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Study on axial-feed mirror finish grinding of hard and brittle materials in relation to micron-scale grain protrusion parameters

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ABSTRACT

An axial-feed mirror finish grinding of hard and brittle materials is proposed by controlling grain protrusion parameters. In this grinding, the grinding wheel feed is along the wheel axial direction rather than in the traditional wheel cutting direction. The objective is to understand how micron-scale grain protrusion parameters influence ductile-mode grinding and ultimately to realize efficient mirror finish grinding using a coarse diamond grinding wheel. In this study, the grain tip truncation (GT-truncation) was performed after dressing to improve grain protrusion topography. First, a formation model of axial-feed ground surface was constructed to analyze the effect of grain protrusion parameters and grinding parameters on the critical cutting depth transferred from brittle-mode removal to ductile-mode removal; then GC dressing and GT-truncation of #180 diamond grinding wheel were experimentally performed to investigate surface roughness and ductile-mode grinding behavior with reference to grinding parameters and grain protrusion parameters; finally, a truncated coarser #60 diamond grinding wheel was employed for mirror finish grinding to observe active grain number and grain protrusion angle. Theoretical analysis shows that this ductile-mode grinding is dominated by active grain number, active grain protrusion angle, wheel rotating speed and axial-feed speed, but it does not depend on the depth of cut assumed to be less than the grain protrusion height. Experimental results indicate that the GT-truncation may increase active grain number and grain protrusion angle for ductile-mode grinding when the axial-feed speed decreases to some extent. Moreover, the micro tip radius of diamond grain also influences the ground surface. It is confirmed that by increasing active grain number and grain protrusion angle synchronously, a truncated #60 diamond grinding wheel can be applied for efficient mirror finish grinding of the SiC ceramic plate at the axial-feed speed of 50 mm/min and the tool path interval of 0.1 mm.

1. Introduction

Generally, a polishing method is employed to achieve final mirror finish surface of hard and brittle materials [1], but the loose abrasive slurry used in polishing operation leads to low production efficiency and pollution. Therefore, a polishing-free mirror finish grinding manner has been developed using a superfine diamond grinding wheel instead of this traditional polishing method [2–4]. This is because the micron-scale or submicron-scale abrasive grains broken off from the working surface of grinding wheel still rub the ground surface without any damage to the ground surface in contrast to coarser ones. However, it is very difficult to dress superfine diamond grinding wheels.

To realize mirror finish grinding without any polishing, a rotating GC cup truer that swings around the grinding wheel has been employed to perform dressing of #3000 diamond grinding wheel [2], but it requires a large-size dressing device and an additional NC system installed in the grinder. Moreover, an ELID method has been successfully applied to the dressing of superfine diamond grinding wheel for mirror grinding because it can efficiently protrude superfine diamond grains from the wheel working surface [3], but it needs to compensate online wheel wear with complex CNC equipment and also requires a pollution-carrying electrolyte solution. Due to the limited cutting ability of superfine abrasive grains, this still brings out low production efficiency.

In traditional grinding process, the coarse diamond grains are often broken off from the working surface of grinding wheel, leading to a mechanical damage to the ground surface. Therefore, the finished surface cannot be achieved using a coarse diamond grinding wheel. In order to improve ground surface, a finer diamond grinding wheel should be employed. In grinding of SiC

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ceramics, #120, #240 and #500 diamond grain sizes are utilized to achieve the surface roughness values of 0.20–0.60, 0.15–0.55 and 0.1–0.45 μm, respectively [5]. Nowadays, the diamond grain size should be finer than #3000 to perform the mirror finish grinding of hard and brittle materials using traditional plunge grinding and traverse grinding approaches.

The recent researches show that the 3D shape and the orientation of coarse diamond abrasive grain greatly influence the critical cutting depth transferred from brittle-mode removal to ductile-mode removal for hard and brittle materials in single point diamond turning experiments [6–7]. For example, the critical cutting depth of optical glass may be enhanced from 60 to 160 nm when the grain rake angle changes from -35 to -90° using a #46 diamond grain tool [6]. Moreover, a straight-nose diamond tool with a rake angle of -20° and a clearance angle of 26° may be used to perform efficient ductile-mode cutting of single-crystal silicon in comparison with traditional arc-nose diamond tool [7]. These researches indicate that if the suitable abrasive grain protrusion shapes and orientations distributed on a wheel working surface could be controlled in grinding operation, ductile-mode grinding may be performed by using a coarse diamond grinding wheel.

