Surface shape control of the workpiece in a double-spindle triple-workstation wafer grinder*

Zhu Xianglong(朱祥龙), Kang Renke(康仁科)†, Dong Zhigang(董志刚), and Feng Guang(冯光)

Key Laboratory for Precision & Non-traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian 116024, China

Abstract: Double-spindle triple-workstation (DSTW) ultra precision grinders are mainly used in production lines for manufacturing and back thinning large diameter ($\geqslant$ 300 mm) silicon wafers for integrated circuits. It is important, but insufficiently studied, to control the wafer shape ground on a DSTW grinder by adjusting the inclination angles of the spindles and work tables. In this paper, the requirements of the inclination angle adjustment of the grinding spindles and work tables in DSTW wafer grinders are analyzed. A reasonable configuration of the grinding spindles and work tables in DSTW wafer grinders are proposed. Based on the proposed configuration, an adjustment method of the inclination angle of grinding spindles and work tables for DSTW wafer grinders is put forward. The mathematical models of wafer shape with the adjustment amount of inclination angles for both fine and rough grinding spindles are derived. The proposed grinder configuration and adjustment method will provide helpful instruction for DSTW wafer grinder design.

Key words: grinder; silicon wafer; surface shape control; chuck dressing; modeling

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1. Introduction

Silicon wafers are the most important and essential substrates for fabricating the vast majority of semiconductor devices and integrated circuits (ICs)[1]. In order to improve their integration and to ensure high quality of chips, the feature sizes on ICs have continuously shrunk from about 125 μm in the beginning of semiconductor device fabrication in the early 1950s to 0.09 μm recently[2]. As the feature sizes decreased and the wafer sizes increased, the flatness requirements of wafers from semiconductor fabrication have become more and more stringent, which directly impacts device line-width capability, process latitude, yield and throughput[3, 4].

Grinding is one of the most important flattening processes in the manufacturing of bare silicon wafers[5]. It is also the most common technology for backside thinning of patterned device wafers. Infeed grinding technology was first proposed by Matsui in 1988[6] and was reported to be used in the fine grinding of etched silicon wafers through a US patent by Vandamme *et al.*[7]. The wafer infeed grinding process is based on the principles of movement reprography, as shown in Fig. 1. The silicon wafer is held onto the porous chuck table and elastically deforms to the chuck shape by means of vacuum. The grinding wheel used in wafer infeed grinding is a diamond cup wheel. The rotational axis of the grinding wheel is offset by a distance of the wheel radius relative to the rotational axis of the wafer, hence the wafer axis passes through the cup edge of the grinding wheel. During grinding, the wafer rotates together with the chuck table about their axes and the grinding wheel rotates about its rotational axis simultaneously. The grinding wheel is fed along its axis towards the wafer until the wafer is ground to the setting thickness. One of the advantages of wafer infeed grinding is that the wafer shape can be actively controlled through adjusting the inclination angle between the grinding wheel and the chuck table, so as to obtain the better wafer flatness. Studies on ground wafer flatness control have attracted more and more interest among researchers owing to its importance. Some papers have mentioned or implied that the chuck surface should not be planar, but did not report how to obtain a certain chuck shape and what effects it might have[8−11]. Tonshoff *et al.*[12] found that the spindle deviation leads to a typical wafer surface profile in their grinding experiments with a rotating wafer. Tian *et al.*[13], Chen *et al.*[14], Sun *et al.*[15], Chidambaram *et al.*[16] and Tso *et al.*[17] developed

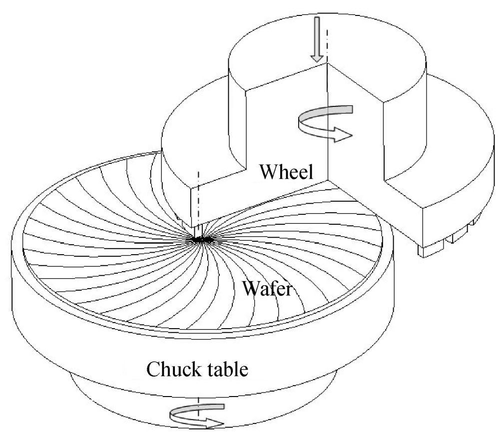

Fig. 1. Illustration of wafer infeed grinding.

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† Corresponding author. Email: kangrk@dlut.edu.cn

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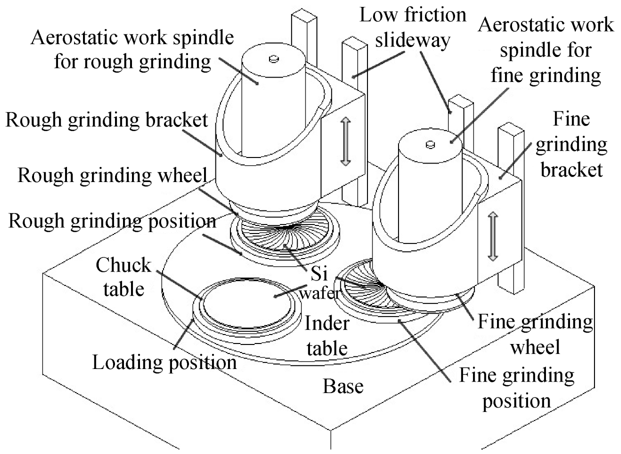

Fig. 2. Double-spindle and triple-workstation wafer grinder.

mathematical models of wafer shape or chuck shape, using the inclination angles of the grinding wheel spindle as the input setup parameters. Sun *et al.*[18] further discussed the grinder configurations for spindle angle adjustments and proposed the proper configuration in terms of ease in spindle adjustments. Zhou *et al.*[19, 20] developed a horizontal single spindle wafer grinding machine with adjustment devices for wafer position and spindle inclination. The desired wafer shape was obtained by the adjustment of the inclination angle of the spindle axis.

