ABSTRACT

This study aims at measuring the characteristic parameters of form grinding wheels used for microdrill fluting, whose wheel contours are specially made up of combinations of multiple curves. With the aid of the indirect duplication of wheel contours and by using computer vision, this paper presents a systematic process for the wheel contour measurement. The measuring process includes five sequential steps: the edge detection, the straight line detection, the contour separation, the circular arc fitting, and the circular arc angle evaluation. To test the proposed measuring process, a measuring apparatus was built, and experiments measuring the characteristic parameters of diamond grinding wheels used for microdrill fluting were conducted. It showed that the proposed measuring process was feasible to measure the characteristic parameters of certain form grinding wheels used for microdrill fluting.

Keywords: form grinding wheel; microdrill fluting; contour measurement; computer vision; image processing; circle-fitting approach.

MESURE DES PARAMÈTRES CARACTÉRISTIQUES DES MEULES UTILISÉES POUR LE CANNELAGE DES MICRO FORETS PAR VISION ARTIFICIELLE

RÉSUMÉ

Cette recherche a pour but de mesurer les paramètres caractéristiques des meules utilisées pour le cannelage des micro forets par vision artificielle, et dont les contours présentent une combinaison de plusieurs courbures. À l’aide de la duplication indirecte des contours de la meule, et de la vision artificielle, cet article présente un procédé systématique pour les mesures du contour de la meule. Le procédé utilisé comporte cinq étapes séquentielles: la détection des contours, la détection en ligne droite, la séparation des contours, le cercle d’ajustement des courbes et l’évaluation de l’angle de cercle. Pour tester le procédé proposé, un appareil de mesure a été conçu et des expériences de mesure des paramètres caractéristiques de la meule diamantée utilisée pour le cannelage des micro forets ont été menées. Elles ont démontré que le procédé était utilisable pour mesurer les paramètres caractéristiques de certaines meules utilisées pour le cannelage des micro forets.

Mots-clés: meule de forme; cannelage des micro forets; mesure des contours; vision artificielle; traitement de l’image; cercle d’ajustement des courbes.
1 INTRODUCTION

Microdrills are precision microtools frequently used by the electric and semiconductor industries to machine microholes in printed circuit boards (PCBs). Nowadays, most microdrill products are of nominal diameters ranging between 0.05 and 0.45 mm [1,2]. In microdrill manufacture, the fluting process, a special type of form grinding process, must be performed to machine helical flutes in microdrills. The helical flutes are necessary to provide space for chip removal in drilling operations. Figure 1 shows the schematic diagram of the fluting process, in which the drill body (a cylindrical workpiece) of a microdrill is ground by a form grinding wheel with specially designed wheel contour. To form helical flutes in the drill body, a relative screw motion between the microdrill and the form grinding wheel is prescribed. To this end, both the microdrill and the form grinding wheel rotate around their axes with a relative translation along the axis of the microdrill being generated. Based on such a relative screw motion, some precision machines have been designed exclusively for microdrill fluting. The mathematical modeling and sensitivity analysis of the fluting process for microdrills have been investigated by Kang [3], which can be helpful to the theoretical contour design of the form grinding wheel and the parameter setting of fluting machines. The wheel contour accuracy of the form grinding wheel will strongly influence the geometric correctness of ground helical flutes in microdrills. Thus, the wheel contour must be regularly dressed and then accurately measured in order to ensure quality of microdrill production. Using a coordinate measuring machine (CMM) or an optical comparator to measure the wheel contour accuracy of grinding wheels are traditional methods. However, because the grinding wheel contours used for microdrill fluting are tiny and usually with non-regular geometry, it is difficult to measure their wheel contour accuracy through the use of the traditional measuring methods. Therefore, alternative means for dealing with the measuring task must be developed.

In recent years, using computer vision to measure or monitor the grinding wheel has been studied by several researchers [4–9]. Sodhi and Tiliouine [4] utilize a charged couple device (CCD) camera to acquire digital images of the speckle patterns caused by impinging a laser beam on a ground surface, the surface roughness and the condition of the grinding wheel are then evaluated through the information on the acquired images. Fan et al. [5] develop an on-line...
non-contact system to measure the wear of a form grinding wheel by directly capturing digital images of the grinding wheel edge with the use of a CCD camera. Lachance et al. [6] as well as Feng and Chen [7] use CCD cameras to directly capture digital images of the grinding wheel surface and then evaluate the surface condition of grinding wheels. Su and Tarng [8] propose an indirect method of measuring the wear of form grinding wheels with the use of computer vision. Their method involves using a thin plate specimen ground to yield a two-dimensional contour in order to duplicate the three-dimensional topography of the form grinding wheel, as shown in Fig. 2. A CCD camera is then used to capture digital images of the ground contour of the specimen for indirectly evaluating the wear of the wheel contour. Chen et al. [9], following the concept of the indirect duplication of wheel contours [8], develop a contour matching method to examine the contour accuracy of grinding wheels. The contour matching method is based on calculating the relative deviations between the theoretical and inspected wheel contours with the use of some optimization methods. The above studies show that computer vision technology should be increasingly important in the applications of grinding wheel measurement and monitoring.

Based on computer vision technology, this study aims at measuring the characteristic parameters of form grinding wheels used for microdrill fluting, whose wheel contours are specially made up of combinations of multiple curves. In this paper, the means of the indirect duplication of wheel contours [8,9], as shown in Fig. 2, is equally applied to yield a two-dimensional contour representing the form grinding wheel. Based on the captured computer image of the yielded two-dimensional contour, a systematic process for the wheel contour measurement is then developed with the use of image processing algorithms. To test the feasibility of the proposed measuring process, a measuring apparatus was built, and experiments measuring the characteristic parameters of form grinding wheels used for machining helical flutes in microdrills were conducted.

