Ultra-precision machining by the cylindrical polishing process

Yaw-Terng Su a,∗, Tu-Chieh Hung b, Chun-Cheng Weng a

a Department of Mechanical Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan, ROC
b Department of Mechanical Engineering, Chinese Military Academy, Kaohsiung, Taiwan, ROC

Received 18 March 2003; accepted 20 May 2003

Abstract

A process planning method for removing an arbitrary and axially symmetric error profile by the cylindrical polishing process (abbreviated as the CPP process) is proposed in this study. This method is to plan the dwelling-time of the polishing tool so that the error profile can be accurately removed. The tool dwelling-time distribution is solved by a non-negative least square method. By using this method, the residual error between actual and desired removal depths may be induced. It is shown that the residual error is related to the width of the machining zone, the wavelength of the error profile, and the tool’s resolution. The computer simulations indicate that the residual error is always negligible when the wavelength of the error profile is larger than the width of the machining zone. If the wavelength of the error profile is large, a small size of the tool’s resolution is found effectively to reduce the residual error. The experimental study confirms that an arbitrary error profile can be accurately removed on the basis of the proposed method.

© 2003 Elsevier Ltd. All rights reserved.

Keywords: Hydrodynamic polishing process; Cylindrical polishing process; Form error compensation; Machining principle

1. Introduction

A machining method for compensating for an arbitrary and axially symmetric error profile by the cylindrical polishing process (abbreviated as the CCP process) is studied in this paper. The cylindrical polishing process, which has a tool with cylindrical shape, is a kind of floating process. A schematic diagram of the process is shown in Fig. 1. The proposed method is to plan a tool dwelling-time distribution so that an arbitrary error profile of a wafer can be accurately removed. Consider a work surface with a specific form error as shown in Fig. 2. The form precision of the work surface can be improved if the shaded part of the error profile in Fig. 1 is removed (compensated). In this study, the process of removing such an arbitrary form error profile is denoted as the form error compensation.

It was stated in the previous study [1] that there are three main advantages to implement the form error compensation task by a polishing process, as compared to diamond turning or precision grinding. First, a polishing process is naturally suitable to perform the form error compensation task for an error profile with small size due to the fact that a polishing process can be an atomic-size [2] machining process. Second, the machining performance of a polishing process is relatively insensitive...
Nomenclature

\[ m' (x',y') \] machining rate of the machining zone
\[ D(r) \] depth function of desired profile (or desired removal depth)
\[ t(\rho) \] tool dwelling-time distribution
\[ L \] range of tool locations
\[ \{T_j\} \] tool dwelling-time distribution at radius
\[ [C_{ij}] \] machining rate
\[ V(r) \] actual removal volume
\[ L_m \] width of the machining zone
\[ \lambda \] wavelength of sinusoidal profile
\[ \Delta \] tool’s resolution
\[ e_R \] residual error
\[ E_R \] residual error percentage

to the relative vibration between tool and work surface. This is because the variation of machining sizes due to vibrations is negligible. Hence, the final machined profile is only slightly related to the pattern of vibrations. Finally, the positioning precision requirement of a machine tool for a polishing process can be made much less than its achievable machining precision through the process of form error compensation. For a polishing process, the machined depth control in the normal direction of the work surface is not determined by the relative position control between the tool and work surface. It is decided by the product of machining rate and machining time. By accurate control of the machining rate and machining time, the high precision requirement of positioning becomes unnecessary. Hence, it is possible for a polishing process to obtain a machining precision higher than the positioning precision of the machine tool itself. Due to the above nature of the polishing process, the machining cost of error compensated for by a polishing process can then be drastically reduced.