All of the workpiece (wafer or chuck) shape models proposed in the above mentioned works used the relative inclination angles of the grinding wheel as the input setup parameters. The relative inclination angles of the grinding wheel and the chuck table axes are space angles, which cannot be measured directly and be used for quantitative adjustment of the wafer shape. For example, the grinding spindles of the most commonly used infeed grinders were supported and fixed by three fixing points, and the inclination angle adjustments were normally realized by fine adjustment of the height of the supporting points instead of the spindle inclination angle. So the current available models using the spindle inclination angles as the input setup parameters are helpful for wafer shape prediction, but cannot be directly used for machine setup. Furthermore, the above mentioned models or grinders are all based on grinders with a single spindle and a single workstation. In production lines, to improve productivity, fully automatic wafer grinder with two grinding spindles and three workstations are commonly used, which are called double-spindle triple-workstation (DSTW) grinders. The wafer is turned to the rough grinding station with the chuck on the index table after being automatically loaded onto the chuck by a robot at the loading workstation. After rough grinding, the wafer is transferred to the fine grinding station on the same chuck, where the fine grinding is performed by a fine spindle, as shown in Fig. 2. To ensure the quality of the grinding surface and the uniformity of material removal, the shape of the wafer held on the same chuck after rough and fine grinding at the corresponding rough and fine grinding stations are desired to be identical. For this, the relative geometric relationship between the axes of the rough grinding spindle and the chuck table are required to be the same as that between the axes of the fine grinding spindle and the chuck table. In addition, the relationships of the three chuck table axes and the grinding spindles have to be the same in order to ensure that the ground wafers on the three chuck tables have consistent shapes. However, to the authors' best knowledge, there are no papers addressing the following important questions. What are the spindle requirements and optimal chuck table configurations needed for a DSTW grinder to obtain consistent ground wafer shapes on the three different chuck tables, and to produce uniform shapes for the same wafer after rough and fine grinding? What is the proper configuration? What is the best way to control the workpiece shape through inclination angle adjustment by adjusting the height of the supporting points of the spindles or chuck tables?

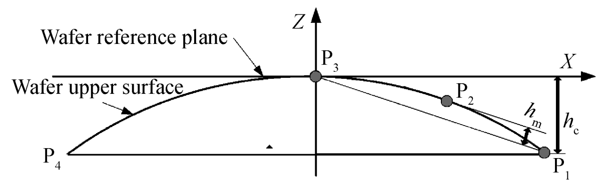

Fig. 3. Two components of the chuck topography.

The requirements for DSTW grinder configuration are discussed in this paper. A proper configuration is proposed, of which the inclination adjustment systems of fine and rough grinding spindles and chuck tables are different. The inclination adjustments of fine and rough spindles are conducted in sequence with respective workpiece shape models. Mathematical models of the workpiece shape for fine grinding and rough grinding are developed. Grinder development and experimental verification will be presented in our next paper.

2. Configurations and inclination angle adjustments for DSTW wafer grinder

2.1. Workpiece shape evaluation

From a geometric point of view, the workpiece (wafer or chuck) shape is formed by the rotational movement of the contact arc between the workpiece and the grinding wheel about the wafer axis. The ground workpiece shape is axisymmetric, the cross section of which is illustrated in Fig. 3. Any ground workpiece shape can be resolved in two parameters, the workpiece central height component and the radial median height component in the axis section. The workpiece central height component characterizes the entire workpiece shape across the workpiece diameter and is evaluated by $h_{\rm c}$, the distance from the workpiece center P_3 to the line P_1P_4 which connects two points on the edge of the workpiece front surface across the center. The radial median height component characterizes the workpiece shape across the wafer radius and is evaluated by $h_{\rm m}$, the distance from the median point of the radius P_2 on the workpiece surface to the workpiece reference plane across point P_3.

2.2. Requirements for DSTW grinder configuration

The workpiece shapes after rough and fine grinding by the rough and fine grinding wheels on a DSTW grinder need to be identical, so, in theory, the relative inclination angles of the chuck table with the rough and fine grinding spindles have to be

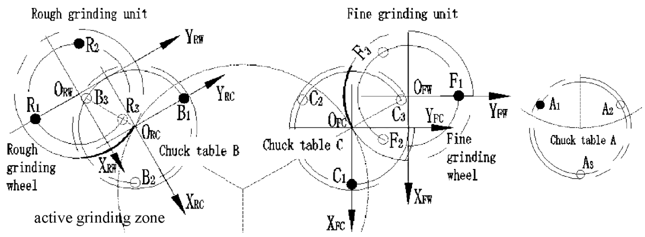

Fig. 4. The configuration of the obliquity adjustment device of grinding spindles and chunk tables.

