The effects of structured grinding wheel designed parameters on the geometries of ground structured surfaces

Amr Monier1,2 · Bing Guo1 · Qingliang Zhao1 · Zhenfei Guo1 · Tamer S. Mahmoud2 · Iman El-mahallawi2

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Abstract
This study investigates the effects of the structured wheels' geometrical parameters on the geometries of structured surfaces machined by grinding operations. First, the geometrical parameters of the structured wheels were determined. The resultant geometrical parameters of structured surfaces were defined and related to the designed operating condition, including the structured wheel and grinding process by mathematical and simulation models. The results showed that each wheel’s geometrical parameter affects the structured surface geometry at different rates. Grinding experiments were then performed to explore experimentally how the geometrical parameters of the structured wheel affect the geometry of structured surfaces and verify the modeling and simulation results and explanations. The results showed a remarkable compatibility between the predicted and machined surfaces and reflected the accuracy of the presented method for machining the structured surfaces by grinding.

Keywords Structured surfaces · Structured grinding wheels · Precision grinding · Geometrical parameters · Mathematical model

1 Introduction
The machining of structured surfaces has been studied as a surface modification methodology to realize specialized surface characteristics [1, 2]. Several studies considered the relationships between the methods, functional attributes, and applications using structured surfaces functionalities as a common denominator of their aims to solve various design-related problems [3–5]. The main physical and technological properties of structured surface characteristics and the technologies used for surface structuring have been investigated in multiple studies [6–8]. For instance, Braun et al. [9] illustrated that friction reduction and avoiding extra severe wear are possible in the case of an optimum surface structure. Costa and Hutchings [10, 11] used the surface structures as micro-hydrodynamic bearings and reservoirs in different lubrication situations to create additional hydrodynamic pressure, increase the load-carrying capacity, and reduce the energy consumed while processing. Many advanced applications have included the structured surfaces, such as seal rings [12], bearings [13], optics [14], engine cylinder liners [15], and grinding tools [16].

Several machining methods for structured surfaces have been presented in the literature, e.g., lapping [17], cutting [18], grinding [19], and laser machining [20]. Among them, grinding the structured surfaces with structured grinding wheels has many advantages: high efficiency, high accuracy, high material adaptability, and reasonable cost are frequent characteristics. In this grinding process, particular geometries shaped on the peripheral wheel surface would be transferred to the workpiece at a specific scale via a selective material removal based on the difference in the movement between the structured wheel speed and the workpiece feed rate.
The geometry of a structured surface represents the main parameter for controlling and determining the characteristics and functionalities of these kinds of surfaces. Two different categories of controlling parameters determine the final geometrical characteristics of the ground structured surfaces. First, the geometrical parameters of the designed structured wheel used during grinding operations. The geometry of a structured wheel \( G_g \) can be defined as follows:

\[
G_g = f(\rho, \varphi, z)
\]

where \( \rho, \varphi, \) and \( z \) are the cylindrical coordinates defined for the grinding wheel as shown in Fig. 1a. The second parameters category is the kinematics and designed condition of the grinding process such that:

\[
M = f(v_s, v_w, d_c)
\]

where \( M \) is the designed motion condition, \( v_s \) is the cutting velocity, \( v_w \) is the feed rate, and \( d_c \) is the grinding depth of cut. Therefore, the geometry of surface structures \( G_w \) can be defined as:

\[
G_w = f(G_g, M)
\]

Many studies have attempted to present a deterministic method for ground structured surfaces by studying the process controlling parameters. Stępień et al. [21, 22] explained the influences related to the kinematics of the grinding process on the obtained structured surfaces. Two critical values were presented for the velocity ratio between the workpiece feed rate and wheel cutting velocity for successfully shaping the surface structures. Oliveira et al. [23] used the novel approach presented in [24] to develop a method to determine and control the characteristics of surface structures. Higher workpiece feed rates were selected to achieve a lower relative velocity ratio and decrease the size of surface structures. It was explained that low velocity ratios resulted in higher grain-surface contacts per workpiece area and denser structures. Mohamed et al. [25] studied separately the effects of the workpiece feed rate and wheel cutting velocity on the size of surface structures. A reverse effect was illustrated between the feed rate and the cutting speed on the size of surface structures. Recently, Monier et al. [26] studied the ability to reshape structured wheels with specialized geometries for machining advanced structured surfaces using a grinding operation. Various regular and irregular geometries have been applied to the structured wheels, and many advanced geometries of surface structures have been studied.

