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Study on grinding force modelling and ductile regime propelling technology in micro drill-grinding of hard-brittle materials

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ABSTRACT

This study developed a new micro drill-grinding tool for precision micro-drilling of hard brittle materials, such as alumina ceramic and soda-lime glass, and analyzed the material removal mechanism of micro drill-grinding. A model of the micro drill-grinding force F_z was built using a physical method based on the undeformed chip thickness h_m. Experiments examining micro drill-grinding were conducted on a micro-machining desktop for micro drill-grinding. The failure modes and the lifespan of this new tool were investigated compared to the conventional micro-grinding method. The variation of the micro drill-grinding force was investigated, and the effects of rotation speed n_g are discussed. The change law of F_z was revealed based on experimental results, which also verified the scientific internal logic relation of the model that this study proposes. The brittle–ductile transition in the micro drill-grinding of hard brittle materials was investigated. A ductile regime propelling technology of a resin coating was proposed and successfully developed in this study. This paper demonstrated that this technology could effectively propel the ductile-regime of soda-lime glass in micro drill-grinding and reduce the fracture size. Experimental machining examples indicate that the average fracture size is reduced from 239.58 μm to 15.11 μm, and the ductile regime is propelled from 50 nm/rev to above 200 nm/rev. The technique and knowledge that this study proposes could provide a significant contribution to the precision micro-machining of hard brittle materials.

1. Introduction

Hard brittle materials, such as ceramic and glass, because of their high hardness and temperature stability, play a pivotal role in products for such fields as aviation and the optical industry (Dornfeld et al., 2006). Moreover, the manufacturing of these products has experienced a recent miniaturization and precision trend. In particular, grinding with the drilling method is a new application for precise small size holing (Chen et al., 2011). Therefore, how to precisely achieve a micro-scale hole with high quality is a critical question that absorbs more and more research interests worldwide.

As previously mentioned, the current trend in drill-grinding of hard brittle materials is towards miniaturization and high precision. Therefore, the precision drill-grinding technology at micro-scale is urgently required by the industry, and how to achieve super high precision and the effects of parameters during the grinding process are obviously important and significant. Laser beam machining (LBM) is an important and effective solution for micro-drilling (Nikumb et al., 2005), but it has a harmful thermal effect on hard brittle materials. Other methods such as ultrasonic grinding (USM) could well solve the heat problem, but the crack and brittle fracture are the main disadvantages (Zhang et al., 2004). Micro-grinding, as a solution for cutting hard brittle materials at micro-scale with high precision, has a tool diameter of almost less than 1 mm (Schaller et al., 1999). Especially in micro-drilling, micro-grinding has superior low heat effects and high accuracy compared to laser machining and electrochemical discharge machining (EDCM). Aurich et al. (2009) achieved the most precise surface through micro-grinding (10 nm roughness) and fabricated a series of micro-grinding tools (diameters between 13 μm and 100 μm). Cheng and Gong (2013) proposed an analytical model to define the ductile-regime transition in the soda-lime micro-grinding process and finally gave two critical ductile conditions: 2 nm and 5 nm. An experiment of micro-grinding on a single crystal silicon was conducted and the crystallographic effect was investigated by Cheng and Gong (2014). Morgan et al. (2007) carried

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out several micro-grinding experiments on glass and tungsten carbide to verify that micro-grinding could improve the surface quality of hard brittle and difficult to cut materials. Liang et al. (2010) built a two-dimensional ultrasonic assisted grinding experiment on monocrystal silicon using single diamond abrasive grain; the grinding results such as the material removal rate and the surface quality were better than the traditional grinding method in different brittle materials. Feng et al. (2012) built two surface generation models to describe different material removal mechanisms and verified the results using the FEM method. Smith et al. (2009) proposed and developed a new micro laser tooling technology that could accurately order single grain parameters such as rake face and flank face. A far superior processing quality and low grinding force were achieved in a grinding experiment on Ti-6Al-4V (Smith et al., 2011), and this study provides an exciting direction for micro-grinding research. Chen and Lai (2012) built several micro-scale grinding tools by WEDG, electroforming, electrochemical co-deposition and RWEDM. For ceramic grinding, Agarwal and Rao (2013) built an analytical model to predict the force and power based on the undeformed chip thickness. Denkena et al. (2013) use a toric grinding pin for biomedical ceramics grinding and built the roughness model.

All the works mentioned above mainly focused on precision process parameters and tool fabrication of micro-grinding, with little concern for the differences between micro-grinding and micro drill-grinding during the micro-drilling process of hard brittle materials. The reviews above show that the micro-machining approaches that have been introduced could provide mostly micro-scale process solutions. However, for machining micro holes of hard brittle materials, some are harmful to the environment and some are costly with low efficiencies. For example, the simple micro-grinding method could bring a large cost for using tools because of the wear at the tool's circle centre in holing. Therefore, finding one more suitable micro-machining method for machining micro holes is significant for research and industrial applications. The new method must be simple to carry out, cost effective and high precision.