2 THEORETICAL CONTOUR OF THE FORM GRINDING WHEEL

In this study, a systematic measuring process is to be developed for inspecting form grinding wheels used for machining helical flutes in some microdrill products. In order to measure the
characteristic parameters of the form grinding wheel, its theoretical contour must be defined first. The diagram of the theoretical wheel contour is shown in Fig. 3(a), in which the wheel size is controlled by the wheel radius $R$ and the wheel width $W$. The theoretical wheel contour is made up of two circular arcs with different radii (arcs $P_2P_3$ and $P_4P_5$ centered at points $O_1$ and $O_2$, respectively) and two straight lines respectively tangent to the end points of the two circular arcs ($P_1P_2$ and $P_4P_3$). The theoretical wheel contour can be determined through four characteristic parameters $r_1$, $a_1$, $r_2$ and $a_2$, in which, $r_1$ and $a_1$ are the radius and angle of the left circular arc $P_2P_3$, respectively, and $r_2$ and $a_2$ are the radius and angle of the right circular arc $P_3P_4$, respectively. The four characteristic parameters $r_1$, $a_1$, $r_2$ and $a_2$ must be measured to examine the contour accuracy of the form grinding wheel.

In order to develop the characteristic parameters measuring process, some geometric relations of the theoretical wheel contour must be derived first. As shown in Fig. 3(b), the extension lines of $P_1P_2$ and $P_4P_5$ intersect at point $P_6$. Point $P_7$ is located at line $P_2P_6$ with line $P_3P_7$ being perpendicular to line $P_2P_6$, also, point $P_8$ is located at line $P_4P_6$ with line $P_3P_8$ being perpendicular to line $P_4P_6$. Thus, the correlations of $P_2P_7 = r_1(1 - \cos a_1)$, $P_4P_8 = r_2 \sin a_2$, $P_3P_8 = r_2(1 - \cos a_2)$, $\angle P_7P_3P_8 = x_1 + x_2$, and $\angle P_7P_6P_8 = 180^\circ - x_1 - x_2$, can be obtained analytically. From triangle $P_3P_7P_8$ and the cosine law,

$$P_7P_8 = \sqrt{(P_3P_7)^2 + (P_3P_8)^2 - 2(P_3P_7)(P_3P_8) \cos (x_1 + x_2)}$$

$$P_7P_8 = \sqrt{r_1^2(1 - \cos x_1)^2 + r_2^2(1 - \cos x_2)^2 - 2r_1r_2(1 - \cos x_1)(1 - \cos x_2) \cos (x_1 + x_2)}$$

From triangle $P_3P_5P_8$ and the sine law,

$$x_3 = \angle P_3P_7P_8 = \sin^{-1}\left[\frac{(P_3P_8) \sin (x_1 + x_2)}{P_7P_8}\right] = \sin^{-1}\left[\frac{r_2(1 - \cos x_2) \sin (x_1 + x_2)}{P_7P_8}\right]$$

$$x_4 = \angle P_3P_8P_7 = \sin^{-1}\left[\frac{(P_3P_7) \sin (x_1 + x_2)}{P_7P_8}\right] = \sin^{-1}\left[\frac{r_1(1 - \cos x_1) \sin (x_1 + x_2)}{P_7P_8}\right]$$

Fig. 3. Diagrams of the theoretical contour of the form grinding wheel: (a) the whole view and (b) the partial view.
Then, from triangle $P_6P_7P_8$ and the sine law,

$$P_6P_7 = \frac{(P_7P_8) \sin (90^\circ - \alpha_4)}{\sin (180^\circ - \alpha_1 - \alpha_2)} = (P_7P_8) \cos \alpha_4 \csc (\alpha_1 + \alpha_2)$$  \hspace{1cm} (4)

$$P_6P_8 = \frac{(P_7P_8) \sin (90^\circ - \alpha_3)}{\sin (180^\circ - \alpha_1 - \alpha_2)} = (P_7P_8) \cos \alpha_3 \csc (\alpha_1 + \alpha_2)$$  \hspace{1cm} (5)

Therefore,

$$P_2P_6 = P_2P_7 + P_6P_7 = r_1 \sin \alpha_1 + (P_7P_8) \cos \alpha_4 \csc (\alpha_1 + \alpha_2) $$  \hspace{1cm} (6)

$$P_4P_6 = P_4P_8 + P_6P_8 = r_2 \sin \alpha_2 + (P_7P_8) \cos \alpha_3 \csc (\alpha_1 + \alpha_2) $$  \hspace{1cm} (7)

Also, from right-angle triangle $P_3P_6P_7$,

$$P_3P_6 = \sqrt{(P_3P_7)^2 + (P_6P_7)^2} = \sqrt{r_1^2(1 - \cos \alpha_1)^2 + (P_7P_8)^2 \cos^2 \alpha_4 \csc^2 (\alpha_1 + \alpha_2)}$$  \hspace{1cm} (8)

$$\alpha_5 = \angle P_3P_6P_7 = \tan^{-1} \left( \frac{P_3P_7}{P_6P_7} \right) = \tan^{-1} \left( \frac{r_1(1 - \cos \alpha_1)}{(P_7P_8) \cos \alpha_4 \csc (\alpha_1 + \alpha_2)} \right)$$  \hspace{1cm} (9)

On the other hand, from right-angle triangle $P_3P_6P_8$,

$$P_3P_6 = \sqrt{(P_3P_8)^2 + (P_6P_8)^2} = \sqrt{r_2^2(1 - \cos \alpha_2)^2 + (P_7P_8)^2 \cos^2 \alpha_3 \csc^2 (\alpha_1 + \alpha_2)}$$  \hspace{1cm} (10)

$$\alpha_6 = \angle P_3P_6P_8 = \tan^{-1} \left( \frac{P_3P_8}{P_6P_8} \right) = \tan^{-1} \left( \frac{r_2(1 - \cos \alpha_2)}{(P_7P_8) \cos \alpha_3 \csc (\alpha_1 + \alpha_2)} \right)$$  \hspace{1cm} (11)

As shown in above equations, if the values of the four characteristic parameters $r_1$, $\alpha_1$, $r_2$ and $\alpha_2$ are given, the other geometric terms dependent on them can be determined correspondingly.