In literature, most studies are concerned with exploring the grinding process’s kinematics on the machined surface structures. To date, few studies have systematically
considered the influences of the structured wheel geometrical parameters on the characteristics of surface structures. Understanding the effects of the designed structured wheel parameters on the formation mechanism of structured surfaces, side by side to the grinding process parameters, is essential for optimizing the characteristics of surface structuring applications. This study attempts to explain the effects of the designed structured wheel on the characteristics of surface structures.

In our previous study [27], a new approach for machining structured surfaces by grinding was presented. In this study, the effects of geometrical parameters of the structured wheel on structured surfaces geometries are explored. The geometry of the structured wheel and the operating parameters of the grinding operation were mathematically modeled. Then, the geometrical parameters of structured surfaces were defined. The studied wheel parameters include the wheel radius, circular pitch, and structuring ratio. An accompanying simulation method to express the obtained geometries of structured surfaces at changing designed parameters of the structured wheel was developed. Additionally, the validity and efficiency of the presented method were measured by performing grinding experiments under several conditions and measuring the model predicted results and those experimentally machined, which reflect the high accuracy of the proposed approach for manufacturing structured surfaces by grinding.

2 Modeling of the grinding process of structured surfaces

This section demonstrates the mathematical model for machining the structured surfaces by structured wheels. First, reshaping the grinding wheel with grooves and the building procedures of its mathematical model are explained. Figure 1 shows schematic illustrations for a conventional grinding wheel of \( R_g \) radius cut in the circumferential direction into \( N \) segments (Fig. 1a and b). Then, the wheel surface is split into many 2D slices where \( n \) regularly shaped abrasive grains are uniformly positioned at each 2D slice circumference (Fig. 1c). The kinematic model for one of the wheel slices before the grooving process is shown in Fig. 1d. An abrasive grain numbered \( n_i \) is placed at an angle \( a_i \) and radius \( r(a_i) \). This geometrical pair \( (a_i, r(a_i)) \) defines the orientation and the polar distance of the \( n_i \) abrasive grain, respectively.

Figure 2 shows a schematic of grooving the grinding wheel. After cutting the wheel surface area into \( N \) segments, all segments are designed to have remaining parts and removed parts or grooves. The repeated circumferential interval between wheel segments is called wheel circular pitch \( P_c \). The geometry of wheel grooves includes additional parameters, such as the groove width \( w_g \), groove depth \( d_g \), and grooves helical angle \( \gamma_g \). The total amount of effective wheel cutting area is estimated using the structuring ratio \( \gamma_s \). Accordingly, the groove width is calculated as follows:

\[
w_g = P_c \cdot (1 - \gamma_s) \tag{4}
\]

The number of wheel segments \( N \) can be obtained using the following equation:

\[
N = \frac{2\pi \cdot R_g}{P_c} \tag{5}
\]

Figure 2c shows the layout of one wheel segment unfolded into a plane. \( n_s \) and \( n_{end} \) represent the starting and ending points of the groove \( N_i \), respectively. The radial depth \( d_i \) of the abrasive grain \( n_i \) is calculated relative to the outermost point from the wheel surface. For the remaining portions, the grains are supposed to be positioned at the outer radius of the grinding wheel. But, a fixed radial depth along the groove width is proposed as rectangular shapes for wheel grooves. Consequently:

\[
d_i(n_i) = \begin{cases} 
0, & n_i < n_{st} \\
d_g, & n_{st} < n_i < n_{end} 
\end{cases} \tag{6}
\]

Subsequently, the radial location of any cutting grain is determined by subtracting the values of the groove depth and wheel radius at that point, such that:

\[
r_i = \begin{cases} 
R_g, & n_i < n_{st} \\
R_g - d_i(n_i), & n_{st} < n_i < n_{end} 
\end{cases} \tag{7}
\]

After calculating the circumferential and radial locations of all abrasive grains above every 2D slice, all slices were merged to generate the 3D shape of the structured grinding wheel.

Next, the structured wheel model is related to a designed grinding condition, and the resultant geometrical parameters are determined to build the structured surface model. As shown in Fig. 3, the structured wheel runs at a grinding velocity \( v_g \), the workpiece moves at a feed rate \( v_w \), and the processing action is performed at a grinding depth of cut \( d_c \). The innermost cutting depth for any abrasive grain is its reference position and is assumed to be at orientation when it is passing perpendicular to the workpiece surface.

