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Generation of rotationally symmetric surfaces by infeed grinding with a rotary table and a cup wheel

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ABSTRACT

In infeed grinding with a rotary table and a cup wheel, the wheel radius, the center distance between the rotary table and the cup wheel, the wheel inclination angle and the rotary table direction angle can be actively chosen. This makes it capable of generating a rich family of rotationally symmetric surface shapes with high accuracy, high surface finish and high surface integrity in a cost effective way. However, its application has long been confined to silicon wafers flattening and thinning. In this study, the theoretical basis for the rotationally symmetric surface generation by this grinding method was developed. The possible shape types of the generating curves and the substantial influence of the machine configuration parameters on their shape characteristics were analyzed. It was found that, besides flat surface, it can be used to generate straight conical surface, convex conical surface, concave conical surface, convex to concave conical surface, concave to convex conical surface, convex to concave to convex conical surface and concave to convex to concave conical surface.

1. Introduction

Rotationally symmetric surfaces are widely used in machine parts, sealing components and optical devices. There are numerous types of grinding processes that can be used to generate rotationally symmetric surfaces, such as surface grinding, cylindrical grinding, internal grinding, centerless grinding, form grinding and contour grinding. They vary according to the shape of the grinding wheel and the kinematic geometry of the wheel relative to the workpiece [1–3]. The first four are usually used to produce rotationally symmetric surfaces with straight radial profiles. Form grinding can be use to machine complex rotationally symmetric surfaces with a profiled grinding wheel [4,5]. Contour grinding is used to produce more complex surfaces by precisely controlling the path of the grinding wheel over the workpiece [2,6–8]. However, it is extremely difficult for grinding to generate rotationally symmetric surfaces with high form accuracy, high surface finish and high surface integrity even on specially designed machine tools with high loop stiffness and high motion resolution [7,9,10]. The primary reason for this is that most of the grinding processes exhibit time-varying characteristics due to the progressive wear of grinding wheels [11–15]. Grinding wheel wear can be categorized as non-uniform wear and overall wear [3]. Grinding wheel is under a non-uniform working condition across the active wheel surface in most grinding processes and the non-uniform wear is usually obvious. Wheel non-uniform wear directly results in fluctuations in wheel depth of cut and grinding force. These fluctuations go against the deterministic material removal for high accuracy surface generation [2,13–15]. The speed of surface generation motion in contour grinding is relatively low and thus the grinding wheel usually needs a large number of rotations and a relative long time to cover the whole surface of the workpiece being machined. The overall wear in such a long time is usually obvious as well and may have a negative influence on the obtainable accuracy of surface generation [7–9,16]. Wheel wear is especially serious when grinding hard and brittle materials such as ceramics, sapphire, single crystal silicon and glass with fine diamond wheels, and it is usually necessary to true and dress wheels periodically to resume its original shape so that the grinding operation can proceed smoothly [1,2,15]. However, it is very difficult to conduct a sub-micron-scale precision truing of the diamond wheel due to its high strength and high wear resistance [17,18]. Moreover, precision measurement of wheel shapes is a challenging task for all measurement methods [19,20] and wheel wear compensation is usually unsatisfactory [21]. The insufficiency in wheel truing, wheel shape measurement and wheel wear compensation makes it extremely difficult to achieve form accuracy up to a micron or better [15,16].

An extreme case, where the wheel wear has almost no influence on the accuracy of surface generation, is infeed grinding with a rotary table and a cup wheel. This grinding method was introduced

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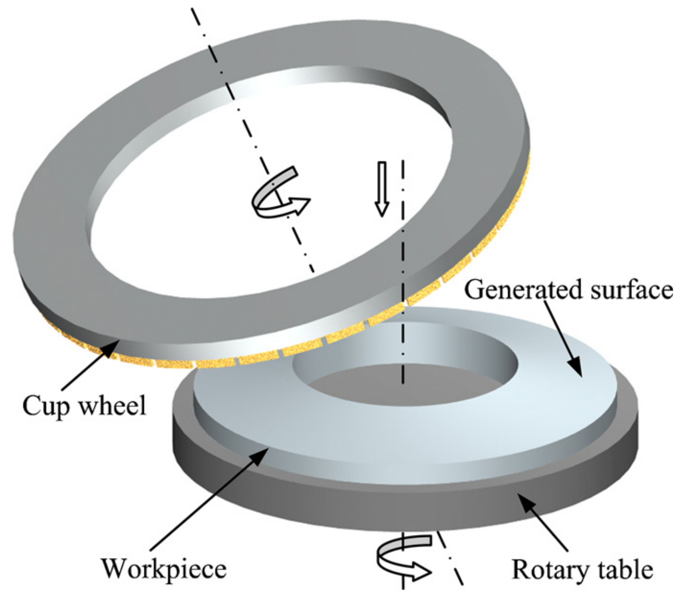

Fig. 1. Illustration of infeed grinding with a rotary table and a cup wheel.