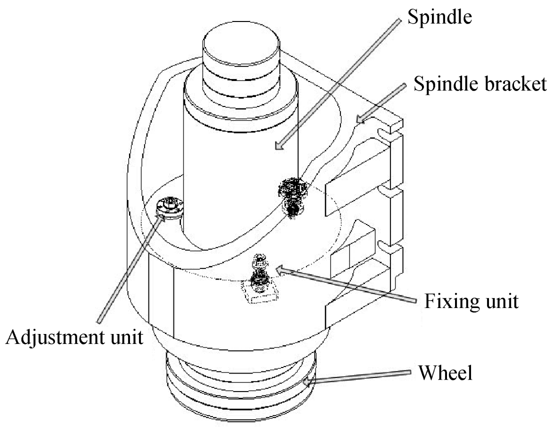

Fig. 5. Obliquity adjustment device of spindle.

the same, which requires the inclination angle of the rough and fine grinding spindle axis to be adjustable. At the same time, to ensure the consistency of the workpiece shapes ground on the three work stations, the relative angles between the spindle axis and the three different chuck table axes during grinding should be the same, which requires the inclination angles of the three chuck table axes to be adjustable individually as well. Sun et al. discussed the spindle angle adjustments of commercially available wafer grinders[21]. The spindle inclination angle adjustment process may consume from 5 to 100 wafers, and take from 30 min to more than 10 hours depending on the skill of the person who adjusts the spindle angle, the wafer shape originally obtained and the flatness requirement. They also found that the major reason for the difficulty in spindle angle adjustments is that tilting the spindle rotation axis around one adjustment axis will affect both components (h_c and h_m) of the wafer shape. So, an important criterion for easy adjustments of the relative inclination angle between the individual spindle and the chuck table is that the two components of wafer shape can be changed individually and independently when adjusting the wheel rotation axis around each of the adjustment axes.

The requirements for a DSTW wafer grinder are then concluded as:

(1) The rough and fine grinding spindles axes' inclination are adjustable.

(2) The inclination angles of the three chuck table axes are individually adjustable.

(3) The two components of the wafer shape can be adjusted individually and independently.

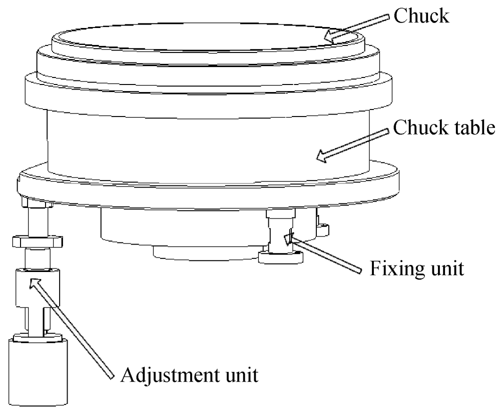

Fig. 6. Obliquity adjustment device of chunk table.

2.3. DSTW grinder configuration and inclination angle adjustment process

Based on the above mentioned requirements, a suitable configuration of spindles and workstations for DSTW wafer grinders are proposed, as shown in Fig. 4. Each of the grinding spindles is supported by three units, respectively. These units are installed evenly on the spindle's circumference between the grinding spindle and the bracket. The obliquity devices of the fine grinding spindle consist of one set of adjustment unit F_1 and two sets of fixing units, F_2 and F_3, but the obliquity devices of the rough grinding spindle consist of two sets of adjustment units (R_1 and R_2) and one fixing unit (R_3), as shown in Fig. 5. The purpose of the difference of the supporting unit arrangement between the rough and fine grinding spindles is that the adjustment order of fine and rough grinding spindles for DSTW grinding is different, and the first adjusted spindle has to be the reference of the next one. The detailed adjustment method and sequence will be given in the next part of this section. Three chuck tables have the same configuration, each of which is supported by three units respectively. These units are installed evenly on the chuck table's circumference between the chuck table and index table, as shown in Fig. 6. The obliquity devices of each chuck table consist of one adjustment unit and two sets of fixing units. The adjustment units of the obliquity devices for the chuck table A, B and C are A_1, B_1 and C_1, respectively, while the fixing units of the obliquity devices for the chuck table A, B and C are A_2–A_3, B_2–B_3, and C_2–C_3, respectively, as shown in Fig. 4. By adjusting the height of the supporting point through the adjustment units, the spindle or the worktable will rotate about the axis through the other two supporting points, and the inclination angle adjustment of the spindles and worktables are realized.

As the precondition of the inclination angle adjustment, each line connecting the two fixing points on the fine grinding spindle and the three worktables are required to be parallel with the index table surface. This has to be achieved by the manufacture, installation and assembly of parts or components. The inclination angle adjustment of the grinding spindles and chuck tables for a DSTW grinder consists of following four steps:

(1) Adjust the relative inclination angle of the fine grinding spindle and the worktable C, which is located at the fine grinding position by adjusting the height of the supporting points.