To implement the form error compensation task, a polishing process should satisfy the following two premises. First, the randomness of polishing behaviors must be minimized as far as possible. In other words, the polishing behavior should be little affected if the operating condition of the polishing process is fixed. Second, the polishing process owns the capability to remove an arbitrary form error profile. One way to minimize the randomness of the polishing process is to enforce the abrasive particles (merged in the slurry) moved in a well-controlled environment. It can be done by properly adjusting the lubrication between the tool and the work surface in the non-contact or semi-contact condition \[3,4\] by the aid of a hydrodynamic effect. A major advantage of these conditions is to allow the slurry or the abrasive particles in the slurry to flow through the gap between the tool and work surface in a less random manner, because of the dominating shear stress field in the lubrication conjunction. This means that, under a given operating condition, the abrasive particles between tool and work surface will tend to sustain a specific load distribution and have a certain particle distribution in the statistic sense. Since the load and particle distributions are the dominant factors in deciding machining behaviors of a polishing process, a floating (non-contact or semi-contact condition) polishing process can have less random machining behavior. This less random tendency is a necessity to the form error compensation task. It will make the machining depth control simple to adjust the machining time. Hence, to remove an arbitrary error profile, it can be done by properly controlling the dwelling time of tool motion around the area to be machined if the machining rate is kept constant during the machining process. It was shown by Su et al. \[3,4\] that the hydrodynamic polishing process (abbreviated as the HDP process) has highly repeatable machining behaviors if the lubrication between tool and work was properly controlled. In addition, Su et al. \[1,5,6\] also proposed a process planning strategy for the HDP process to remove an arbitrary error profile through the design of the dwell-
ing-time distribution of the tool motion. It indicated [1,5,6] that the highly repeatable machining feature and the arbitrary profile removal capability makes the HDP process a suitable tool in implementing the task of form error compensation.

However, the previous study [7] revealed that the machining rate of the HDP process would not be maintained constant, if the tool was used for a certain period of time. The main cause of this time-varying machining behavior may come from the tool wear during the polishing process [7]. In a polishing process, the curvature and surface irregularities of the tool surface will be changed due to the occurrence of tool wear. From the lubrication theorem [8] and the machining mechanism of the HDP process [3,4], the machining rate of the HDP process is sensitive to the variation of the tool’s curvature. Thus, the machining rate will change due to the curvature variation of the tool surface. This implies that the tool wear has a significant effect on the machining rate in a polishing process. Hence, to obtain a highly repeatable machining behavior, the effect of tool wear must be considered.

There are two ways to achieve this goal. The first approach is to model the tool wear effect before machining and then compensate for the wear effect afterward. The major difficulty of this approach comes from the complex relationship between tool wear and machining behavior [7]. The second method is to reduce the sensitivity of the machining rate due to tool wear. It can be done by properly redesigning the shape of the tool. For a spherical tool in the HDP process, the variation of curvature in both the longitudinal and transverse directions are all critical to the change of machining rate. However, a cylindrical tool may maintain its curvature in the longitudinal direction constant and have its curvature in the transverse direction little changed in the wear process. The tool wear effect on the machining behaviors of a cylindrical tool can then be significantly reduced. Accordingly, from a highly repeatable machining rate point of view, a tool with cylindrical shape may be a better choice than one with spherical shape.

Several works have been published about the process design method to compensate for the form error. The extensive work done by Jones [9-13] proposed a computer-controlled optical surfacing (CCOS) method for the fabrication of aspheric optical surfaces. However, the effect of the tool size and the influence of the wavelength of work surface irregularities on the efficiency of error removal were unexplored. In recent years, Su et al. [1,5,6] proposed several machining strategies for the form error compensation by the HDP process. These studies indicated that the work precision can be improved from 2 to 0.1µm by a polishing machine with a positioning precision of 10 µm. However, as stated above, the compensation precision by the HDP process is vulnerable to the wear effect of the tool. Hence, the selection of a cylindrical tool for the form error compensation task becomes attractive.

In the following, the method to remove an arbitrary and axially symmetric error profile by the cylindrical polishing process is first discussed. The error analysis of the method is then investigated. Finally, several experiments are done to examine the validity of the proposed method.

2. A process planning method

A machining principle for a polishing process to removing an arbitrary error profile, as suggested in [1], is first discussed before the planning method is proposed. Consider a work surface with an arbitrary and axially symmetric error profile (as shown in Fig. 2), left by a previous machining method (such as diamond turning or precision grinding). Let the depth function of the arbitrary and axially symmetric error profile be denoted as \(D(r)\). The process planning is to design a dwelling-time distribution of the polishing tool around a corresponding area so that the error profile can be accurately removed (compensated). To do so, the following machining principle must be satisfied.

**Machining principle**: To remove an arbitrary error profile by a polishing process, the distribution of the total machining action sustained by each point of the work surface should be equal to the depth function of the error profile.

Here, the total machining action is defined as the multiplication of machining rate and machining time. The machining rate is volume-removing rate per unit area and has a unit of depth/time.