3 MEASURING APPARATUS SETUP

To identify the characteristic parameters of the form grinding wheel by indirectly measuring the two-dimensional contour of the specimen marked by the same wheel (as shown in Fig. 2), a measuring apparatus based on computer vision was built, the setup of which is shown in Fig. 4. A specially designed leadscrew linear stage, which was characterized by a movable carriage and a stationary carriage simultaneously constrained by the two straight rails of the linear stage, was adopted as the fundamental mechanism of the measuring apparatus. The stationary carriage was fixed to the two straight rails without being driven by the leadscrew. When the leadscrew was rotated manually, only the movable carriage could translate along the direction paralleling...
the straight rails. (The translating direction of the movable carriage is called the Z-direction of the measuring apparatus). An Imaging Source DMK41BUC02 complementary metal-oxide-semiconductor (CMOS) camera coupled with a Navitar 12X telecentric lens was mounted on a lens tube holder and a backlighting board was prepared as the light source for the vision system. The measured specimen, made of high-carbon steel, was placed on a vertical observation stage formed by a miniature X-Y table with a magnetic fixture that magnetizes the specimen. The lens tube holder was fixed to the movable carriage, while the backlighting board and the vertical observation stage were fixed to the stationary carriage. Through the translation of the movable carriage, focusing adjustment of the vision system could be performed. The CMOS camera was connected to a personal computer (not shown in the figure) using the universal serial bus (USB) port.

For the measurement, the specimen was placed between the backlighting board and the telecentric lens. In order to enhance the contrast of the vision system, red backlighting was chosen. The red light projecting on the back of the specimen created a silhouette in front of the telecentric lens, which was sensed and captured by the CMOS camera, then stored by the personal computer as a digital image. The captured digital image consisted of a $1280 \times 1024$ array of pixels of grayscale intensity values ranging from 0 to 255. By applying the spatial calibration method that had been used by Chen et al. [9], the conversion factor of the captured digital image corresponding to its real world dimension was found to be 0.756 μm/pixel. Also,
by employing the subpixel localization algorithm [9–11], the built computer vision system could achieve an estimated resolution of 1/25 of a pixel [10], that is, 0.0302 μm.

4 THE CHARACTERISTIC PARAMETERS MEASURING PROCESS

After the digital image of the ground contour of the thin plate specimen was captured, image processing algorithms were used in order to measure the characteristic parameters of the ground contour. To this end, a characteristic parameters measuring process was developed and is introduced here. As referred to in Fig. 5, once a digital image has been captured and read, the sequential image processing procedure described below is executed.

**Step 1. Edge detection [8–12], which aims to detect the edge coordinates of the inspected contour by evaluating significant discontinuities in pixel intensity that characterize the boundaries of an object in a digital image.**

As shown in Fig. 5(a), by assigning a rectangular region of interest (ROI), called ROI 1, and appropriately covering the ground contour in the digital image, edge points are then detected by applying the edge detection method introduced by Chen et al. [9]. Their method combines the one-dimensional grayscale profile scanning [10–12] with an improved thresholding process and the subpixel localization algorithm [10,11]. In the figure, vertical search lines with equal horizontal intervals are generated within ROI 1 to detect coordinates of edge points passed by their corresponding search lines. Figure 5(b) shows the detected edge points $E_i$ located at the inspected contour, in which the highest edge point is labeled as $E_h$.

**Step 2. Straight line detection, which aims to detect the two straight-line portions of the inspected contour by using the linear least-squares approach [13].**

As shown in Figs. 5(b) and 5(c), after coordinates of detected edge points are obtained, two rectangular ROIs, called ROI 2 and ROI 3, are assigned to appropriately include the edge points located at the left and right portions of the inspected contour, respectively. The boundaries of ROI 2 and ROI 3 are defined according to the location of point $E_h$. As referred to in Figs. 3 and 5(b), the location of point $E_h$ relative to the inspected contour should be close to that of point $P_3$, the highest point, relative to the theoretical contour. Thus, considering that ROI 2 and ROI 3 cannot cover the circular-arc portions, the vertical distances from the upper boundaries of ROI 2 and ROI 3 to point $E_h$ must be larger than the amounts of $\lambda r_1 \sin\left(\frac{x_1}{2}\right) \sqrt{2(1 - \cos x_1)}$ and $\lambda r_2 \sin\left(\frac{x_2}{2}\right) \sqrt{2(1 - \cos x_2)}$, respectively. [In which, the terms $\lambda r_1 \sin\left(\frac{x_1}{2}\right) \sqrt{2(1 - \cos x_1)}$ and $\lambda r_2 \sin\left(\frac{x_2}{2}\right) \sqrt{2(1 - \cos x_2)}$ mean that the vertical components of $P_2P_3$ and $P_4P_3$ are multiplied by a conservative coefficient $\lambda$. For this case, $\lambda = 1.2$ is given.] Also, the vertical distances between the upper and lower boundaries of ROI 2 and ROI 3 must be close to $r_1 \cos x_1$ and $[r_1 - r_2(1 - \cos x_2)]$, respectively. (In which, the terms $r_1 \cos x_1$ and $[r_1 - r_2(1 - \cos x_2)]$ are the vertical components of $P_3P_5$ and $P_4P_5$, respectively.) The left and right boundaries of ROI 2 and ROI 3 are then defined according to the extreme horizontal positions of the edge points ranging between the defined upper and lower boundaries. After extracting the edge points within ROI 2 and ROI 3, two fitted straight lines, $l_L$ and $l_R$, are then obtained by using the linear least-squares approach. That is, for each fitted straight line represented as an explicit form of $y = ax + b$, its slope $a$ and intercept $b$ are calculated by [13]...
Fig. 5. An illustrative example of the sequential procedure for measuring the characteristic parameters of an inspected form grinding wheel.