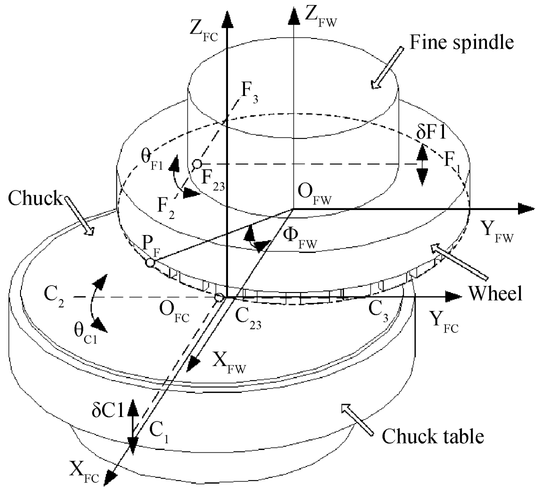

Fig. 7. Mathematical model of chuck topography control of fine grinding spindle.

According to the desirable wafer shape (h_c, h_m), the adjustment amounts of F_1 and C_1, (δ_{F1}, δ_{C1}), are calculated by the fine grinding unit prediction model, the derivation of which will be given later. After adjustment, wafers are ground and the ground surface shape parameters of h'_c and h'_m are measured. The rectified values of F_1 and C_1, (δ'_{F1}, δ'_{C1}) are then determined according to the difference of the practical and theoretical values (h_c–h'_c ,h_m–h'_m), by the same model. F_1 and C_1 are readjusted by the value of (δ'_{F1}, δ'_{C1}). Repeat this process until the desired ground wafer shape is obtained;

(2) Adjust the inclination angle of the rough grinding spindle. Rotate the index table 120° CCW to take the chuck table C at the fine grinding station to the rough grinding station. Using this chuck table as the reference, the inclination angle of the rough grinding spindle is adjusted by adjusting R_1 and R_2. The adjustment amounts of R_1 and R_2, (δ_{R1}, δ_{R2}), are calculated by the prediction model for the rough grinding unit according to the theoretical values of h_c and h_m. The same as the previous one, after adjustment, a wafer is ground and the ground surface shape parameters of h''_c and h''_m are measured. The rectified value of δ''_{R1} and δ''_{R2} for R_1 and R_2 are then calculated according to the difference of the practical and theoretical values, (h_c–h''_c ,h_m–h''_m) by the same model. F_1 and C_1 are readjusted by the value of δ'_{F1} and δ'_{C1}. Repeat this process until the desired ground wafer shape is obtained;

(3) Adjust the inclination angle of chuck table A. Using the fine grinding spindle as a reference, the inclination angle of chuck table A is adjusted by adjusting A_1. The adjustment amount, δ_{A1}, is determined by the prediction model for the fine grinding unit according to the h_c. A wafer is ground and the inclination angle is readjusted according to the ground wafer shape. Repeat this process to get the needed wafer shape;

(4) Adjust the inclination angle of chuck table B. Turn chuck table B to the fine grinding station and adjust its inclination angle using the same method used above.

3. Mathematical model of surface shape control

From the proposed adjusting processes, it can be seen that the workpiece surface shape model of the fine grinding unit is different from that of the rough grinding unit. Consequently, it is necessary to establish two different surface shape control models of the workpiece for the fine and rough grinding units, respectively.

3.1. Mathematical model for surface shape control of the fine grinding unit

The obliquity adjustment model of the fine grinding spindle is established in Cartesian coordinate systems O_{FW} (X_{FW}, Y_{FW}, Z_{FW}) and O_{FC} (X_{FC}, Y_{FC}, Z_{FC}), as shown in Fig. 7. Coordinate system O_{FW} (X_{FW}, Y_{FW}, Z_{FW}) is used for the development of the fine grinding wheel equations, whose origin is fixed at the center of grinding wheel with its Z_{FW}-axis being the rotational axis of the wheel. The X_{FW}- and Y_{FW}-axes lie on the plane of the diagram of Fig. 4. The origin of the O_{FC} (X_{FC}, Y_{FC}, Z_{FC}) system is fixed at the center of the workpiece front surface, Z_{FC}-axis is parallel to the rotational axis of the workpiece, and X_{FC} and Y_{FC}-axes are both located on the plane of the workpiece. X_{FC}-axis is perpendicular to the line segment C_2C_3 while Y_{FC}-axis is parallel to C_2C_3. The coordinates of perpendicular foots F_{23} and C_{23} are (X_{F23}, Y_{F23}, Z_{F23}) in O_{FW} system and (X_{C23}, Y_{C23}, Z_{C23}) in the O_{FC} system, respectively.

The contact area between the wheel and the workpiece is constant at any instant for the in feed grinding, which is helpful for obtaining a stable grinding performance. Generally, in order to eliminate or reduce the central dimples[22], the grinding force, the average depth of grinding marks and the roughness on the ground wafers, the axes of the chuck table and the grinding wheel are aligned not parallel to each other. Therefore, the workpiece is half ground from the edge to the center along the arc $O_{FC}O_F$, marked as in Fig. 4.

The convex or concave workpiece surface shape is formed as the arc $O_{FC}O_F$ rotating in the space about the Z_{FC} axis. Therefore, the major focus in developing the mathematical model for the workpiece surface shape is to derive the mathematical expression of arc $O_{FC}O_F$ in the O_{FC} system.