From the above principle, to remove an arbitrary error profile of the work surface, one can either properly control the machining rate or machining time distribution of the process. For a cylindrical polishing process, the machining action at a point will occur not only when the tool is at the location of this point. It is because the region (denoted as the machining zone), where machining action occurs, is not a mathematical line but has a finite area (Fig. 1). The machining zone has a shape and dimension close to that due to the Hertzian contact. The machining action will occur at a point as long as the location of this point is inside the region of the machining zone. Consequently, the total machining time sustained by a point at the work surface is not the tool dwelling time at that point. It should be the accumulation of tool dwelling time that the tool is at a location with this point inside its machining zone. If the size of the machining zone and its machining rate are kept constant during the machining process, the distribution of total machining action depends only on the tool dwelling-time...
distribution. Hence, the task to remove an arbitrary error profile becomes to plan a proper tool dwelling-time distribution. In addition, because of the axially symmetric feature of the error profile, the tool dwelling-time distribution is only a function of the radius of the work surface if the work rotates at a constant speed.

Assume the work surface will rotate along its symmetric axis with a fixed angular speed and the cylindrical tool can only move transversely along a line passing through the center of the work surface. For the convenience of analysis, let the machining zone have a rectangular shape with width \( L_m \) and a coordinate system \((x', y')\) be attached to the machining zone with its centroid \( o' \) as the origin (Fig. 3). The machining rate at the machining zone is assumed to be a fixed distribution \( m'(x', y') \). If the origin of the machining zone is located at a distance \( \rho \) from the center of the work surface, the machining zone will intersect with the infinitesimal region between \( r \) and \( r + \delta r \) at two spots with areas \( A_1 \) and \( A_2 \), respectively. Hence, the volume removal rate \( \delta V_\rho (r) \) at these two spots in radius \( r \), when the tool dwells at location \( \rho \), can be written as

\[
\delta V_\rho (r) = \int_{A_1} m'(x', y') \, dA_1 + \int_{A_2} m'(x', y') \, dA_2.
\]

From Fig. 3, the tool location that its machining zone will intersect with the infinitesimal area is not limited to \( \rho \). Let the range of tool location that its machining zone intersects with the infinitesimal area be denoted as \( L \). Hence, the actual removal volume \( V(r) \) at radius \( r \), when the tool dwells in the range \( L \), can be expressed as

\[
V(r) = \int_L t(\rho) \delta V_\rho (r) \, d\rho = \int_L t(\rho) \int_{A_1} m'(x', y') \, dA_1 \, d\rho + \int_L t(\rho) \int_{A_2} m'(x', y') \, dA_2 \, d\rho.
\]

where \( t(\rho) \) is the tool dwelling-time distribution. Because the error at radius \( r \) is \( D(r) \), the volume desired to be removed in the infinitesimal region around the radius \( r \) is \( 2\pi r \delta r D(r) \). If the actual removal volume is equal to the volume needed to be removed, the error at this radius is then eliminated. Thus, to remove this error, the following relationship should be satisfied.

\[
\int_L t(\rho) \int_{A_1} m'(x', y') \, dA_1 \, d\rho + \int_L t(\rho) \int_{A_2} m'(x', y') \, dA_2 \, d\rho = 2\pi r \delta r D(r)
\]

From Fig. 3, the geometric relationships between \((x', y')\) and \((r, \theta)\) with the tool located at \( \rho \) are

\[
x' = r \cos \theta - \rho
\]

and

\[
y' = r \sin \theta.
\]

By some manipulations,

\[
\int_{A_1} m'(x', y') \, dA_1 = \int_{\theta_1}^{\theta_2} m'(r, \theta, \rho) \delta r \, d\theta\]

and

\[
\int_{A_2} m'(x', y') \, dA_2 = \int_{\theta_3}^{\theta_4} m'(r, \theta, \rho) \delta r \, d\theta.
\]

where the limits \((\theta_1, \theta_2)\) and \((\theta_3, \theta_4)\) denote the angle range corresponding to the areas of \( A_1 \) and \( A_2 \), respectively, when examined in the polar coordinate. From Eqs. (3) and (5a, b),

\[
\left[ \int_{\theta_1}^{\theta_2} m'(r, \theta, \rho) \delta r \, d\theta \right] + \left[ \int_{\theta_3}^{\theta_4} m'(r, \theta, \rho) \delta r \, d\theta \right] = 2\pi r \delta r D(r)
\]