\[
a = \frac{n \sum_{i=1}^{n} x_{E_i} y_{E_i} - \left( \sum_{i=1}^{n} x_{E_i} \sum_{i=1}^{n} y_{E_i} \right)}{n \sum_{i=1}^{n} x_{E_i}^2 - \left( \sum_{i=1}^{n} x_{E_i} \right)^2}
\]
Step 3. Contour separation, which aims to separate the two circular-arc portions and the two straight-line portions from the inspected contour by applying the concept of the region of uncertainty (ROU).

For the theoretical contour shown in Fig. 3, the two circular-arc portions and the two straight-line portions are separated by the locations of points $P_2$, $P_3$ and $P_4$, respectively. Likewise, for the inspected contour, locations of approximate points $\tilde{P}_2$, $\tilde{P}_3$ and $\tilde{P}_4$ shown in Fig. 5(d) can be found in order to aid the contour separation. As shown in Fig. 5(c), the two fitted straight lines, $l_L$ and $l_R$, intersect at point $P_6$. The location of point $P_6$ relative to the inspected contour should be close to that of point $\tilde{P}_6$ relative to the theoretical contour. When the coordinate of point $\tilde{P}_6$ is determined, the position of point $\tilde{P}_2$ is calculated by finding a point on line $l_L$ that satisfies the correlation of $P_2P_6 = P_2\tilde{P}_6$, where $P_2P_6$ can be calculated by using Eq. (6) with the values of the theoretical characteristic parameters $r_1$, $x_1$, $r_2$ and $x_2$ being given. Also, the position of point $\tilde{P}_4$ is calculated by finding a point on line $l_R$ that satisfies the correlation of $P_4P_6 = P_4\tilde{P}_6$, where $P_4P_6$ can be calculated by using Eq. (7). Then, by using Eq. (9) and the information on line $l_L$ and point $\tilde{P}_6$, an auxiliary line passing through point $\tilde{P}_6$ and forming an included angle of $z_5$ with line $l_L$ can be determined; similarly, by using Eq. (11) and the information on line $l_R$ and point $\tilde{P}_6$, another auxiliary line passing through point $\tilde{P}_6$ and forming an included angle of $z_6$ with line $l_R$ can be determined. On each auxiliary line, an auxiliary point with a relative distance of $P_3P_6$ to point $\tilde{P}_6$ can be found by using Eq. (8) or Eq. (10). The position of point $P_3$ is thus obtained by averaging the coordinates of the two auxiliary points. However, since there must be slight deviations between the inspected and theoretical contours, points $\tilde{P}_2$, $\tilde{P}_3$ and $\tilde{P}_4$ cannot be regarded as exact contour separation points for the inspected contour. The exact contour separation points should be closed to points $P_2$, $P_3$ and $P_4$ but with uncertainty. Therefore, the concept of region of uncertainty (ROU) can be applied to perform the contour separation. As shown in Fig. 5(d), by assigning three ROUs, ROU 1, ROU 2 and ROU 3, centered at points $\tilde{P}_2$, $\tilde{P}_3$ and $\tilde{P}_4$, respectively, edge points within the ROUs are regarded as contour separation points. The remaining edge points are then separated into the two circular-arc portions and the two straight-line portions. In this case, a ROU is simply defined by assigning the left and right horizontal distances from a calculated approximate point.

Step 4. Circular arc fitting, which aims to measure the radii of the two circular arcs of the inspected contour by applying the so-called circle-fitting approaches (CFAs) with the information on the detected edge points belonging to the two circular-arc portions.

This step is considered a critical task of the measuring process. Both the circle-fitting approaches (CFAs) based on least-squares (LS) [5,8] and genetic algorithm (GA) [14–18] are adopted in this study in order to evaluate their adaptability for the measurement. Both approaches are briefly described below.
**Least-squares circle-fitting approach (LSCFA):**

Considering a group of detected edge points $E_i$ (for $i=1, 2, \ldots, n$) belonging to a circular-arc portion, by applying the linear least-squares approach for circle fitting [5,8], three coefficients $C_1$, $C_2$ and $C_3$ of the equation of the fitted circle can be solved by

$$
\begin{bmatrix}
  C_1 \\
  C_2 \\
  C_3
\end{bmatrix} = 
\begin{bmatrix}
  \sum_{i=1}^{n} x_{E_i}^2 & \sum_{i=1}^{n} x_{E_i}y_{E_i} & \sum_{i=1}^{n} x_{E_i} \\
  \sum_{i=1}^{n} x_{E_i}y_{E_i} & \sum_{i=1}^{n} y_{E_i}^2 & \sum_{i=1}^{n} y_{E_i} \\
  \sum_{i=1}^{n} x_{E_i} & \sum_{i=1}^{n} y_{E_i} & n
\end{bmatrix}^{-1}
\begin{bmatrix}
  -\sum_{i=1}^{n} x_{E_i}(x_{E_i}^2 + y_{E_i}^2) \\
  -\sum_{i=1}^{n} y_{E_i}(x_{E_i}^2 + y_{E_i}^2) \\
  -\sum_{i=1}^{n} (x_{E_i}^2 + y_{E_i}^2)
\end{bmatrix}
$$