The position and orientation of arc $O_{FC}O_F$ in the space is solely determined by three factors: the radius of the grinding wheel R_W and workpiece R_C, and the relative obliquity between the rotational axes of the fine grinding spindle and the chuck table.

Assuming that the chuck is stationary, the arc $O_{FC}O_F$ will be generated on the chuck by the rotation of the arbitrary grain P_F (x_F, y_F, z_F) about the center O_{FW} in the O_{FW} system when it is in contact with the chuck. The coordinate of the arc can be expressed as:

$$\begin{bmatrix} x_F \\ y_F \\ z_F \\ 1 \end{bmatrix} = \begin{bmatrix} R_W \sin\phi_{FW} \\ -R_W \cos\phi_{FW} \\ 0 \\ 1 \end{bmatrix}, \tag{1}$$

where ϕ_{FW} is the angle between the line $O_{FW}P_F$ and the X_{FW} on the $X_{FW}O_{FW}Y_{FW}$ plane, which uniquely describes the position of point P_F in the O_{FW} system when R_W is determined. The range of ϕ_{FW} is:

$$0 \leqslant \phi_{FW} \leqslant 2\arcsin\frac{R_C}{2R_W}. \tag{2}$$

The coordinate of the point $P_F(x_F, y_F, z_F)$ in the O_{FW} system is then transformed into (x'_F, y'_F, z'_F) in the O_{FC} system by the following equation:

$$\begin{bmatrix} x'_F \\ y'_F \\ z'_F \\ 1 \end{bmatrix} = T(X_{C23}, Y_{C23}, Z_{C23}) R(\theta_{C1}) \times T(-X_{OC}, -Y_{OC}, -Z_{OC}) \times T(X_{F23}, Y_{F23}, Z_{F23}) R(-\theta_{F1}) \times T(-X_{F23}, -Y_{F23}, -Z_{F23}) \begin{bmatrix} x_F \\ y_F \\ z_F \\ 1 \end{bmatrix}, \quad (3)$$

where

$$T(X_{C23}, Y_{C23}, Z_{C23}) = \begin{bmatrix} 1 & 0 & 0 & X_{C23} \\ 0 & 1 & 0 & Y_{C23} \\ 0 & 0 & 1 & Z_{C23} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (4)$$

$$R(\theta_{C1}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{C1} & -\sin\theta_{C1} & 0 \\ 0 & \sin\theta_{C1} & \cos\theta_{C1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5)$$

$$T(-X_{OC}, -Y_{OC}, -Z_{OC}) = \begin{bmatrix} 1 & 0 & 0 & -X_{OC} \\ 0 & 1 & 0 & -Y_{OC} \\ 0 & 0 & 1 & -Z_{OC} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (6)$$

$$T(X_{F23}, Y_{F23}, Z_{F23}) = \begin{bmatrix} 1 & 0 & 0 & X_{F23} \\ 0 & 1 & 0 & Y_{F23} \\ 0 & 0 & 1 & Z_{F23} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (7)$$

$$R(-\theta_{F1}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{F1} & \sin\theta_{F1} & 0 \\ 0 & -\sin\theta_{F1} & \cos\theta_{F1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (8)$$

$$T(-X_{F23}, -Y_{F23}, -Z_{F23}) = \begin{bmatrix} 1 & 0 & 0 & -X_{F23} \\ 0 & 1 & 0 & -Y_{F23} \\ 0 & 0 & 1 & -Z_{F23} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (9)$$

The rotational angle θ_{C1} in Eq. (5) is the angle that C_1C_{23} rotates around C_2C_3 on X_{FC}–Z_{FC} plane when the adjustment unit C_1 is adjusted, which can be expressed as the function of δ_{C1}, R_{CS}:

$$\theta_{C1} = 2\arcsin\frac{\delta_{C1}}{3R_{CS}}, \quad (10)$$

where δ_{C1} is the adjustment amount of the adjustment unit C_1, R_{CS} the distribution circle radius of obliquity adjustment device of chuck table.

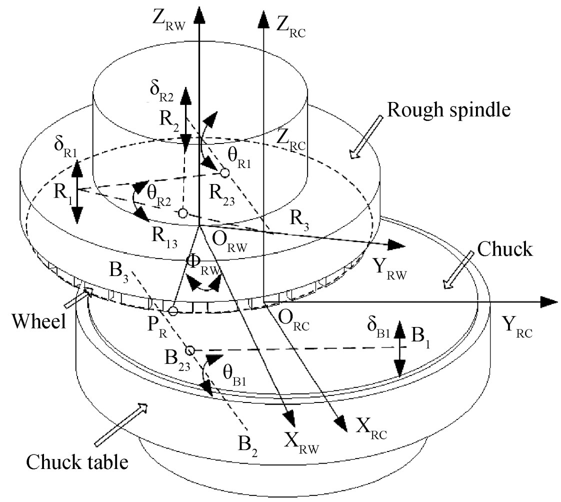

Fig. 8. Mathematical model of chuck topography control of rough grinding spindle.

The rotational angle θ_{F1} in Eq. (8) is the angle that F_1F_{23} rotates around F_2F_3 in Y_{FW}–Z_{FW} plane, which can be expressed as the function:

$$\theta_{F1} = 2\arcsin\frac{\delta_{F1}}{3R_{WS}}, \quad (11)$$

where δ_{F1} is the adjustment amount of unit F_1 and R_{WS} is the distribution circle radius of the spindle obliquity adjustment device.