The orientation of an \( i^{th} \) abrasive grain, at any orientation, is determined by an angle \( \theta_i \) related to its reference position. Assuming the engaging radius of the \( i^{th} \) abrasive grain is the nominal wheel radius \( R_n \) and at a depth of cut \( d_c \). Thus, the workpiece surface was positioned at a displacement \((R_n - d_c)\) below the wheel center before grinding. For rigid body motion and neglecting deformations accompanying the motions, therefore:
\( \phi_i = \cos^{-1} \left( \frac{R_g - d_i}{R_g} \right) \) \hspace{1cm} (8)

where \( \phi_i \) is the orientation angle at which the \( i^{th} \) abrasive grain engages the workpiece surface. If the arc length of the contact area while the cutting grain engages the surface till reaching its reference position is denoted by \( C_i \), then:

\[ C_i = R_g \cdot \phi_i \] \hspace{1cm} (9)

Figure 4 shows a schematic for the formation mechanism of a structured surface and defines its geometrical parameters. In Fig. 4a, every abrasive grain rotates and translates simultaneously along a perfect cycloidal path when the grinding wheel begins processing. The remaining grains (green lines) perform the grinding operation and grind the workpiece surface. In contrast, the removed ones (red lines) run without machining over the surface quitting surface structures. Black segments signify the final structured surface formed by the interaction between the structured wheel and the machined surface (Fig. 4b).
In Fig. 4b, the structure fabricated on the workpiece is replicated over the ground surface with uniform separating displacements between structures called longitudinal pitch or in short pitch $P$. The pitch includes a bearing width $l_b$ and ground width $l_w$. The ground width involves a flooring width $l_f$ and two sidewall widths $l_{sw}$. While the flooring width defines the magnitude of the ground width straight bottom, the sidewall width is the projection of the wheel-workpiece arc length of contact. The geometry of surface structures has a structure height $h$, sidewall angle $\zeta$, and slope angle to the direction perpendicular to the feeding direction $\theta$ additional to the bearing width $l_b$. The geometrical parameters of surface structures are related to the geometry of the structured wheel and kinematic parameters of the designed grinding condition. Meanwhile, for longitudinal pitch $P$:

$$P = P_c \cdot \frac{v_w}{v_g} = P_c \cdot v^*$$

(10)

where $v^*$ is the velocity ratio between the workpiece feed rate and the wheel cutting velocity. The flooring width can be determined as follows:

$$l_f = P_c \cdot \gamma_s \cdot \frac{v_w}{v_g} = P_c \cdot \gamma_s \cdot v^*$$

(11)

Therefore, the sidewall width can be determined by:

$$l_{sw} = \frac{l_w - l_f}{2}$$

(12)

The angle of the structure sidewall $\zeta$ can be calculated by:

$$\zeta = \tan^{-1} \left[ \frac{l_{sw}}{h} \right]$$

(13)

where the angle $\zeta$ represents the inclination of the imaginary line connecting the engagement point to the point of the innermost depth of cut for any abrasive grain (Fig. 4c). After grinding, the bearing width can be calculated as follows:

$$l_b = P - l_w$$

(14)

It should be noted that the bearing width value is estimated relative to the outer surface of the workpiece.

Figure 5 shows a schematic for determining the structure height $h$ relative to the wheel geometrical orientation and designed grinding condition. The structure height $h$ depends on the coordinates of the groove limits’ cycloidal paths. Assuming the groove limits are operating at radii equal to the outer wheel radius. Additionally, at the intersection point, while the first limit ($O_{L1}$) leaves the workpiece surface in the orientation ($\varphi_{L1}=\varphi$), the other limit ($O_{L2}$) is interlocking ($\varphi_{L2}=-\varphi$). Consequently, according to Malkin [28], the height $H$ of the point $I$ between the intersecting cycloids can be calculated as the following:

$$H = R_g \cdot \left(1 - \cos \varphi \right)$$

(15)
The intersection between the paths of the groove limits may occur above or below the outer surface of the workpiece. Thus, the structural height can be determined by:

\[ h = \begin{cases} H, & H < d_c \\ d_c, & d_c < H \end{cases} \] (16)

In Fig. 6, a method determining the slope angle \( \theta \) of surface structures is illustrated. The orientation of the surface structures is represented as a reflection of the geometrical orientation of wheel grooves at the designed grinding condition. A wheel segment is unfolded as a circular pitch \( P_c \) with the reflected structured surface as a pitch \( P \) of the ground surface. According to this geometrical representation, the slope angle \( \theta \) of the workpiece surface structures is related to the helical angle \( \psi \) of wheel grooves such that:

\[ \tan \theta = \frac{P}{P_c} \cdot \tan \psi \] (17)

Using Eq. (10), then:

\[ \tan \theta = \frac{v_w}{v_g} \cdot \tan \psi \] (18)

Then, for up grinding:

\[ \theta = \tan^{-1} \left[ \frac{v_w}{v_g} \cdot \tan \psi \right] \] (19)

For down grinding:

\[ \theta = 180 - \tan^{-1} \left[ \frac{v_w}{v_g} \cdot \tan \psi \right] \] (20)