(14)

Then, the radius of the fitted circle, $\tilde{r}$, can be calculated by

$$
\tilde{r} = \sqrt{C_1^2 + C_2^2 - 4C_3}
$$

and the coordinate of the circular center, $\tilde{O}$, can be calculated by

$$
\begin{bmatrix}
  x_{\tilde{O}} \\
  y_{\tilde{O}}
\end{bmatrix} = 
\begin{bmatrix}
  -C_1/2 \\
  -C_2/2
\end{bmatrix}
$$

(15)

(16)

**Genetic algorithm circle-fitting approach (GACFA):**

Considering a group of detected edge points $E_i$ (for $i=1, 2, \ldots, n$) belonging to a circular-arc portion, by randomly choosing three edge points $E_j$, $E_k$ and $E_l$ in them, a candidate circle passing through the three edge points can be determined [18]. The coordinate of the circular center, $\tilde{O}$, can be calculated by

$$
\begin{bmatrix}
  x_{\tilde{O}} \\
  y_{\tilde{O}}
\end{bmatrix} = 
\begin{bmatrix}
  (x_{E_k}^2 + y_{E_k}^2 - x_{E_l}^2 - y_{E_l}^2)(y_{E_l} - y_{E_j}) - (x_{E_l}^2 + y_{E_l}^2 - x_{E_j}^2 - y_{E_j})(y_{E_k} - y_{E_j}) \\
  2[(x_{E_k} - x_{E_l})(y_{E_j} - y_{E_j}) - (x_{E_l} - x_{E_j})(y_{E_k} - y_{E_j})]
\end{bmatrix}
\begin{bmatrix}
  (x_{E_k}^2 + y_{E_k}^2 - x_{E_l}^2 - y_{E_l}^2)(x_{E_l} - x_{E_j}) - (x_{E_l}^2 + y_{E_l}^2 - x_{E_j}^2 - y_{E_j})(x_{E_k} - x_{E_j}) \\
  2[(x_{E_k} - x_{E_l})(y_{E_j} - y_{E_j}) - (x_{E_l} - x_{E_j})(y_{E_k} - y_{E_j})]
\end{bmatrix}
$$

(17)

Then, the radius of the candidate circle, $\tilde{r}$, can be calculated by

$$
\tilde{r} = \sqrt{(x_{E_k} - x_{\tilde{O}})^2 + (y_{E_k} - y_{\tilde{O}})^2}
$$

(18)

A transformation operation $T$ between the three indices of the randomly chosen points, $(j, k, l)$, and the determined candidate circle, $(x_{\tilde{O}}, y_{\tilde{O}}, \tilde{r})$, can be represented by
\[(x_\theta, y_\theta, \tilde{r}) = T(j, k, l)\]  \hspace{1cm} (19)

For the use of GA, the three indices of the randomly chosen edge points, \((j, k, l)\), are considered the design variables and encoded to binary strings as genes of a chromosome. For the circle-fitting approach, a fitness function to be minimized can be defined by

\[
F(x_\theta, y_\theta, \tilde{r}) = F(T(j, k, l)) = \sum_{i=1}^{n} \sqrt{(x_{Ei} - x_\theta)^2 + (y_{Ei} - y_\theta)^2 - \tilde{r}}\]  \hspace{1cm} (20)

which means to minimize the sum of absolute radial deviations between the determined candidate circle and all detected edge points \(E_i\). For the evolution process, each chromosome is 21 bits in length and the population size is 10. The reproduction operator used is the tournament selection. The crossover operator used is the one-cut-point method with a crossover probability of 0.9. The mutation operator used is the one-bit inversion with a mutation probability of 0.9. For each generation (iteration), the old population is totally replaced by the new mated one. The stopping criteria is when the number of generations being larger than 10000. After performing above GA-based optimization, the best-fit circle with the use of three detected edge points can be found.

As shown in Fig. 5(e), through using the LSCFA or the GACFA, two fitted circular arcs (FCAs), FCA 1 and FCA 2, can be determined, and their radii, \(\tilde{r}_1\) and \(\tilde{r}_2\), and circular centers, \(\tilde{O}_1\) and \(\tilde{O}_2\), can also be obtained. The evaluated radii, \(\tilde{r}_1\) and \(\tilde{r}_2\), are regarded as the measured circular arc radii of the inspected contour.

**Step 5. Circular arc angle evaluation, which aims to measure the angles of the two circular arcs of the inspected contour by using the information on the two FCAs.**

After FCA 1 and FCA 2 are determined in Step 4, the information on their circular centers, \(\tilde{O}_1\) and \(\tilde{O}_2\), are adopted to evaluate their circular arc angles. As shown in Fig. 5(f), by finding a line \(l_O\) passing through points \(\tilde{O}_1\) and \(\tilde{O}_2\), the left circular arc angle \(\tilde{\alpha}_1\) can be determined by calculating the subtending angle between lines \(l_O\) and \(m_L\), where line \(m_L\) is perpendicular to line \(l_L\) and passes through point \(\tilde{O}_1\). Similarly, the right circular arc angle \(\tilde{\alpha}_2\) can be determined by calculating the subtending angle between lines \(l_O\) and \(m_R\), where line \(m_R\) is perpendicular to line \(l_R\) and passes through point \(\tilde{O}_2\). The evaluated angles, \(\tilde{\alpha}_1\) and \(\tilde{\alpha}_2\), are regarded as the measured circular arc angles of the inspected contour.