If the tool dwells only at certain discrete points in the range of \( L \), Eq. (6) can be rewritten as

\[
\sum_j T(\rho_j) \left[ \int_{\theta_1}^{\theta_2} m'(r, \theta, \rho) \, d\theta + \int_{\theta_3}^{\theta_4} m'(r, \theta, \rho) \, d\theta \right] = \sum_j T(\rho_j) \cdot C_j(r) = 2\pi D(r)
\]

Fig. 3. A polar coordinate system for the machining zone.
The constant $C_j$ and the dwell time $T_j$ of the tool at the $j$th location. By some manipulations, Eq. (8) can also be written in a single matrix form

$$\frac{1}{2\pi}\sum_{j} T_j C_j = D_j, \quad i = 1, 2, \ldots, m \quad \text{and} \quad j = 1, 2, \ldots, m$$

where the $r_i$ and $\rho_j$ denote the $i$th radius of work surface and the $j$th tool dwelling location, respectively. The constant $C_{ij}$ denotes the machining rate at the $i$th point of the work surface while the tool dwells at the $j$th tool location. By some manipulations, Eq. (8) can also be written in a single matrix form

$$\frac{1}{2\pi}[C_{ij}]_{m \times m'} [T_i]_m = [D_i]_m.$$  \hfill (9)

For the given machining rate $[C_{ij}]_{m \times m'}$ and the depth function of error profile $[D_i]_m$, a unique solution of tool dwelling-time distribution $[T_i]_m$ can be solved from the simultaneous solution of Eq. (9).

From the extensive computer simulations, the simultaneous solution of $[T_i]_m$ in Eq. (9) may not always be positive. That means the dwelling-time distribution in the range of tool locations may have a negative value (as shown in Fig. 4). It is not possible to control the tool with a negative dwelling time. Hence, to ensure the tool dwelling-time distribution is non-negative in the range of tool locations, the non-negative least square method is introduced. This method is to minimize the difference between the actual and desired removal depths at various radii under the constraint of non-negative time distribution. Accordingly, to find the $[T_i]_m$, the following criterion is adopted,

$$\min \left\{ \frac{1}{2\pi} [C_{ij}]_{m \times m'} [T_i]_m - [D_i]_m \right\}^2 \quad \text{with} \quad [T_i]_m \geq \delta$$  \hfill (A)

where $\delta$ is a positive small value. The selection of $\delta$ can be more or less arbitrary. The only issue of concern is that the value of $\delta$ cannot be too small to implement.

The above derivation concludes that the way to compensate for the work surface errors at $m$ locations is simply to design the tool dwelling-time distribution at these locations based on Criterion (A).

### 3. Residual error analysis

The planning method based on Criterion (A) does not guarantee that the profile error can be completely removed. There may exist error between the actual and desired removal depths of the error profile. This error is defined as the residual error in this study. In this section, the qualitative properties of the residual error are analyzed.

From Eq. (7) to (9), the residual error $e_r$ at radius $r$ can be written as

$$e_r(r) = \frac{1}{2\pi} \sum_j T_j C_j - D_j$$  \hfill (10)

To simplify the error analysis, the machining zone is assumed to have a rectangular area with a smooth machining rate distribution

$$m'(x', y') = m_c \cos \left( \frac{\pi}{L_m} x' \right)$$  \hfill (11)

where $m_c$ is a constant. Further, from the Fourier transformation, an arbitrary depth function $D(r)$ can be viewed as the synthesis of a uniform function and many sinusoidal functions with different wavelengths. It is then possible to comprehend the qualitative characteristics of residual error by looking at the cases with $D(r)$ as a constant or a simple sinusoidal function. Therefore, in the following analysis, two cases are simulated to examine the effects of various parameters on the residual error. The mathematical expressions of $D(r)$ in the two cases are

$$D(r) = \text{a constant}$$  \hfill (12a)

and

$$D(r) = a_1 + a_2 \sin \left( \frac{2\pi}{\lambda} r \right)$$  \hfill (12b)

where $\lambda$ is the wavelength of sinusoidal profile. The values $a_1$ and $a_2$ are constant. The ratio $a_1/a_2$ can represent the degree of error profile variation.
The residual error percentage at different radii is shown in Fig. 5 when $D(r)$ is a constant. Here, the residual error percentage is defined as

$$E_R(r) = \frac{1}{2\pi} \sum_j T(p) \cdot C_j(r) - D(r) \times 100\%.$$  (13)