3 The effects of the structured wheel geometrical parameters on geometries of the ground structured surfaces

This section studies and illustrates the changes in the structured surface geometrical parameters, defined in the previous section, along with the variations in the designed structured wheel parameters. A kinematic simulation method is developed using programming, and two compatible algorithms were used to generate the structured surface and the designed structured wheel at the estimated grinding condition. Procedures of the simulation method for both structured wheel and structured surfaces are shown in Fig. 7a and b, respectively. A constant designed grinding condition was assumed along this section to highlight the effects of the structured wheel geometrical parameters. The studied parameters of the structured wheel include the wheel radius, circular pitch, and structuring ratio. The investigated structured surface geometrical parameters involve the bearing width, structure height, sidewall width, flooring width, sidewall angle, slope angle, and spacing between structures over the workpiece surface. The spacing between surface structures was evaluated by determining the pitch values, and values of the bearing width were determined at the top surface of the workpiece. The effects of each parameter of the structured wheel on structures’ geometrical parameters were studied individually. This is explained in subsequent sections.

3.1 The effects of the grinding wheel radius

First, the effects of the wheel radius \( R_g \) on geometrical parameters of the structured surface were studied. The number of wheel grooves \( N \) increased to keep the circular pitch \( P_c \) constant while the wheel radius increased. See Eq. (5). Table 1 lists the geometrical and grinding parameters used in this study. Figure 8 displays the changes in the geometry of the surface structures related to the change in the wheel radius.

As shown in Fig. 8a, at small wheel radii, increasing the wheel radius increases the sidewall width \( l_{sw} \) (black curve), but the flooring width \( l_f \) remains constant (orange curve). The sidewall width reaches the maximum value when the workpiece surface is wholly machined with increasing wheel radii. Thereafter, the sidewall width curve converted to a horizontal line similar to the flooring width curve. The ground width \( l_g \) is the summation of the sidewall and flooring widths. Consequently, as shown in Fig. 8b, the increasing radii raise the ground width (blue curve) until it acquires its highest value at the inflection point of the sidewall width curve. Then, the ground width and sidewall width curves become parallel, horizontal, and shift by the...
Fig. 7 The flowchart diagram of the simulation method for (a) the structured wheel, and (b) the structured surface.

![Flowchart Diagram]

Table 1 The geometrical and processing parameters used at the different wheel radii

| Circular Pitch $P_c$ (mm) | Structuring Ratio $y$, | Grooves Angle $\psi$ (deg) | Depth of Cut $d_c$ (mm) | Velocity Ratio $v^*$ | Wheel Radius $R_g$ (mm) |
|---------------------------|------------------------|-----------------------------|------------------------|----------------------|------------------------|
| 31.42                     | 0.35                   | 60.00                       | 0.0200                 | 0.091                | 5.00       | 15.00 | 35.00 | 50.00 |
constant flooring width. Furthermore, while the ground width increases, the bearing width \( l_b \) decreases at the same rate until it diminishes at the inflection point of the ground width curve (cyan curve). The straight horizontal line of the pitch curve clarifies that the structures’ pitch is not affected by the increasing wheel radius value.

Figure 8c shows that the sidewall angle \( \zeta \) increases with the increasing wheel radius (purple curve), whereas the slope angle of the structure \( \delta \) is not affected by the change in the wheel radius (green curve). Figure 8d illustrates that the structure height \( h \) remains constant and equivalent to the depth of the cut until the inflection point of the bearing width curve. Then, it decreases with an increase in the wheel radius (magenta curve). Figure 9 shows structured wheels at an increasing radius and related structured surfaces with the 2D profiles at the designed grinding condition listed in Table 1. The effects of the rising wheel radius on the structured surface geometrical parameters are significant. Table 2 lists the geometries of the structured surfaces represented in Fig. 9.

Therefore, the wheel radius does not affect the surface structures’ separating distances (pitch \( P \)). Instead, the raising wheel radius increases the length of the wheel-workpiece contact zone since the cutting grain engages the workpiece surface until leaving during the grinding operation (see Fig. 10a and Eq. (9)). So that, the sidewall and in accompany ground widths increase, but the bearing width decreases due to the constant separating distance until the surface is completely removed. At this point, the ground width becomes equal to the separating distance between surface structures, and the sidewall and ground widths reach their maximum value (Fig. 10b).
After removing the surface, structures separation fails, and increasing the wheel radius shears the wall-sides of the surface structures (Fig. 10b). Consequently, the sidewall angle increases, and the structure height decreases owing to the sides shearing process accompanied by increasing the wheel radius (Fig. 10c). Additionally, the wheel radius affects neither the flooring width nor the inclination of the surface structures.