On the other hand, for the combination of grinding and drilling techniques in holing, some researchers have made some achievements. Chen et al. (2011) developed and successfully applied a new grinding-drilling tool at small-scale, which notes and verifies that micro-grinding is suitable for micro holes machining of hard brittle materials. Yan et al. (2002) fabricated micro-holes of 150 μm diameter by micro EDM on borosilicate glass. Baek et al. (2013) used the ultrasonic machining method to fabricate small holes with wax coating and abrasive slurry, and the thickness of the coating affected the micro-grinding surface quality. All of these studies provide valuable contributions for drill-grinding research. However, some of those works are not within the micro-scale, and the brittle–ductile transition and its propelling method, which are important for precision micro drill-grinding, are not discussed in detail.

This study attempts to investigate the material removal mechanism in micro drill-grinding of hard brittle materials. A diamond micro drill-grinding tool is fabricated, and micro drill-grinding experiments of alumina ceramic and soda-lime glass are carried out on a precision micro-machining desktop. Moreover, a model is built for predicting the micro drill-grinding force. The change law of the micro drill-grinding force has been revealed. To achieve a super high precision without reducing productivity in micro drill-grinding, a ductile regime propelling technology of resin coating, which could highly effectively propel the ductile regime in micro drill-grinding of hard brittle materials, is first proposed and successfully verified in micro drill-grinding experiments of soda-lime glass in this study. The experiment results indicate that this technique could propel the ductile regime from 50 nm/rev to 200 nm/rev in the micro drill-grinding process of soda-lime glass, which notably increases the processing range for high precision micro drill-grinding.

2. Micro drill-grinding principle

2.1. Development of a diamond micro drill-grinding tool

Micro drill-grinding, unlike the current common micro-grinding method, is a new technology for micro-drilling. In the conventional micro-grinding method in holing, the micro-grinding tool works through a spiral trajectory, which is simple for tool fabrication and holing processes. Moreover, the rotational velocity of the tool centre is 0 mm/s during the micro-grinding process. This method has several disadvantages such as rapid grains falling off from substrate and chip squeeze, which can decrease the micro-grinding tool's life. Therefore, considering these weak points of conventional micro-grinding technology in holing, this paper proposes a micro drill-grinding method and develops its micro drill-grinding tool, as Fig. 1(a) shows.

This micro drill-grinding tool has four grinding blades, straight up and down when drill-grinding. A long hollow central hole is fabricated to avoid the occurrence of zero speed grinding. Two grinding circular truncated cone structures for chambering are designed behind the tool tip to satisfy more processing requirements by one working step. The grinding blades and central hole are all machined by micro-milling, which is indeed low cost and effective compared to the existing techniques, which use Micro-EDM, etc.

The inner diameter and outer diameter of the micro drill-grinding tool are designed to be 300 μm and 900 μm. The two chambering steps' diameter are 2 mm and 3.53 mm, and the grain number is supposed to be 500#, which has a nearly 20 μm grit size.

The geometry model of the micro surface-grinding is shown in Fig. 1(b). The micro-surface grinding path is single grit in, and the movement along the work piece's surface is the previous grit's cutting path. “AA′” equals “s”, which is the work piece's movement during the cutting time of the two adjacent grits and could be expressed by the work piece's feed rate speed (v_w) multiplied by time.

The undeformed chip thickness h_m of the micro-surface grinding could be expressed by Eq. (1) after considering the relation between d_s and a_p in the micro-grinding process.

$$h_m = 2s\left(\frac{a_p}{d_s}\right)^{1/2}\left(1-\frac{a_p}{d_s}\right)^{1/2} - \frac{s^2}{d_s} \quad (1)$$

where h_m is the undeformed chip thickness, a_p is the grinding depth, and d_s is the wheel diameter.

Meanwhile, a component variable M_d was proposed to describe the effects when grinding enters micro-scale (Cheng et al., 2014), and its value is derived by regression analysis based on experimental results. Then, h_m could be expressed by the following equation.

$$h_m = M_d\left[2s\left(\frac{a_p}{d_s}\right)^{1/2}\left(1-\frac{a_p}{d_s}\right)^{1/2} - \frac{s^2}{d_s}\right] \quad (2)$$

Finally, the undeformed chip thickness in micro-grinding is defined by the following equation, where L is the distance between two adjacent grits.

$$h_m = M_d\left[2\left(\frac{Lv_w}{v_s}\right)\left(\frac{a_p}{d_s}\right)^{1/2}\left(1-\frac{a_p}{d_s}\right)^{1/2} - \frac{L^2}{d_s}\left(\frac{v_w}{v_s}\right)^2\right] \quad (3)$$

Different from the conventional micro-grinding method, the micro drill-grinding tool tip's structure and its grinding zone have their own material removal mechanism. A hollow central long hole is designed to avoid the zero grinding velocity and squeezing effect, as Fig. 1(c) shows, where h (1 mm) and r_h (150 μm) are its depth and radius. r_1 (150 μm) is the arc radius of the grinding blade and r_2