In the simulation, the machining zone is assumed to have a width of 1 mm. The $m_o$ in Eq. (11) is set to 2 nm/s. The errors at 1000 uniformly spaced radii in the range from 0 to 100 mm are to be removed. The result indicates a trend that the larger the radius the larger the residual error will be. Nevertheless, the error percentages at different radii are all less than 0.3%.

If the $D(r)$ becomes a form of eq. (12b), the residual error percentage at different radii is shown in Fig. 6. The wavelength of $D(r)$ in this case is 1 mm, which is the same as the width of the machining zone. The ratio $a_1/a_2$ has a value of 5. Similarly, the residual error percentage tends to be large at a work surface with a large radius.

However, the magnitude of error percentage is obviously magnified as compared to that of Fig. 5.

The effect of the wavelength of $D(r)$ (in the form of Eq. (12b)) on residual error under different widths of the machining zone is shown in Fig. 7. In this figure, the ratio $a_1/a_2$ is set to 6. The PV (peak to valley) value of error percentage denotes the maximum difference of error percentage among the various radii (as indicated in Fig. 6). A large value of this PV percentage represents a large value of residual error. The result indicates that a small wavelength of $D(r)$ will result in a large residual error. Further, the residual error can be decreased through the reduction of the width of the machining zone.

The effect of the tool’s resolution on residual error under various wavelengths of $D(r)$ is presented in Fig. 8. Here, the tool’s resolution is defined as the distance between two consecutive locations in which the tool dwells. Its value is also equal to the distance between two consecutive radii on work, whose form errors are desired to be removed. The figure reveals a general trend that a small size of the tool’s resolution can result in a small residual error. This tendency is more obvious...
when the wavelength of $D(r)$ is large. It is noted that the PV value of error percentage is significantly increased when the magnitude of $D(r)$ is smaller than the width of the machining zone.

The effect of the ratio $a_1/a_2$ on residual error is indicated in Fig. 9. A small value of $a_1/a_2$ represents a large variation in the error profile. The simulation shows that the effect of $a_1/a_2$ becomes obvious only when its value is smaller than a critical value. This critical value is found to be a function of the wavelength of $D(r)$. The smaller the wavelength is the larger the critical value will be. This implies that the removal of the error profile with a large variation can be more effectively done when its wavelength is large.

From the above simulations, several points can be concluded. First, the residual error is found to be related to the width of the machining zone, the wavelength of the error profile and the tool’s resolution. The residual error is always negligible when the wavelength of the error profile is larger than the width of the machining zone. If the wavelength is large, a small size of the tool’s resolution is found effectively to reduce the residual error.

4. Experimental study

Several experiments are carried out to examine the characteristics of the CCP process in the form error compensation task. A schematic diagram of the CCP polishing system is shown in Fig. 10. In the following experiments, the cylindrical tool is made of rubber with a diameter of 55 mm and an axial length of 60 mm. The slurry is a mixture of water and abrasive particles and has a viscosity of 0.004 N s/m² at 25 °C. The particle is Al₂O₃ powder particle with a hardness of 8 Mohs and a primary grain size of 50 nm. The work material is a silicon wafer. During the polishing process, the tool will sustain a constant load of 24 N and a constant tool angular speed of 300 rpm. To measure the machined depth of profile, a Form Talysurf machine is used.

Two preliminary experiments are done to show the machining characteristics of the CCP process. The first one is to examine the repeatability of the machining rate. It is shown in Table 1 that the machining rate has less than a 2% variation under a fixed operating condition. The second one is to investigate the tool wear effect on the machining rate. The results represented in Table 2 reveal that the machining rate has only a 5% change after 50 h of machining. (A detailed examination of tool wears characteristics of the CCP process will be presented in the later study.) These results meet the previous expec-

### Table 1

<table>
<thead>
<tr>
<th>Tool number</th>
<th>Machining depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.40</td>
</tr>
<tr>
<td>2</td>
<td>2.34</td>
</tr>
<tr>
<td>3</td>
<td>2.37</td>
</tr>
<tr>
<td>4</td>
<td>2.34</td>
</tr>
<tr>
<td>5</td>
<td>2.38</td>
</tr>
<tr>
<td>Mean</td>
<td>2.38</td>
</tr>
<tr>
<td>Standard</td>
<td>0.039</td>
</tr>
</tbody>
</table>

* Tool angular speed 300 rpm; applied load 24 N; machining time 15 min.