**3.2 The effects of the wheel circular pitch**

Next, the circular pitch $P_e$ effects on the structures’ geometrical parameters were investigated. Table 3 includes the working conditions for the structured wheel and grinding process applied in the current investigation. Increasing the circular pitch at a constant wheel radius $R_g$ is compensated by decreasing the number of wheel grooves $N$. See
Figure 11 shows the variations in the geometrical parameters of surface structures according to the growing circular pitch.

In Fig. 11a, at small wheel circular pitches, while the circular pitch increases, the sidewall width $l_{sw}$ increases. This parameter acquires its maximum allowable value when structuring the surface does not affect its nominal surface dimensions. At this point, the sidewall width curve converted to be a horizontal straight line (black curve). Additionally, the flooring width $l_{f}$ increases with the rising circular pitch at the same rate, directly proportional. Consequently, the ground width $l_{g}$ increases with increasing circular pitch as the sidewall width and/or flooring widths increase (blue curve). See Fig. 11b.

Furthermore, the bearing width $l_{b}$ and pitch $P$ values of the structured surface also increase. Before the inflection point of the sidewall width curve, the ground width and pitch values are equal, and their two curves are identical (blue curve and gray curve). After that point, the similar curves separate. Moreover, a directly proportional relationship between the pitch and circular pitch is shown in Fig. 11b (gray curve).

Figure 11c illustrates that changing the circular pitch does not affect the surface structures' slope angle $\theta$ represented in the horizontal straight line (green curve). Besides, the sidewall $\zeta$ angle decreases; by contrast, the structure height $h$ increases with the increasing circular pitch till the inflection point of the bearing width. Then, both variables reach stable values, and both curves become horizontal straight lines (Fig. 11d). Figure 12 shows structured wheels and structured surfaces with the 2D profiles for the working parameters mentioned in Table 3, where the circular pitch

| Table 2 | Values of the geometrical parameters of surface structures obtained at different radii for the structured wheel |
|---------|--------------------------------------------------------------------------------------------------|
| Wheel Radius $R_g$ (m) | Straight Width $l_f$ (m) | Sidewall Width $l_{sw}$ (m) | Ground Width $l_g$ (m) | Bearing Width $l_b$ (m) |
| 5.00    | 0.99 | 0.495 | 1.98 | 0.88 |
| 15.00   | 0.99 | 0.85  | 2.69 | 0.17 |
| 35.00   | 0.99 | 0.935 | 2.86 | 0    |
| 50.00   | 0.99 | 0.935 | 2.86 | 0    |

| Wheel Radius $R_g$ (m) | Pitch $P$ (m) | Structure Height $h$ (m) | Sidewall Angle $\zeta$ (deg) | Slope Angle $\theta$ (deg) |
|------------------------|--------------|------------------------|---------------------------|--------------------------|
| 5.00                   | 2.86         | 0.0200                 | 87.65                     | 8.95                     |
| 15.00                  | 2.86         | 0.0200                 | 88.64                     | 8.95                     |
| 35.00                  | 2.86         | 0.0103                 | 89.36                     | 8.95                     |
| 50.00                  | 2.86         | 0.0072                 | 89.56                     | 8.95                     |

Table 3 | The geometrical and processing parameters used at the different circular pitches
|---------|----------------------------------------------------------------------------------------------------------------------------------|
| Wheel Radius $R_g$ (mm) | Structuring Ratio $\gamma$ | Grooves Angle $\psi$ (deg) | Depth of Cut $d_c$ (mm) | Velocity Ratio $v^*$ | Circular Pitch $P_c$ (mm) |
| 50.00   | 0.35 | 60.00 | 0.0200 | 0.091 | 31.42 | 39.27 | 52.36 | 78.54 |
is increasing. In this figure, the influences of the circular pitch on the structured surfaces can be noted. In Table 4, the geometrical parameters of surfaces shown in Fig. 12 are included.

Accordingly, increasing the circular pitch $P_c$ increases the swept distance at the machined surface for a single wheel segment (Fig. 13a). So, the structures’ separating distances increase by the ground width increments. Meanwhile, the wheel-workpiece contact zone increases, and the sidewall width and flooring width increase by extension. Also, while the length of the wheel-workpiece contact zone increases with the circular pitch, the wall-sides of surface structures are being built, increasing the structures’ heights and decreasing the sidewall angles (Fig. 13b).

Once surface structures separate, the achieved sidewall widths and heights are maximum; by contrast, the sidewall angle is minimum, and the bearing width is created. However, the flooring width and bearing width continue increasing. Thus, the ground width, bearing width, and structures’ pitch keep rising with the circular pitch (Fig. 13c). Also, the circular pitch does not affect the slope angle of surface structures.