3.2. Mathematical model for surface shape control of a rough grinding unit

As shown in Fig. 8, the obliquity adjustment model of rough grinding spindle is described by establishing Cartesian coordinate systems O_{RW} (X_{RW}, Y_{RW}, Z_{RW}) and O_{RC} (X_{RC}, Y_{RC}, Z_{RC}). Coordinate system O_{RW} (X_{RW}, Y_{RW}, Z_{RW}) is used for the development of the rough grinding wheel equations, whose origin is fixed at the center of grinding wheel with its Z_{RW}-axis being the rotational axis of the wheel. The X_{RW}- and Y_{RW}-axes lie on the plane of the diagram of Fig. 4. The origin of O_{RC} (X_{RC}, Y_{RC}, Z_{RC}) system is fixed at the center of the workpiece front surface. Z_{RC}-axis is parallel to the rotational axis of the workpiece and X_{RC}- and Y_{RC}-axes are both located on the plane of the workpiece. The X_{RC}-axis is parallel to the line segment B_2B_3 while the Y_{RC}-axis is perpendicular to B_2B_3. The coordinates of the perpendicular foots R_{13}, R_{23} and B_{23} are (X_{R13}, Y_{R13}, Z_{R13}), (X_{R23}, Y_{R23}, Z_{R23}) in O_{RW} system, and (X_{B23}, Y_{B23}, Z_{B23}) in O_{RC} system, respectively.

The same as the arc $O_{RC}O_R$ in fine grinding, the position and orientation of arc $O_{RC}O_R$ is solely determined by three factors. The convex or concave workpiece surface shape is formed as the rotation of the arc $O_{RC}O_R$ about the Z_{RC} axis in the space. Therefore, the major focus in developing the mathematical model for the workpiece surface shape is to derive the mathematical expression of arc $O_{RC}O_R$ in O_{RC} system.

The arc $O_{RC}O_R$ on the chuck is generated by the movement of the arbitrary grain P_R with the coordinate of (x_R, y_R, z_R) in the O_{RW} system when it is in contact with the chuck. The function of the arc can be expressed as:

$$\begin{bmatrix} x_{\rm R} \\ y_{\rm R} \\ z_{\rm R} \\ 1 \end{bmatrix} = \begin{bmatrix} R_{\rm W}\sin\phi_{\rm RW} \\ -R_{\rm W}\cos\phi_{\rm RW} \\ 0 \\ 1 \end{bmatrix}, \tag{12}$$

where $\phi_{\rm RW}$ is formed by line $O_{\rm RW}P_{\rm R}$ and the $X_{\rm RW}$ on the $X_{\rm RW}O_{\rm RW}Y_{\rm RW}$ plane, and uniquely describes the position of point $P_{\rm R}$ in the $O_{\rm RW}$ system. Where $\phi_{\rm RW}$ can be approximately expressed as:

$$0 \leqslant \phi_{\rm RW} \leqslant 2\arcsin(\frac{R_{\rm CS}}{2R_{\rm WS}}). \tag{13}$$

The coordinates of the point $P_{\rm R}(x_{\rm R}, y_{\rm R}, z_{\rm R})$ in the $O_{\rm RW}$ system can be transformed into $(x'_{\rm R}, y'_{\rm R}, z'_{\rm R})$ in the $O_{\rm RC}$ system by the following equation:

$$\begin{aligned} \begin{bmatrix} x'_{\rm R} \\ y'_{\rm R} \\ z'_{\rm R} \\ 1 \end{bmatrix} &= T(X_{\rm OR2}, Y_{\rm OR2}, Z_{\rm OR2})M(\theta_{\rm R2}) \\ &\times T(-X_{\rm R3}, -Y_{\rm R3}, -Z_{\rm R3}) \\ &\times T(X_{\rm R23}, Y_{\rm R23}, Z_{\rm R23}) \\ &\times R(\theta_{\rm R1})T(-X_{\rm R23}, -Y_{\rm R23}, -Z_{\rm R23}) \\ &\times T(X_{\rm B23}, Y_{\rm B23}, Z_{\rm B23}) \\ &\times R(\theta_{\rm B1})T(-X_{\rm B23}, -Y_{\rm B23}, -Z_{\rm B23}) \cdot \begin{bmatrix} x_{\rm F} \\ y_{\rm F} \\ z_{\rm F} \\ 1 \end{bmatrix}, \end{aligned} \tag{14}$$

where

$$T(-X_{\rm B23}, -Y_{\rm B23}, -Z_{\rm B23}) = \begin{bmatrix} 1 & 0 & 0 & -X_{\rm B23} \\ 0 & 1 & 0 & -Y_{\rm B23} \\ 0 & 0 & 1 & -Z_{\rm B23} \\ 0 & 0 & 0 & 1, \end{bmatrix}, \tag{15}$$

$$R(\theta_{\rm B1}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{\rm B1} & \sin\theta_{\rm B1} & 0 \\ 0 & -\sin\theta_{\rm B1} & \cos\theta_{\rm B1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{16}$$