5 EXPERIMENTAL RESULTS AND DISCUSSION

Experiments in which the characteristic parameters of form grinding wheels were measured were conducted in order to test the feasibility and effectiveness of the proposed measuring process.

In this study, diamond grinding wheels used for machining helical flutes in some Topoint microdrill test products were measured. The information on the form grinding wheels used for the experiments is listed in Table 1, in which, Case I refers to the grinding wheel used for machining microdrills with nominal diameters of 0.25 mm, and Case II refers to that used for machining microdrills with nominal diameters of 0.35 mm. As shown in Table 1, tolerances of the circular arc radii are \(\pm 3\%\) of their nominal values, and those of the circular arc angles are...
2% of their nominal values. For each case, a thin plate specimen was ground by an inspected grinding wheel to yield a two-dimensional contour for duplicating the topographical profile of the same grinding wheel.

For the measurement, each specimen was placed on the vertical observation stage and its digital image captured once, then immediately removed from the magnetic fixture. This operation was repeated twelve times, during which the position of the specimen in the camera scene was adjusted by moving the miniature X-Y table. The measuring process illustrated in Section 4 was then applied to measure the characteristic parameters of the inspected grinding wheels. For each case, the ROU was assigned to be 0, 3, 6 and 9 mm, respectively, with the LSCFA and GACFA being adopted for comparison purpose. The experimental results and a discussion are presented in the following sub-sections.

5.1 Results of Case I

Figure 6(a) shows one of the twelve captured images of the specimen, and its detected edge contour and FCAs with the use of the LSCFA and the assignment of ROU= ± 3 μm are shown in Fig. 6(b). For the FCA 1 and FCA 2, their circular centers, O₁ and O₂, located at (x₁, y₁) = (519.14, 295.69) μm and (x₂, y₂) = (509.29, 383.70) μm, respectively. The measured circular arc radii were ₁ = 158.474 μm and ₂ = 69.294 μm, and the measured circular arc angles were ₁ = 49.0° ± 1.0° and ₂ = 61.5° ± 1.2°. The evaluated results (mean values with ranges of uncertainties) for this case are listed in Table 2 in which, ₁, rms and ₂, rms represent the root-mean-square deviations of the measured radii and can be calculated by

\[
\varepsilon_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{n} \left( (x_{E_i} - x_{O_i})^2 + (y_{E_i} - y_{O_i})^2 - r_i \right)^2}{n}}
\]

Table 1. Information on the grinding wheels used for the experiments.

<table>
<thead>
<tr>
<th>Specification of the grinding wheels</th>
<th>Wheel type</th>
<th>SD1000P150M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive type</td>
<td>Synthesized diamond</td>
<td></td>
</tr>
<tr>
<td>Grade</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Bond type</td>
<td>Metal</td>
<td></td>
</tr>
<tr>
<td>Averaged grain size</td>
<td>15 μm</td>
<td></td>
</tr>
<tr>
<td>Wheel radius R</td>
<td>100 mm</td>
<td></td>
</tr>
<tr>
<td>Wheel width W</td>
<td>6 mm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristic parameters of the theoretical wheel contours</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left circular arc radius r₁</td>
<td>160.0 ± 4.8 μm</td>
<td>270.0 ± 8.1 μm</td>
</tr>
<tr>
<td>Left circular arc angle α₁</td>
<td>49.0° ± 1.0°</td>
<td>51.5° ± 1.0°</td>
</tr>
<tr>
<td>Right circular arc radius r₂</td>
<td>69.5 ± 2.1 μm</td>
<td>69.5 ± 2.1 μm</td>
</tr>
<tr>
<td>Right circular arc angle α₂</td>
<td>61.5° ± 1.2°</td>
<td>59.5° ± 1.2°</td>
</tr>
</tbody>
</table>

As seen from Table 2, the mean values of the measured parameters with the assignment of ROU $= \pm 3 \, \mu m$ all lay within their specified tolerance bands, although the relative difference between the mean measured values of $\bar{r}_1$ by using the two CFAs was about $1.3 \, \mu m$. For the LSCFA, by using the three-standard-deviation-band approach, the maximum uncertainties fell within the ranges of $\pm 0.957 \, \mu m$ and $\pm 0.389^\circ$ when the ROU was assigned to be $\pm 9 \, \mu m$. For the GACFA, the maximum uncertainties fell within the ranges of $\pm 3.328 \, \mu m$ and $\pm 0.927^\circ$ when the ROU was assigned to be $\pm 9 \, \mu m$. No matter how large the range of ROU being
and measured values of lay within their specified tolerance bands, however, the relative difference between the mean values and uncertainties of either related to the GACFA kept about 1.5 to 3 times those related to the LSCFA. Also, the mean values and uncertainties of either \(\varepsilon_{1,\text{rms}}\) or \(\varepsilon_{2,\text{rms}}\) were quite close to each other and had less significance on influencing the measurement of the circular arc radii.