### 3.3 The effects of the wheel structuring ratio

Besides the wheel radius $R_w$ and circular pitch $P_c$, the effects of the structuring ratio $r_s$ were studied. Raising the structuring ratio at the constant circular pitch was achieved by...
increasing the groove width $w_g$. See Eq. (4). Table 5 contains the geometrical and processing parameters used in this study. Figure 14 illustrates the changes in structures geometry due to changing the structuring ratio.

As shown in Fig. 14a, the sidewall width $l_{sw}$ is not affected by the small values of the structuring ratio, and its curve is a horizontal line (black curve). Once the surface is removed entirely by grinding, the sidewall width reduces with an increasing structuring ratio. In addition, a directly proportional relationship is observed between the flooring width $l_f$ and structuring ratio (orange curve).

While the sidewall width is constant, the ground width $l_g$ increases with the structuring ratio because of the increasing flooring width, but the bearing width $l_b$ decreases. At
Table 4 Values of the geometrical parameters of surface structures obtained at the different circular pitches

| Circular Pitch \(P_c\) (m m) | No. of Grooves \(N\) | Straight Width \(l_f\) (m m) | Sidewall Width \(l_{sw}\) (m m) | Ground Width \(l_w\) (m m) | Bearing Width \(l_b\) (m m) |
|-----------------------------|------------------|------------------------|------------------------|------------------------|------------------------|
| 31.42                       | 10               | 0.99                   | 0.935                  | 2.86                   | 0                      |
| 39.27                       | 8                | 1.25                   | 1.16                   | 3.57                   | 0                      |
| 52.36                       | 6                | 1.67                   | 1.54                   | 4.75                   | 0.01                   |
| 78.54                       | 4                | 2.50                   | 1.54                   | 5.58                   | 1.56                   |

Table 5 The geometrical and processing parameters used at the different structuring ratios

| Wheel Radius \(R_g\) (mm) | Circular Pitch \(P_c\) (m m) | Grooves Angle \(\psi\) (deg) | Depth of Cut \(d_c\) (mm) | velocity Ratio \(v^*\) | Structuring Ratio \(\gamma_s\) |
|---------------------------|-----------------------------|-----------------------------|--------------------------|------------------------|-----------------------------|
| 50.00                     | 78.56                       | 60.00                       | 0.0200                   | 0.091                  | 0.30 0.40 0.60 0.70         |

the inflection point of the sidewall width curve, the ground width reaches the maximum allowable value. In contrast, the bearing width is removed completely, and both curves are turned to a horizontal line (blue curve and cyan curve). Also, the structuring ratio does not influence the structures’ pitch \(P\) (gray curve). See Fig. 14b.

Figure 14c and d show that before the inflection of the bearing width curve, both the sidewall angle \(\zeta\) and structure height \(h\) have constant values and are not affected by the growing structuring ratio (purple curve and magenta curve). After that, the sidewall angle grows while the structure’s height falls by increasing the structuring ratio. On the other side, the structuring ratio does not affect the structures’ slope angle (green curve). Figure 14 shows structured wheels and structured surfaces with 2D profiles at increasing structuring ratio and the working parameters recorded in Table 5. Table 6 includes geometries of structured surfaces shown in Fig. 15.

Therefore, increasing the structuring ratio \(\gamma_s\) does not affect the separating distance between surface structures. Instead, as shown in Fig. 16a, it raises the percent of the remaining cutting portion of the circular pitch \(P_c\) (Eq. (4)), resulting in increasing the ground width and decreasing the bearing width (Fig. 16b). While the surface retains its nominal dimensions throughout grinding the structures, the resultant sidewall width and height of structures are maximum; the sidewall angle is minimum, and the ground width increases by a growing flooring width.

![Sketch for the variations in the geometry of surface structures by changing the circular pitch, (a) cycloids of grinding paths at increasing circular pitch, changes in (b) the bearing width, (c) the structure height at the increasing wheel radius](image)

Table 4 Values of the geometrical parameters of surface structures obtained at the different circular pitches

| Circular Pitch \(P_c\) (m m) | No. of Grooves \(N\) | Straight Width \(l_f\) (m m) | Sidewall Width \(l_{sw}\) (m m) | Ground Width \(l_w\) (m m) | Bearing Width \(l_b\) (m m) |
|-----------------------------|------------------|------------------------|------------------------|------------------------|------------------------|
| 31.42                       | 10               | 0.99                   | 0.935                  | 2.86                   | 0                      |
| 39.27                       | 8                | 1.25                   | 1.16                   | 3.57                   | 0                      |
| 52.36                       | 6                | 1.67                   | 1.54                   | 4.75                   | 0.01                   |
| 78.54                       | 4                | 2.50                   | 1.54                   | 5.58                   | 1.56                   |