$$T(X_{\rm B23}, Y_{\rm B23}, Z_{\rm B23}) = \begin{bmatrix} 1 & 0 & 0 & X_{\rm B23} \\ 0 & 1 & 0 & Y_{\rm B23} \\ 0 & 0 & 1 & Z_{\rm B23} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{17}$$

$$T(-X_{\rm R23}, -Y_{\rm R23}, -Z_{\rm R23}) = \begin{bmatrix} 1 & 0 & 0 & -X_{\rm R23} \\ 0 & 1 & 0 & -Y_{\rm R23} \\ 0 & 0 & 1 & -Z_{\rm R23} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{18}$$

$$R(\theta_{\rm R1}) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{\rm C1} & -\sin\theta_{\rm C1} & 0 \\ 0 & \sin\theta_{\rm C1} & \cos\theta_{\rm C1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{19}$$

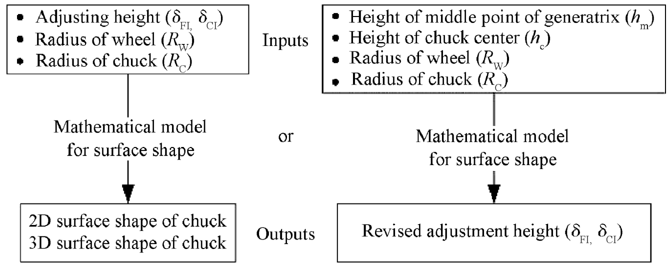

Fig. 9. Inputs and outputs of themathematical model for the chuck topography.

$$T(X_{\rm R23}, Y_{\rm R23}, Z_{\rm R23}) = \begin{bmatrix} 1 & 0 & 0 & X_{\rm R23} \\ 0 & 1 & 0 & Y_{\rm R23} \\ 0 & 0 & 1 & Z_{\rm R23} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{20}$$

$$T(-X_{\rm R3}, -Y_{\rm R3}, -Z_{\rm R3}) = \begin{bmatrix} 1 & 0 & 0 & -X_{\rm R3} \\ 0 & 1 & 0 & -Y_{\rm R3} \\ 0 & 0 & 1 & -Z_{\rm R3} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{21}$$

$$M(\theta_{\rm R2}) = \hat{A} + \cos\theta_{\rm R2} \cdot \left(I - \hat{A}\right) + \sin\theta_{\rm R2} \cdot A^*, \tag{22}$$

$$\begin{aligned} \hat{A} &= \frac{3}{4R_{\rm WS}^2} \\ &\times \begin{bmatrix} (X_{\rm R1} - X_{R3})^2 & (X_{\rm R1} - X_{\rm R3})(Y_{\rm R1} - Y_{\rm R3}) \\ (X_{\rm R1} - X_{\rm R3})(Y_{\rm R1} - Y_{\rm R3}) & (Y_{\rm R1} - Y_{\rm R3})^2 \\ (X_{\rm R1} - X_{\rm R3})(Z_{\rm R1} - Z_{\rm R3}) & (Y_{\rm R1} - Y_{\rm R3})(Z_{\rm R1} - Z_{\rm R3}) \\ 0 & 0 \end{bmatrix} \\ &\times \begin{bmatrix} (X_{\rm R1} - X_{\rm R3})(Z_{\rm R1} - Z_{\rm R3}) & 0 \\ (Y_{\rm R1} - Y_{\rm R2})(Z_{\rm R1} - Z_{\rm R3}) & 0 \\ (Z_{\rm R1} - Z_{\rm R3})^2 & 0 \\ 0 & 1 \end{bmatrix}, \end{aligned} \tag{23}$$

$$A^* = \begin{bmatrix} 0 & Z_{\rm R3} - Z_{\rm R1} & Y_{\rm R1} - Y_{\rm R3} & 0 \\ Z_{\rm R1} - Z_{\rm R3} & 0 & X_{\rm R3} - X_{\rm R1} & 0 \\ Y_{\rm R3} - Y_{\rm R1} & X_{\rm R1} - X_{\rm R3} & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{24}$$

$$T(X_{\rm CR3}, Y_{\rm CR3}, Z_{\rm CR3}) = \begin{bmatrix} 1 & 0 & 0 & X_{\rm CR3} \\ 0 & 1 & 0 & Y_{\rm CR3} \\ 0 & 0 & 1 & Z_{\rm CR3} \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{25}$$

The rotational angle $\theta_{\rm B1}$ in Eq. (16) is the angle that B_1B_{23} rotates around B_2B_3 on the $X_{\rm RC} - Z_{\rm RC}$ plane if the B_1 adjustment unit increases $\delta_{\rm B1}$ comparably, which can be expressed as the function of $\delta_{\rm B1}$, $\theta_{\rm B1}$:

