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A novel method for determination of the subsurface damage depth in diamond turning of brittle materials

De Ping Yu *, Yoke San Wong [1], Geok Soon Hong [2]

National University of Singapore, Deptartment of Mechanical Engineering, Singapore 119260, Singapore

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ABSTRACT

Micro-structured surfaces on brittle materials, e.g. ceramic and glass, are gaining increasing industrial applications such as optics, semiconductor and biomedical. However, these materials tend to be damaged with brittle fracture in machining. To generate crack-free surfaces, ductile-regime machining should be maintained for the entire micro-structured surface. In ductile-regime machining the material is removed by both plastic deformation and brittle fracture, but the cracks produced are prevented from extending into the finished surface. In this paper, a machining model has been developed for fast tool servo (FTS) diamond turning of micro-structured surfaces on brittle materials. Based on the model, a damaged region analysis method (DRAM) is proposed to determine the subsurface damage depth (C_m) by analyzing the surface damaged region of a machined micro-structured surface with sinusoidal wave along radial direction. Only one micro-structured surface is required to be machined to obtain C_m, which greatly reduces the effort for determination of C_m. With C_m, the maximum feedrate for machining a crack-free micro-structured surface can be determined. Machining experiments have verified the validity of DRAM.

1. Introduction

There has been an increasing use of precision components with micro-structured surfaces, e.g. micro-lens arrays, Fresnel lenses, pyramids array, polygon mirrors, aspheric lenses, multi-focal lenses, corner-cubes, two-dimensional planar encoders, and antireflective gratings or channels, on hard and brittle materials such as ceramics and glasses in a range of industries such as optics, semiconductor and biomedical [1–3]. However, it is challenging to machine micro-structured surfaces with mirror surface finish on brittle materials due to their low fracture toughness. It is widely accepted that ductile regime machining should be maintained during machining in order to achieve high quality finish.

According to the hypothesis of ductile regime machining, all brittle materials will undergo a transition from brittle to ductile machining region at a critical undeformed chip thickness. Below this threshold, plastic deformation becomes energetically favorable as compared with fracture and the material will deform instead of fracture [4,5]. Liu et al. [6] observed that the ductile cutting mode can be realized when the undeformed chip thickness is smaller than the tool cutting edge radius and the tool cutting edge radius is small enough. Cai et al. [7] studied the nanoscale ductile mode cutting of monocrystalline silicon wafer by the employing molecular dynamics method. He found that the thrust force dominates the cutting force, leading to compressive stress in the cutting zone. However, as the undeformed chip thickness increases, this compressive stress decreases, giving way to crack propagation in the chip formation zone. Fang et al. [8] proposed an extrusion-based model for nanometric cutting and explained that when the undeformed chip thickness is smaller than the tool cutting edge radius, the negative effective rake angle produces necessary compressive stress in the cutting zone to enable plastic deformation. Nevertheless it does not necessarily mean that the larger the tool cutting edge radius, the better the ductile mode cutting. Arefin et al. [9] reported that there is an upper bound of the tool cutting edge radius for ductile mode cutting of brittle materials, e.g. 700–800 nm for silicon.

There are two important parameters relating to ductile regime machining, i.e. critical depth of cut (t_c) and subsurface damage depth (C_m), which may be experimentally or analytically obtained. Marshall and Lawn [10] performed indentation experiments on different materials and proposed Eq. (1) to t_c of penetration by the indenter for crack initiation:

$$t_c = \Psi(E/H)(K_c/H)^2, \quad (1)$$

* Corresponding author.
E-mail addresses: williamydp@yahoo.com.cn (D.P. Yu), mpewys@nus.edu.sg (Y.S. Wong), mpehgs@nus.edu.sg (G.S. Hong).
[1] Tel.: +65 6516 2221.
[2] Tel.: +65 6516 2272.

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where E is the elastic modulus, H is the hardness, K_c is the fracture toughness and Ψ is a dimensionless constant dependent on indentation geometry. Bifano et al. [11] extended Eq. (1) to relate the grinding in-feed rate necessary for ductile material-removal with the properties of the brittle workpiece material and estimated Ψ to be 0.15. However, for a specific machining process, e.g. micro-milling and diamond turning, the complex tool–workpiece interaction differs dynamically and geometrically from the deformation produced in indentation. Therefore, different experimental methods have been proposed to determine t_c for different machining processes. For micro-milling, Matsumura et al. [12] related the ductile and brittle mode machining to the behavior of the cutting force and found that the ductile mode machining is characterized by a smooth force signal while that from the brittle mode machining oscillates about a constant mean value. Thus, t_c can be estimated from the differences in the two types cutting force signals. For diamond turning, plunge cutting is a quite straightforward method to determine t_c by observing the transition of the cutting mode from ductile to brittle [13]. In addition, Blake and Scattergood [5] proposed an interrupted-cutting test to study the ductile-to-brittle transition at the shoulder region and a machining model to determine t_c from the location of the ductile-to-brittle transition. As to the subsurface damage depth C_m, Marshall et al. clearly identified the various radial and lateral crack systems associated with indentation [14] and proposed models to predict the size of the radial and lateral cracks [15,16]. Arif et al. [17] claimed the milling process to be analogous to indentation and derived an analytical model to determine the critical feed per edge to achieve ductile mode machining based on Marshall et al.'s models [15]. For diamond turning, Blackley and Scattergood [18] proposed a phenomenological model of the ductile-to-brittle transition to quantitatively determine t_c and C_m.