### Table 2

<table>
<thead>
<tr>
<th>Tool number</th>
<th>Machining depth at the beginning (µm)</th>
<th>Machining depth after 50 h machining (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.41</td>
<td>2.32</td>
</tr>
<tr>
<td>2</td>
<td>2.34</td>
<td>2.27</td>
</tr>
<tr>
<td>3</td>
<td>2.44</td>
<td>2.35</td>
</tr>
</tbody>
</table>

* Tool angular speed 300 rpm; applied load 24 N; machining time 15 min.
tation that the CCP process has high repeatable machining behavior and sustains little effect from tool wear.

To verify the error removal capability by the proposed method, two sets of experiments are conducted. The first one is to show the accuracy of the CCP process in ‘carving’ an arbitrary profile based on Criterion (A). The second one is to present the capability of the form error compensation by the CCP process. In the first experiment, the work surface is presumed to be perfectly flat. A profile with a specified depth function with the mathematical form of

\[ D(r) = a_1 + a_2 \sin \left( \frac{2\pi}{\lambda} r \right) \]  

(14)

with

\[ 5 \text{ mm} \leq r \leq 25 \text{ mm} \]

is to be removed, where \( \lambda = 6 \text{ mm} \), \( a_1 = 4 \mu\text{m} \) and \( a_2 = 1 \mu\text{m} \). By minimizing the residual error in Criterion (A), the dwelling-time distribution of tool is determined. The tool’s resolution is set to 100 \( \mu\text{m} \). The width of machining zone is measured to be about 1.62 mm. The experimental result is shown in Fig. 11(a). The difference between the machined and desired profiles is found small [Fig. 11(b)]. This result indicates that with the aid of Criterion (A) in designing the dwelling-time distribution an arbitrary shape of profile can be accurately obtained.

In the second experiment, an artificially made, non-flat and axially symmetric surface is first created. The profile of the surface drawn along the radius is shown in Fig. 12. Then, the proposed form error compensation method is used to obtain a flat surface. The result is also indicated in Fig. 12. A fairly flat surface is obtained.

To further examine the effectiveness of this compensation job, the wavelength spectra (Fig. 13) of the work surface before and after machining are compared. If an arbitrary profile, measured relative to regression of its line, is regarded as the synthesis of various wavelengths of sinusoidal functions, its wavelength spectrum presents the energy distribution of the sinusoidal function at different wavelengths. A large magnitude of wavelength spectrum indicates that the variation of profile relative to its regression line is large. In other words, if the desired profile is the regression line, a large magnitude of wavelength spectrum equivalently indicates that the difference between desired and real profiles are large. Fig. 13 shows that the compensation process can effectively reduce the magnitude of the error profile at a wide band of wavelengths.

5. Discussions

The above studies indicated that the CPP process did have the capability to remove an arbitrary error profile based on the proposed method. However, there are three issues worthy of attention. First, the machining rate of the polishing process is sensitive to the curvature of the work surface [3,8]. Hence, it is highly recommended that
the machining action should not be finished at one stroke of tool motion around the machining area when the proposed method is adopted. During the polishing process, if the tool continuously dwells at a spot until the desired depth is removed, the work surface at that spot will have a profile conformable to the tool surface (as depicted in Fig. 14). This profile may significantly increase the curvature effect on the machining rate of a polishing process that makes use of the hydrodynamic effect to float the tool. Then, the machining rate of the process cannot be maintained constant and the machining accuracy is influenced. One way to reduce this effect is to remove the error profile in a layer-by-layer approach [3]. The error profile is first divided into a certain number of layers (Fig. 15). Each layer can be the same as the others.