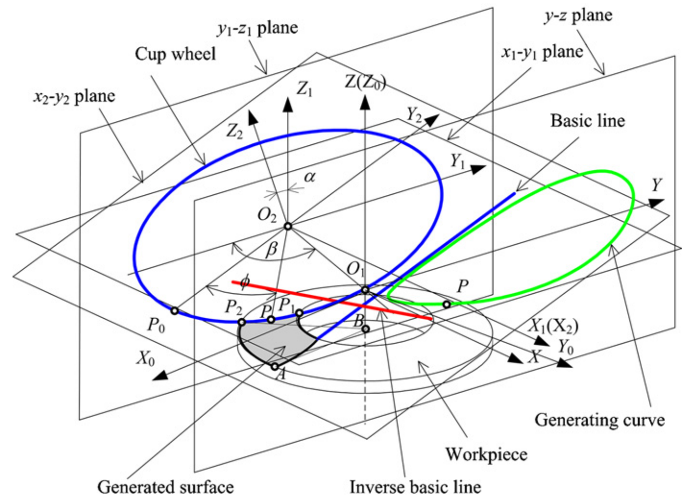

Fig. 2. Coordinate systems for model development.

to grind silicon wafers in the 1980s [22]. Fig. 1 illustrates the grinding principle. A cup wheel of radius from 100 mm to 200 mm with a rim of a few millimeters wide performs the grinding action with its end face. The workpiece is held on the center of the rotary table, and the wheel inclination angle relative to the rotational axis of the rotary table and the work table direction angle relative to the cup wheel are both adjustable so that the rotational axes of the wheel spindle and the rotary table can be skew, parallel, or intersect. During grinding, the cup wheel and the rotary table rotate about their own rotational axes simultaneously, and the wheel is fed downward to the workpiece until it reaches its final geometry [22–25]. This grinding method has several major advantages. Firstly, it uses a line contact kinematics and the grinding requires only three basic movements, namely the rotational motion of the wheel spindle, the rotational motion of the rotary table and the wheel infeed motion. It offers a high dynamic stiffness and a compact structure [22]. Secondly, it uses a narrow cup wheel with a flat end face that is a few millimeters wide, and the depth of cut, the cutting speed and the cutting path length is almost identical for all the cutting points on the active wheel surface. Therefore the wheel wear is uniform across the wheel end face and the shape of the end face is consistent from start to finish [2]. Thirdly, the rotational speed of the rotary table is usually in the range of several ten to several hundred revolutions per minute and the wheel rotational speed is usually several thousand revolutions per minute, and hence the cup wheel takes only several or even zero point several seconds to cover the whole surface of the workpiece being machined. The overall wear in such a short time is extremely small and its effect on the form accuracy of surface generation is neglectable [25]. Fourthly, the cup wheel and the rotary table is relatively static without consideration of wheel infeed motion. This leads to a constant contact position and a constant contact area, hence the grinding stiffness and the grinding force are constant, and the deformation of the workpiece and the machine induced by grinding force is constant [22,23]. Finally, the wheel depth of cut is the ratio of the wheel feed rate and the table rotation speed and a wheel depth of cut down to tens of nanometers is easily achieved. This very small depth of cut is indispensable for grinding with low surface roughness and low subsurface damage [2,22].

In recent years, this grinding method has been widely adopted for the production of large sized silicon wafers [2,25–27]. Current technology is capable of producing 300 mm silicon wafers with global flatness less than 0.2 μm and surface roughness R_a less than 1 nm [28]. Extremely smooth silicon wafer with surface roughness of 0.6 nm R_a and subsurface defected layer less than 60 nm has been successfully achieved by using a mesh #12,000 vitrified bond diamond wheel [29].

However, the application of this grinding method has long been confined to grinding flat wafers. In infeed grinding with a rotary table and a cup wheel, the wheel radius, the center distance between the rotary table and the wheel, the wheel inclination angle and the rotary table direction angle are variable. A great diversity in selection of these machine configuration parameters enables to grind rotationally symmetric surfaces with various shapes. In this study, the theoretical basis for the rotationally symmetric surface generation by this grinding method was developed. The possible shape types of the generating curves and the substantial influence of the machine configuration parameters on their shape characteristics were analyzed.

2. Mathematical model for the rotationally symmetric surface generation

In infeed grinding with a rotary table and a cup wheel, since the end face of the cup wheel is only a few millimeters wide, the arc shaped grinding contact zone between the wheel and the workpiece is so narrow that it can be regard as a contact arc. While grinding, the trailing edge of the end face is responsible for the surface generation, hence the trailing edge circle is defined as the cutting circle of the cup wheel. Point O_2 is at the center of the cutting circle. Point O_1 is the perpendicular foot at which a straight line through Point O_2 intersects perpendicularly to the rotational axis of the rotary table. As shown in Fig. 2, four right-handed Cartesian coordinate systems are used to define the rotationally symmetric surface generation. Point O_2 and point O_1 are designated as the origins of the wheel coordinate system O_2 (X_2, Y_2, Z_2) and the workpiece coordinate system O_1 (X_0, Y_0, Z_0) respectively. The wheel inclination angle relative to the rotational axis of the rotary table is represented by α. The z_2-axis is aligned with the rotational axis of the cup wheel. The bottom most point of the cutting circle is on the y_2–z_2 plane and the intersection of the cutting circle with the negative y_2-axis is defined point P_0. The z_1-axis is parallel with the axis of the work table and the x_1-axis is consistent with the x_2-axis. Coordinate system O_2 (X_1, Y_1, Z_1) can be obtained by rotating the coordinate system O_2 (X_2, Y_2, Z_2) by an angle α about the x_2-axis. The z-axis is aligned with the axis of the rotary table, and the x-axis is aligned with the x_2-axis. The rotary table direction angle,