressive wear of all the active grits result in a monotonic reduction in the mean protrusion height as shown in Fig. 14. At higher plunging depths, when
bond erosion starts at around $t=61$ min, an increase in the mean protrusion height is observed due to exposure of the fresh underlying grits (see Fig. 14).

![Variation of mean protrusion height with time](image)

**Fig. 14** Variation of mean protrusion height with time

The protrusion height distribution of the grits at different time intervals was plotted as shown in Fig. 15.

![Effect of (a) no bond wear (b) bond wear on the protrusion height distribution](image)

**Fig. 15** Effect of (a) no bond wear (b) bond wear on the protrusion height distribution with time

From Fig. 15, it can be observed that due to the wear of the higher protruding grits in the initial stages, the height distribution gets skewed to the left (lower protrusion heights). The grit count starts getting concentrated between 1-2 µm at the end of the dressing stage ($t = 55.55$ min). The
protrusion height of the highest protruding grit in the initial stage is 22.06 µm. However, at increased plunge depth, when bond interacts with the workpiece surface, the mean protrusion height increases, which is reflected in the protrusion height distribution of the grits as shown in Fig. 14 (b). From the Figure, it can be observed that due to the exposure of fresh grits caused by bond erosion, the protrusion height distribution shifts right to the higher protrusion heights. The shift in the protrusion height distribution to the higher values due to wear as shown in Fig. 16 is also reported by Yao et al. during grinding [31]. A deeper insight into the protrusion height distribution is obtained by the statistical analysis of these distributions in terms of standard deviation, skewness and kurtosis as shown in Fig. 16.

From Fig. 16, it can be observed that the initial stage when grit wear is in dominance, there is an increase in the skewness of the protrusion height distribution with time. As more and more higher protruding grits wear out, the distribution tends to get skewed to the lower protrusion heights which is reflected in Fig. 15(a) and Fig. 16. The wear of higher protruding grits also affects the standard deviation of the protrusion heights. The progressive wear of the larger grits results in the narrowing down of the range of protrusion heights which reduces the standard deviation (see Fig. 15(a) and Fig. 16). During no bond-workpiece contact, an increase in the kurtosis is observed which rises steeply to around 12. Higher kurtosis is the result of infrequent extreme deviations which occur in the protrusion heights in the initial stages of no bond wear. In the later stages of grinding, when bond wear also comes into play, the protrusion height distribution variation is the combined effect of both the grit and bond wear. The simultaneous

**Fig. 16 Statistical behavior of grit protrusion height as the grinding progresses**
wear of bond along with grit wear assists in the continuous exposure of new grits thereby keeping a check on the monotonous increase in the skewness and kurtosis of the protrusion height distribution. From Fig. 16, it can also be observed that in the region of bond wear, the kurtosis is fairly constant between 2 and 3 which indicate the proximity of the protrusion heights towards a normal probability distribution. These model results highlight the role of bond erosion and exposure of new grits towards the protrusion height variation. The lower variations in the standard deviation, skewness and kurtosis of the protrusion height distribution during bond wear indicates a stable balance between the dulling of grits and exposure of fresh grits which is necessary for a good surface finish during grinding.

5. Conclusions

This work focuses on the study of dynamic wear behavior of a multi-layered microgrinding tool. An exhaustive model has been developed and its detailed analysis has been carried out for understanding the topographical evolution of the microgrinding tool due to the bond and grit wear during grinding. Based on the model analysis and the experimental validations, following conclusions can be derived from the analysis:

- Bond wear has significant influence on the dislodgement of grits and the active grit count during the process. It exposes the inner underlying grits and increases the mean protrusion height of the grits which result in more utilization of the tool life.
- Grit wear rate during the process is not constant. The variation in the active grit during material removal causes inconsistent loading conditions which affects the grit wear rate.
- As seen in the statistical analysis of the protrusion height distribution, the exposure of fresh grits reduces the skewness and standard deviation of the protrusion height distribution and restores the normal distribution characteristics for a fairly significant time duration.

The model captures the underlying phenomenon of the topographical evolution with time in a microgrinding tool, which is very difficult to capture experimentally, but has a profound effect on the process output responses. Thus, this study on the wear analysis of the metal bonded microgrinding tool is significant as it emphasizes the topographical variations occurring in the working life of a microgrinding tool. All the topographical features such as the grit density, grit protrusion height and the intergrit spacing have a significant effect on the machined surface. Thus, the study of the topographical evolution during grinding gives an insight into
the surface finish variations occurring during the process as the tool wears out. This study is thus proved to be essential, especially in those applications where surface finish and accuracy cannot be compromised with.

**Statements & Declarations**

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