Second, the anisotropy polishing phenomenon can occur in the CCP process. In this study, a polishing is defined as isotropic if each spot on the work surface sustains machining actions (from abrasive particle) with equal opportunity (or probability) in all directions of particle motion. Here, the direction of particle motion is measured relative to the radial direction of work. On the other hand, if the machining action from one direction of particle motion is different from others, the polishing process is anisotropic. The CMP (chemical-mechanical polishing) process used in the semi-conductor industry is an isotropic polishing process. The HDP and the CCP process are in essence anisotropic. In Fig. 16, the direction of particle motion at a spot on the work surface is shown. It is found that the probability of particle motion is not always uniformly distributed in all directions for a spot at radius \( r \) even when the work rotates at a fixed speed. If a polishing process possesses the anisotropic feature, should it result in a severe non-uniform distribution of surface roughness on the work surface? If it is the case, the usefulness of the CCP process as a tool for form error compensation is limited.

The computer simulations disclosed that for the CCP process the probability distribution (versus the direction of particle motion) of the machining action at a spot on the work surface depends on the spot’s location (or
radius). In Fig. 17, the polishing probability distribution, calculated from computer simulation with a specific dwelling-time distribution of tool motion, for a spot at a radius of 20 mm is shown. For the purpose of the comparison, a corresponding experiment with the same tool motion was conducted. The surface roughness for the spot with the same location as the simulation was measured in various directions. The surface roughness versus the measured direction is shown in Fig. 18. A little variation of surface roughness is observed. By comparing Figs. 17 and 18, it seems that the magnitude of surface roughness in one direction was related to the probability that abrasive particles were acting on the spot in this direction. A high probability of machining action in one direction is likely to result in a low surface roughness at this direction. At a first glance, this correlation looks obvious. However, if the correction holds, what will happen when the probability of machining action in a certain direction is zero? The experimental result reveals that the surface roughness at one direction is only enhanced a little as compared to the others when the probability of machining action is zero at this direction.

This phenomenon suggests that the effect of anisotropic polishing on the variation of surface roughness may not be significant. To ease the suspicion of the effect of anisotropic polishing on the uniformity of the surface roughness, a further study is needed.

Another interesting issue is that the experimental data of form error compensation presented a better result than the analytical expectation. The above study in section 3 indicated that the error profile could not be effectively removed if its wavelength is less than the width of the machining zone. From the wavelength spectrum of the surface profile before compensation (Fig. 13), there existed significant energy in the band with a wavelength less than 1.62 mm (the width of the machining zone). Such band of energy cannot be successfully removed by the proposed compensating technique. However, the spectrum (Fig. 13) of the surface profile after compensation revealed that the component of the original profile with small wavelength was practically removed.

The most likely cause of this result is due to the irregularity reduction capability of the polishing process. It is acknowledged that the surface irregularities of the work surface may be reduced in a polishing process. The experimental study by Su et al. [5] indicated that the surface irregularities could be obviously reduced in a polishing process simply by making the tool move back and forth. The ultimate roughness achievable by such a back and forth polishing motion was found to be dependent on the wavelength of surface irregularities. It was shown that the smaller the wavelength the smaller the ultimate magnitude of irregularities could be. To further lessen the magnitude of surface irregularities with large wavelength, one requires a more skilled approach, such as the proposed form error compensation method. On the other hand, the irregularities with small wavelength can be reduced to a small value only by the aid of a regular polishing process. Hence, the improvement of surface profile with small wavelength is automatically done in the ‘polishing practices’ of the compensation process.

6. Conclusions

In this study, a process planning method for removing an arbitrary and axially symmetric error profile by the cylindrical polishing process was proposed. This method suggested a layer-by-layer approach to remove an arbitrary error profile. In each layer, the tool dwelling-time distribution was designed by using a non-negative least square method under the constraint of non-negative time distribution. It was shown that the residual error is closely related to the width of the machining zone, the wavelength of the error profile, and the tool’s resolution. When the wavelength of the error profile is larger than the width of the machining zone, the residual error is
almost negligible. If the wavelength of the error profile were large, a small size of the tool’s resolution would help reduce the residual error. It is noted that the PV value of residual error percentage is significantly increased when the wavelength of the error profile is smaller than the width of the machining zone. The experimental study confirmed that an arbitrary and axially symmetric error profile could be accurately removed based on the proposed method.

Acknowledgements

This paper presents the results of one phase of research sponsored by the National Science Council of R.O.C. (under the contract NSC 91-2212-E145-002).

References