Figure 7 shows the mean measured values of the four characteristic parameters with respect to assigned ROUs. As shown in Fig. 7(a), the mean measured radius \(\bar{r}_{1,\text{avg}}\) related to the LSCFA had a decreased trend with the increased ROU, while that related to the GACFA increased when ROU was larger than \(\pm 3\) \(\mu\)m. On the other hand, as shown in Fig. 7(b), the mean measured radius \(\bar{r}_{2,\text{avg}}\) related to both CFAs had quite similar trends and magnitudes. When ROU = \(\pm 9\) \(\mu\)m, the magnitudes of \(\bar{r}_{2,\text{avg}}\) were less than its lower bound (67.4 \(\mu\)m). Such a situation showed that the assignment of ROU = \(\pm 9\) \(\mu\)m was not appropriate for the measurement of the right circular arc of the inspected contour. In Figs. 7(c) and 7(d), the mean measured angles \(\bar{\alpha}_{1,\text{avg}}\) and \(\bar{\alpha}_{2,\text{avg}}\) related to the LSCFA had obvious variations, while those related to the GACFA had relatively stable trends. When ROU was larger than the range of \(\pm 6\) \(\mu\)m, the LSCFA could not provide sufficient adaptability for measuring the circular arc angles. That is, the GACFA was more reliable than the LSCFA for measuring the circular arc angles for this case.

### 5.2 Results of Case II

For this case, one of the twelve captured images of the specimen is shown in Fig. 8(a), and its detected edge contour and FCAs with the use of the LSCFA and the assignment of ROU = \(\pm 3\) \(\mu\)m are shown in Fig. 8(b). For the FCA 1 and FCA 2, their circular centers located at \((x_{D_1}, y_{D_1})=(545.61, 207.82)\) \(\mu\)m and \((x_{D_2}, y_{D_2})=(546.34, 406.57)\) \(\mu\)m, respectively. The measured circular arc radii were \(\bar{r}_1=267.976\) \(\mu\)m and \(\bar{r}_2=68.843\) \(\mu\)m, and the measured circular arc angles were \(\bar{\alpha}_1=51.609^\circ\) and \(\bar{\alpha}_2=59.148^\circ\). The evaluated results (mean values with ranges of uncertainties) for this case are listed in Table 3, as similar to those listed in Table 2. As shown in Table 3, the mean values of the measured parameters with the assignment of ROU = \(\pm 3\) \(\mu\)m all lay within their specified tolerance bands, however, the relative difference between the mean measured values of \(\bar{r}_2\) by using the two CFAs was about 2.6 \(\mu\)m. For the LSCFA, the maximum uncertainties fell within the ranges of \(\pm 1.227\) \(\mu\)m and \(\pm 0.166^\circ\) when the ROU was assigned to be \(\pm 9\) \(\mu\)m. For the GACFA, the maximum uncertainties fell within the ranges of \(\pm 1.994\) \(\mu\)m and \(\pm 0.410^\circ\) when the ROU was assigned to be \(\pm 9\) \(\mu\)m. For this case, most uncertainties related to the GACFA kept about 1.5 to 3 times those related to the LSCFA. Also, the mean values and uncertainties of either \(\varepsilon_{1,\text{rms}}\) or \(\varepsilon_{2,\text{rms}}\) related to both CFAs were quite close to each other and could be ignored.

<table>
<thead>
<tr>
<th>ROU ((\mu)m)</th>
<th>CFA</th>
<th>(\bar{r}_1) ((\mu)m)</th>
<th>(\bar{r}_2) ((\mu)m)</th>
<th>(\bar{\alpha}_1) (deg)</th>
<th>(\bar{\alpha}_2) (deg)</th>
<th>(\varepsilon_{1,\text{rms}}) ((\mu)m)</th>
<th>(\varepsilon_{2,\text{rms}}) ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pm 0)</td>
<td>LS 159.214</td>
<td>70.235</td>
<td>0.352</td>
<td>49.529</td>
<td>0.270</td>
<td>61.571</td>
<td>0.216</td>
</tr>
<tr>
<td>(\pm 3)</td>
<td>GA 159.605</td>
<td>70.950</td>
<td>1.165</td>
<td>49.384</td>
<td>0.821</td>
<td>61.716</td>
<td>0.818</td>
</tr>
<tr>
<td>(\pm 6)</td>
<td>LS 157.085</td>
<td>68.345</td>
<td>0.693</td>
<td>50.269</td>
<td>0.335</td>
<td>60.831</td>
<td>0.296</td>
</tr>
<tr>
<td>(\pm 9)</td>
<td>LS 156.368</td>
<td>65.820</td>
<td>0.812</td>
<td>50.985</td>
<td>0.389</td>
<td>60.116</td>
<td>0.348</td>
</tr>
</tbody>
</table>

Table 2. Evaluated results for Case I.
Fig. 9 shows the mean measured values of the four characteristic parameters with respect to assigned ROUs. As shown in Fig. 9(a), the mean measured radius $\bar{r}_{1,\text{avg}}$ related to both CFAs had similar trends in substance, while their maximum relative difference occurring at ROU = ±3 μm was about 1.3 μm. However, in Fig. 9(b), the mean measured radius $\bar{r}_{2,\text{avg}}$ related to both CFAs had quite different trends and magnitudes. The magnitudes of $\bar{r}_{2,\text{avg}}$ related to the GACFA were quite close to the upper bound (71.6 μm), while those related to the LSCFA appeared an obviously decreased trend with the increased ROU; their maximum relative difference occurring at ROU = ±9 μm was about 4.1 μm. In Figs. 9(c) and 9(d), the mean measured angles $\bar{\alpha}_{1,\text{avg}}$ and $\bar{\alpha}_{2,\text{avg}}$ related to the GACFA had obvious variations, while those related to the LSCFA had relatively stable trends. Such situations were contrary to those appeared in Case I.