Unlike conventional diamond turning the fast tool servo (FTS) diamond turning enables precision machining of complicated micro-structured surfaces, including both axisymmetric and non-axisymmetric surfaces, which is difficult to be achieved by grinding and lapping. Most of the previous researches focused on the development of the FTS itself for higher performance, i.e. higher bandwidth, larger stroke, higher stiffness, etc. [19–23]. In addition, ductile materials, e.g. copper, brass and aluminum were machined to prove the performance of their developed FTS. However, few researches have been devoted to FTS diamond turning of micro-structured surfaces on brittle materials. Therefore, in this paper, a machining model has been developed for FTS diamond turning of micro-structured surfaces on brittle materials. Based on the model, a damaged region analysis method (DRAM) has been proposed to determine the subsurface damage depth (C_m) by analyzing the surface damaged region of a machined micro-structured surface with sinusoidal wave in the radial direction. With C_m, the maximum feedrate for machining a crack-free micro-structured surface can be determined. Machining experiments have been carried out to verify the validity of DRAM.

2. Theory on FTS diamond turning of brittle materials

2.1. FTS diamond turning of micro-structured surfaces

FTS diamond turning evolves from conventional diamond turning to ultra-precision fabrication of complicated micro-structured surfaces, including both axisymmetric and non-axisymmetric surfaces. It is realized by integrating a specially designed tool servo into conventional diamond turning machine to drive the cutting tool in and out of the workpiece when it is rotating. Depending on the bandwidth of the tool servo, it can be named as slow tool servo (STS) [24,25] or fast tool servo [19–23,26]. Fig. 1 shows a FTS diamond turning machine in which there are totally four axes: X axis—the x slide, Z axis—the z slide, C axis—the spindle and W axis—the FTS. Such a machining system is expressed in cylindrical coordinates (ρ, φ, z), whereas, the surface model to be machined is expressed in Cartesian coordinates (X, Y, Z). For conversion between the two coordinate systems, it is convenient to assume that the Z-axis of both systems is coaxial and then the correspondence between the cylindrical coordinates (ρ, φ) and Cartesian coordinates (x, y) is

$$\begin{cases} \rho = \sqrt{x^2+y^2} \\ \varphi = F(\tan^{-1}(x/y)) \end{cases} \Leftrightarrow \begin{cases} x = \rho\cos\varphi \\ y = \rho\sin\varphi \end{cases}, \tag{2}$$

where $F(\cdot)$is to determine the total angle rotated after start machining.

Consider the micro-structured surface with sinusoidal wave along radial direction (SWR); it can be described by

$$z(x,y) = A\sin\left(\frac{2\pi\sqrt{x^2+y^2}}{\lambda}\right), \tag{3}$$

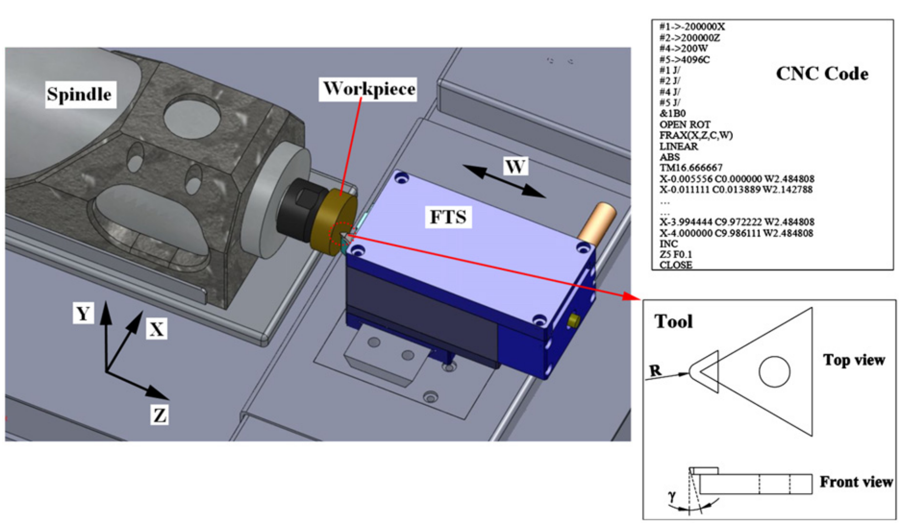

Fig. 1. Working principle of FTS diamond turning.