In actual grinding operation, the abrasive grain protrusion shapes and orientations are dispersedly distributed on the wheel working surface. Actually, it is very difficult to investigate and control the micron-scale grain protrusion topography. Therefore, many researchers focused on online monitoring wheel protrusion topography during grinding. For example, a grinding sound discrimination was carried out to evaluate wheel working surface [8,9], a laser localizer was used to adjust the condition changes of wheel working surface [10], and a discharge current trace was monitored to regulate micro-removal of wheel bond for electro-contact discharge dressing of fine diamond grinding wheel [11]. Although they can achieve some information about active grain number and mean grain protrusion height, the grain protrusion shape and orientation have not yet been investigated and controlled for actual precision grinding.

Recently, it has been found that 3D distribution of grain protrusion heights and its 3D spatial attitudes may be qualified by computer processing of 3D coordinate data derived from the working surface of #180 diamond grinding wheel using a self-adaptive measurement on a CMM meter [12]. In this research, a dressing method may be employed to enhance the active grain number and the negative grain rake angle, but it has not yet been applied to actual grinding of hard and brittle materials.

It has also been reported that after dressing, a truncation approach is employed to truncate grain protrusion profile for increasing active grain number [13]. It is found that this truncation approach can improve ground surface of hard and brittle materials. However, until now it has not yet been known how actual grain protrusion parameters influence ductile-mode grinding and whether improving grain protrusion parameters can realize mirror finish grinding.

In order to save dressing time, a #140 diamond grinding wheel has been employed in an axial-feed grinding manner to perform super-smooth grinding of hard and brittle materials instead of a traditional grinding manner [14]. It can eliminate the scratches on the ground surface along the wheel cutting direction. Moreover, in planning 3D tool paths for envelope grinding of free-form surface, the arc-shaped grinding wheel is driven to move along the wheel axial direction, leading to a super-smooth curve surface of steel mould core [15]. However, how grain protrusion parameters influence ductile-mode grinding of hard–brittle materials in the axial-feed grinding has not yet been studied in detail.

In this paper, an axial-feed mirror finish grinding is proposed by controlling grain protrusion parameters and grinding parameters. In this grinding manner, the grinding wheel is driven by CNC system to move along the wheel axial direction rather than the wheel cutting direction in traditional plunge grinding or traverse grinding. The objective is to understand how grain protrusion parameters and grinding parameters influence ductile-mode grinding of various hard and brittle materials such as SiC ceramics and granite. Its advantage is to realize efficient mirror finish grinding using a coarse diamond grinding wheel. First the theoretical formation model of axial-feed ground surface was constructed to analyze the effect of grain protrusion parameters and grinding parameters on critical grain cutting depth, then the axial-feed grinding experiments were carried out using a #180 diamond grinding wheel to observe the ductile-mode grinding behavior related to grain protrusion parameters and grinding parameters, finally mirror finish grinding of SiC ceramic plate was performed using a coarser #60 diamond grinding wheel to investigate the changes of grain protrusion parameters.

2. Surface formation model of axial-feed grinding

Fig. 1 shows the scheme of the axial-feed grinding. In this grinding, the grinding wheel is driven by the CNC system along the wheel axial direction that is perpendicular to the wheel cutting direction. The envelope traces on the ground surface along the wheel cutting direction are produced by bordering wheel outer profiles. The distance between bordering tool paths is called tool path interval f_x. Because the outer diameter D_w of grinding wheel is much larger than f_x, the envelope trace height h_e is given by

$$h_e \approx \frac{f_x^2}{4D_w} \quad (1)$$

It is indicated in Eq. (1) that a decrease in tool path interval f_x yields a decrease in envelope trace height h_e. For example, h_e may be decreased to 14 nm and less as f_x=0.1 mm and D_w=180 mm in this study. This also means that the ground surface may become smooth by decreasing the f_x to some extent.

Fig. 2 shows the formation model of axial-feed ground surface for a single abrasive grain cutting. On the YZ-section specialized by wheel axis, the grain protrusion profile is replicated on the workpiece surface to form the ground surface profile in grinding operation. The replicated YZ-section profile may stand for the microscopic rough topograpy of ground surface. This rough profile height h_r is dominated by grain protrusion angle β and grain cutting interval f_g on the assumption that the h_r is less than the depth of cut a, or grain cutting depth d_g is always equal to the depth of cut a. f_g is given by

$$f_g = \frac{v_f}{Nn_g} \quad (2)$$

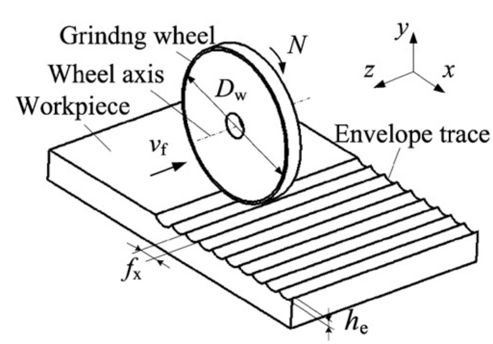

Fig. 1. Scheme of axial-feed grinding.