5.3 Discussion

From the experimental results, it can be found that the assignment of the range of the ROU considerably influences the reasonability of the characteristic parameter measuring results. Assigning a larger range of the ROU leads to less edge points being considered in the circle.
fitting, and thus results in certain unreasonable measuring results. For the two cases, the assignment of $\text{ROU} = \pm 3\,\mu\text{m}$ should be most appropriate for the measurement. When the range of the assigned ROU was larger than $\pm 6\,\mu\text{m}$, some measuring results could be considered incorrect because of the elimination of some meaningful edge points for representing the circular-arc portions of the inspected contour. Also, no matter how large the range of ROU being assigned, most uncertainties related to the GACFA kept about 1.5 to 3.5 times those related to the LSCFA.

When the range of the assigned ROU was less than $\pm 6\,\mu\text{m}$, the maximum relative difference between the measured radii obtained by using the two CFAs was about $2.6\,\mu\text{m}$. That is, both the LSCFA and GACFA were feasible to the measurement of the circular arc radii provided that appropriate range of the ROU was assigned. In addition, for Case I, the use of the GACFA could result in relatively stable results for the measurement of the circular arc angles as compared with the use of the LSCFA. But, a contrary situation to a slighter extent appeared in

Fig. 8. Characteristic parameters measured result for Case II: (a) the captured digital image of the inspected specimen and (b) the detected edge and the fitted circular arcs.
Case II. In practice, the number of detected edge points belonging to the two circular-arc portions in Case I was less than that of Case II. Such a situation combining with the assignment of a larger range of the ROU might contribute to a worse adaptability of using the LSCFA for the measurement of the circular arc angles. However, the use of the GACFA involved much iterative computation and was therefore more time-consuming than the use of the LSCFA. In summary, with an appropriate range of the ROU being assigned, both the LSCFA and GACFA could achieve reasonable measuring results, but the use of the GACFA led to relatively lower efficiency as compared with the use of the LSCFA.

The feasibility and effectiveness of the proposed measuring process were verified through experiments. It must be emphasized that the presented measuring method was developed for inspecting form grinding wheels with specially designed contours used for microdrill fluting. It does not intend to replace traditional methods of usual wheel contour measurement, such as the use of a CMM or an optical comparator. Also, some commercially available vision systems could replace the built measuring apparatus, in case they can achieve sufficient resolution and measuring accuracy.

6 CONCLUSIONS

With the aid of the indirect duplication of wheel contours [8,9] and by using computer vision and image processing algorithms, a characteristic parameter measuring process for inspecting form grinding wheels with specially designed contours used for microdrill fluting has been introduced in this study. The measuring process includes five sequential steps, which are the edge detection, the straight line detection, the contour separation, the circular arc fitting, and the circular arc angle evaluation. For the step of contour separation, the concept of ROU has been applied. For the step of circular arc fitting, both the LSCFA and the GACFA has been adopted for comparison purpose. The proposed measuring process was tested by applying it to inspect diamond grinding wheels used for machining helical flutes in microdrills, and a measuring apparatus was built for the experiments. From the experimental results, the proposed measuring process had shown its feasibility and effectiveness for the measurement of the characteristic parameters. With an appropriate range of the ROU being assigned, both the LSCFA and GACFA could achieve reasonable measuring results, but the use of the GACFA led to relatively lower efficiency as compared with the use of the LSCFA. In conclusion, this study presents a feasible means for measuring the characteristic parameters of certain form grinding wheels used for microdrill fluting.

Table 3. Evaluated results for Case II.

<table>
<thead>
<tr>
<th>ROU</th>
<th>CFA</th>
<th>( \hat{r}_1 (\mu m) )</th>
<th>( \hat{r}_2 (\mu m) )</th>
<th>( \hat{\alpha}_1 (\text{deg}) )</th>
<th>( \hat{\alpha}_2 (\text{deg}) )</th>
<th>( \varepsilon_{1,\text{rms}} (\mu m) )</th>
<th>( \varepsilon_{2,\text{rms}} (\mu m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>267.975±0.493</td>
<td>69.899±0.431</td>
<td>51.550±0.093</td>
<td>59.190±0.098</td>
<td>0.323±0.011</td>
<td>0.287±0.017</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>268.743±1.312</td>
<td>71.242±0.492</td>
<td>51.258±0.174</td>
<td>59.482±0.147</td>
<td>0.328±0.014</td>
<td>0.303±0.016</td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>267.795±0.483</td>
<td>69.020±0.394</td>
<td>51.613±0.081</td>
<td>59.126±0.079</td>
<td>0.307±0.014</td>
<td>0.290±0.018</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>269.080±1.388</td>
<td>71.595±0.957</td>
<td>51.104±0.242</td>
<td>59.636±0.228</td>
<td>0.314±0.019</td>
<td>0.306±0.019</td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>268.436±0.535</td>
<td>68.615±0.553</td>
<td>51.509±0.097</td>
<td>59.231±0.092</td>
<td>0.299±0.015</td>
<td>0.292±0.019</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>269.262±1.479</td>
<td>71.677±1.003</td>
<td>51.010±0.275</td>
<td>59.729±0.266</td>
<td>0.306±0.022</td>
<td>0.313±0.018</td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>268.801±0.567</td>
<td>66.675±1.227</td>
<td>51.608±0.166</td>
<td>59.132±0.161</td>
<td>0.284±0.015</td>
<td>0.295±0.019</td>
<td></td>
</tr>
<tr>
<td>GA</td>
<td>269.518±1.536</td>
<td>70.807±1.994</td>
<td>51.018±0.410</td>
<td>59.722±0.399</td>
<td>0.289±0.015</td>
<td>0.317±0.024</td>
<td></td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

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REFERENCES