$$\theta_{\rm B1} = 2\arcsin\frac{\delta_{\rm B1}}{3R_{\rm CS}}. \tag{26}$$

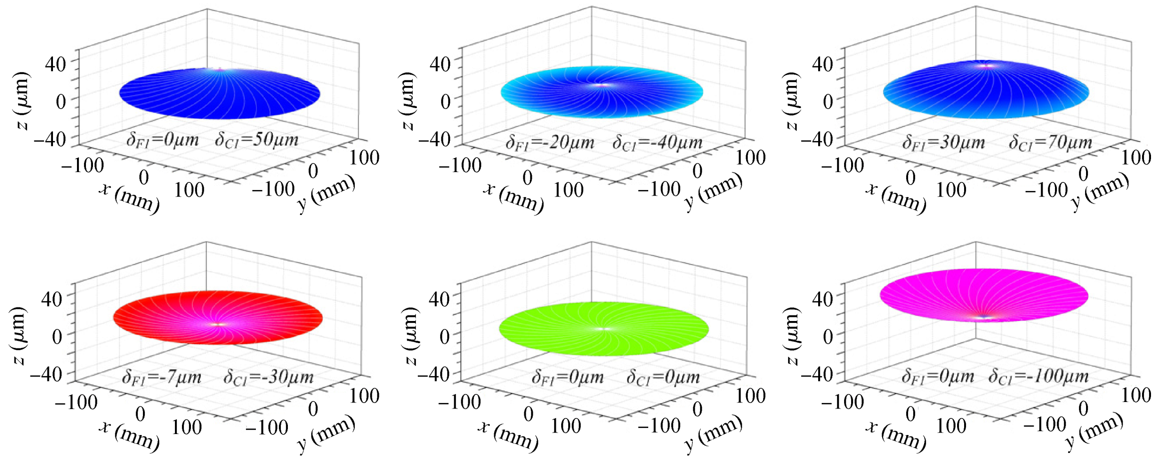

Fig. 10. Relation between thechuck shape and setup parameters F_1 and C_1.

The rotational angle θ_{R1} in Eq. (19) is the angle that R_1R_{23} rotates around R_2R_3 corresponding to the increased height δ_{R1} adjusted the adjustment unit R_1, which can be expressed as the function of δ_{R1}, θ_{R1}:

$$\theta_{R1} = 2\arcsin\frac{\delta_{R1}}{3R_{CS}}. \tag{27}$$

The rotational angle θ_{R2} in Eq. (22) is the angle that R_2R_{13} rotates around R_1R_3 corresponding to the increased height δ_{R2} adjusted the adjustment unit R_2, which can be expressed as the function of δ_{R2}, θ_{R2}:

$$\theta_{R2} = 2\arcsin\frac{\delta_{R2}}{3R_{CS}}, \tag{28}$$

where δ_{F1} is the adjustment amount of the adjustment unit F_1, R_{WS} the distribution circle radius of obliquity adjustment device of spindle.

3.3. Solution of the mathematical model for surface shape control

To obtain the solution of the surface shape control models derived in the preceding sections, a program was developed using Matlab software, the inputs and outputs of which are shown in Fig. 9. Only the solution of the mathematical model for the fine grinding unit is given below because the solving processes for the fine and rough grinding unit models are similar.

(1) The input variables to the model can be either (δ_{F1}, δ_{C1}) or (h_m, h_c).

(2) The output can be either the two or three-dimensional surface shape of the chuck, or the revised adjustment (i.e., δ_{F1}, δ_{C1}) according to the surface shape of the ground chuck.

Given the adjusting height (δ_{F1}, δ_{C1}), the final 3D surface shape of the ground chuck can be obtained. The workpiece shape calculated by mathematical model of fine grinding unit with the different inputs is demonstrated in Fig. 10. The input values are marked as well. From the above results it can be seen that the desirable convex or concave surface shape on the chuck surface can be obtained by properly adjusting the combination of δ_{F1}, δ_{C1}. The result indicates that the convexity of the central part of the chuck increases as the height is reduced. This result also demonstrates the importance of the obliquity device for the control of surface shape in infeed grinding.

After inputting (h_m, h_c) into the surface shape model developed earlier, the rectified value (δ_{F1}, δ_{C1}), can also be obtained, which is helpful for adjusting the grinder.

4. Conclusions

The requirements of the inclination angle adjustment of grinding spindles and work tables for a DSTW wafer grinder were analyzed and concluded. Based on the requirements, a reasonable configuration of the grinding spindles and work tables for DSTW wafer grinders is proposed. In this grinder configuration, the spindles and the work tables are all supported by three points, one or two of which out of three for each spindle are adjustable, and the other supporting points are fixed. The inclination angles are adjusted by changing the supporting points' height. The positions of the supporting points (adjustment units) are arranged particularly so as to ensure that only one component of the wafer shape is affected when adjusting the inclination angle of the spindle or worktable in one direction.

According to the proposed grinder configuration, an adjustment method for the inclination angle of the grinding spindles and work tables for DSTW wafer grinders is put forward, by which the inclination angles of rough and fine grinding spindles relative to three worktables can be adjusted to be the same, so as to ensure the integrity of wafers ground on the three work tables by the rough and fine grinding wheels.

The mathematical models of the wafer shape with the adjustment amount of the supporting points' height, i.e. the inclination angles, for both fine and rough grinding spindles were derived. Using the models will greatly help the adjustment process and save operator's time, because the models give quantitative instruction for inclination angle adjustment. However, wafer grinding and measurement are still necessary during the adjustment because of the elastic deformation of the grinder.

The research results on the feasible and easy inclination angle adjustment method and configuration for DSTW wafer grinders in this paper provides a significant contribution to the design of DSTW wafer grinders.

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