Table 5 The geometrical and processing parameters used at the different structuring ratios

| Wheel Radius \(R_g\) (mm) | Circular Pitch \(P_c\) (m m) | Grooves Angle \(\psi\) (deg) | Depth of Cut \(d_c\) (mm) | velocity Ratio \(v^*\) | Structuring Ratio \(\gamma_s\) |
|---------------------------|-----------------------------|-----------------------------|--------------------------|------------------------|-----------------------------|
| 50.00                     | 78.56                       | 60.00                       | 0.0200                   | 0.091                  | 0.30 0.40 0.60 0.70         |
Fig. 14 The effects of changing the structuring ratio on the components of surface structures geometry: the effects on (a) the sidewall and flooring widths, (b) the ground & bearing widths and the pitch, (c) the sidewall and slope angles, and (d) the height (dimensions in mm & angles in deg)

Table 6 Values of the geometrical parameters of surface structures obtained at the different structuring ratios

| Structuring Ratio $\gamma_s$ | Straight Width $l_f$ (m m) | Sidewall Width $l_{sw}$ (m m) | Ground Width $l_g$ (m m) | Bearing Width $l_b$ (m m) |
|-------------------------------|-----------------------------|-------------------------------|--------------------------|--------------------------|
| 0.30                          | 2.14                        | 1.57                          | 5.28                     | 1.86                     |
| 0.40                          | 2.86                        | 1.57                          | 5.94                     | 1.14                     |
| 0.60                          | 4.28                        | 1.43                          | 7.14                     | 0                        |
| 0.70                          | 4.99                        | 1.075                         | 7.14                     | 0                        |

| Structuring Ratio $\gamma_s$ | Pitch $P$ (m m) | Structure Height $h$ (m m) | Sidewall Angle $\zeta$ (deg) | Slope Angle $\theta$ (deg) |
|-------------------------------|-----------------|-----------------------------|-------------------------------|---------------------------|
| 0.30                          | 7.14            | 0.0200                      | 89.26                         | 8.95                      |
| 0.40                          | 7.14            | 0.0200                      | 89.26                         | 8.95                      |
| 0.60                          | 7.14            | 0.0171                      | 89.31                         | 8.95                      |
| 0.70                          | 7.14            | 0.0096                      | 89.49                         | 8.95                      |
When the machined surface is removed, the bearing width completely disappears, and a decreasing sidewall width meets the increase in the flooring width at the same rate keeping the structures pitch constant. Also, the wall-sides of structures are sheared by the increasing structuring ratio leading to decreasing structures height and increasing sidewall angles of surface structures (Fig. 16c). On the other side, the structures slope angle is not affected by the structuring ratio.

Fig. 15 The structured wheels and structured surfaces at different structuring ratios (dimensions in mm)
4 Experimental work

In this section, the experiments were performed to machine surface structures by grinding. In Table 7, three different designs for D15 resin-bond fine-grained diamond wheel were involved. These wheels were adapted for working at the same grinding processing parameters. The response of the structured surfaces to the change in wheel geometries was studied, including the trending behavior with changing wheel geometric variables and the deviation between the predicted and experimental values of the structure geometries.

The three wheels were reshaped using a laser machining system unit based on our previous work. Figure 17 shows the laser machining unit and schematic of the laser structuring operation of the grinding wheels. A detailed explanation of the laser structuring process can be found in [29].

The grinding experiments for structuring were then performed on surfaces of Titanium specimens of the TC4 alloy using each wheel design.

After that, the experimental installation of the used platform was prepared as shown in Fig. 18. A designed fixture was installed on a multi-axis precision machine table and carried the electric rotating spindle. The structured wheel
was mounted on the spindle, which moves along the Z-axis to satisfy the grinding depth. The workpiece holder was fixed to the machine head and adjusted to move along the X-axis to feed the workpiece. The wheels were dynamically balanced using set screws upon starting the experiment, and the runouts were minimized. According to the designed structured wheels, effects of two-wheel geometrical parameters, i.e., the wheel radius and structuring ratio, were adapted for the current investigations.

Figure 19 shows the results of the grinding experiments performed under designed experiments in Table 7. The continuous curves represent the predicted values, whereas a single mark point describes the experimental values at the designed operating condition. Also, the expected and machined results for one wheel have been designated differently in the line type and mark-point from other wheels. Meanwhile, dot-line and triangle-mark for wheel I, centerline and circle-mark for wheel II, and straight-line and square-mark for wheel III have been used in Fig. 19a–f. The results of the wheels I and III, shown in Table 7, were used to investigate the effects of the wheel radius, whereas those of wheels II and III were used for the structuring ratio.

In Fig. 19c, it can be observed that the surface structures’ pitch is neither affected by the wheel radius nor the structuring ratio. Therefore, at the same grinding condition, pitch curves are matched for the simulation values (continuous lines), and experiments values, marked by points, were approximately attached to the simulation curves. In Fig. 19b, the flooring width increases by an increasing structuring ratio (wheels I and III) compared to that of smaller ratio (wheel II). However, the wheel radius does not affect the flooring width at a constant structuring ratio (wheels I and III), and hence simulation curves and experimental mark points are identical. Therefore, the sidewall width shows an inverse behavior to the flooring width because of the constant separating distances (pitch) for all wheels (Fig. 19a). This behavior agrees with what is explained in Sect. 3 (represented in Figs. 8 and 14) and Sect. 2 (modeled in Eqs. (10), (11), and (12)).

In Fig. 19d, the slope angle shows an identical response to that explained in Sects. 2 and 3. The wheel of the highest groove angle machines structures at the highest slope angle. Concerning the sidewall angle (Fig. 19e), the higher the wheel radius and/or structuring ratio, the higher the surface-wheel contact resulting in a higher surface shearing. So, the slope angle decreases at the larger radius and/or structuring ratio (wheel I and wheel III). Conversely, the smallest height (Fig. 19f) is for the wheel of a higher radius and/or structuring ratio due to the higher shearing operation that occurred at the machined surface (wheel I and wheel III).

Figure 20 represents the ground structured surfaces under the grinding condition numbered (1) in Table 7 for the designed wheels I, II, and III, respectively. The analogy in behaviors and the high degree of compatibility between the predicted and experimental results reflect the accuracy and reliability of the presented method for grinding structured surfaces using the grinding method by structured grinding wheels.

### Table 7: The operating parameters for the structured wheel and grinding process designed for the experimental investigation

| Experiment No. | Wheel I | Wheel II | Wheel III |
|----------------|--------|---------|-----------|
|                | $R_g$  | $P_c$   | $\gamma_s$ | $\psi$ | $R_g$  | $P_c$   | $\gamma_s$ | $\psi$ | $R_g$  | $P_c$   | $\gamma_s$ | $\psi$ |
| 1              | 15     | 39.27   | 0.41      | 70     | 25     | 78.56   | 0.31      | 70     | 25     | 78.56   | 0.41      | 80     |
| 2              | 15     | 39.27   | 0.41      | 70     | 25     | 78.56   | 0.31      | 70     | 25     | 78.56   | 0.41      | 80     |
| 3              | 15     | 39.27   | 0.41      | 70     | 25     | 78.56   | 0.31      | 70     | 25     | 78.56   | 0.41      | 80     |

| Experiment No. | Velocity ratio ($v_s$) | Depth of cut ($d_c$) $\mu$m |
|----------------|------------------------|-----------------------------|
| 1              | 0.00572                | 10                          |
| 2              | 0.00482                | 10                          |
| 3              | 0.00417                | 10                          |
Fig. 19 The predicted and experimental values for the geometrical parameters of the structured surfaces manufactured by the designed grinding operations (dimensions in mm & angles in deg)
Fig. 20  The simulation and experimental results of the structured surfaces using (a) wheel I, (b) wheel II, and (c) wheel III

(a) $v^*=0.00572$, $d_c=10 \mu m$

(b) $v^*=0.00572$, $d_c=10 \mu m$

(c) $v^*=0.00572$, $d_c=10 \mu m$
5 Conclusion

This study presented the effects of the designed structured wheel geometrical parameters on the structured surfaces’ geometries. The relationship between geometrical and processing parameters was formulated using a mathematical model. Two algorithms and simulation methods for expressing the structured wheel and structured surface at the designed grinding condition were developed. Several parameters affecting the operation were discussed. Finally, the following conclusions can be made:

1. The designed geometrical parameters of the structured wheel affect the geometry of structured surfaces at different rates.
2. The wheel radius and structuring ratio do not affect the separation distance between surface structures. Instead, they affect the percentage of the removed and remaining parts (ground width and bearing width) and the structure height.
3. The sidewall width and flooring width show an inverse behavior at increasing radius or structuring ratio to retain the constant separation distance between structures.
4. Increasing the circular pitch increases the separating distance between structures simultaneously by increasing either/both the bearing width and ground widths.
5. Wheel geometrical parameters, except the helical angle of the grooves, do not affect the surface structures’ slope angle. An increasing relationship was found between the helical angle of the grooves and the structure slope angle.

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Declarations

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate Informed consent was obtained from all individual participants included in the study.

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