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Theoretical modelling and FE simulation on the oblique diamond turning of ZnS crystal

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ABSTRACT

In diamond turning of Cleartran ZnS crystal, the input cutting parameters have significant influences on the appearance of pit or crack defects on the finished surface. Therefore, a novel oblique cutting model is developed in this work to improve the surface quality of Cleartran ZnS crystal, in which a crack-free surface is supposed to be finished in a brittle–ductile coupled mode. And subsequently, fly-cutting experiments are performed to find the brittle–ductile transition depth of Cleartran ZnS substrates, which is employed to qualitatively determine the critical uncut chip thickness and predict the critical cutting parameters, including depth of cut, tool feed rate and rake angle. Moreover, a 3D finite element cutting model of Cleartran ZnS crystal is also constructed by using the nanoindentation test and dimensional analysis method, with which the crack propagation in chip formation can be simulated. In such a way, the predicted critical cutting parameters can be validated by the cutting experiments and finite element simulation. The results show that the oblique cutting process is an effective approach to relax the critical cutting parameters and reduce the shear stress ahead of tool cutting edge, which in return heavily suppresses the crack propagation and grain breakage. As a result, the achieved surface quality is improved.

1. Introduction

Single point diamond turning (SPDT) process is of great importance for the fabrication of precision parts in various industrial sectors, such as optics, clean energy, information and communication technology, and others [1,2]. Due to the lower production cost and satisfactory surface damages, SPDT has become a promising solution to fabricate the high-quality soft and brittle crystals, such as zinc selenide (ZnSe), zinc sulfide (ZnS) and calcium fluoride (CaF_2) [3,4].

ZnS crystal is one of the most popular materials used in infrared transmitting windows or domes for systems operating in the long wave region [5]. However, it is difficult to be machined due to its poor fracture toughness, low hardness and random crystal orientation. Such properties tend to arouse the unwanted fractures or pits, which finally results in a damaged or non-transparent surface. Therefore, in order to achieve a damage-free surface, the topmost surface layer of ZnS crystal is supposed to be removed in ductile mode, in which the critical uncut chip thickness (CUCT) is usually configured at the submicron scale [6]. As known in diamond turning of brittle materials, to finish a smooth surface heavily relies on the machining environment, performance of machine tool, process parameters, tool geometries, cutting edge radius as well as material properties of workpiece [1,7]. In diamond turning of metallic materials, it has also been demonstrated that the critical cutting condition, such as the minimal or maximal undeformed chip thickness, is primarily attributed to the process parameters, tool geometries, cutting edge radius, properties of workpiece, and so forth [8,9]. Thus, interesting questions are raised but not answered satisfactorily: is there a brittle–ductile coupled model that accurately predicts the critical cutting condition in diamond turning of ZnS crystal? Furthermore, can the oblique cutting well improve the finished surface quality?

In order to answer those questions, it is important to know the properties of such soft and brittle material. In general, the CVD ZnS crystal has a grain size of 2–8 μm. And the Cleartran ZnS crystal, i.e. the so-called m-ZnS crystal, can be prepared from the CVD ZnS crystal through hot isostatic pressing process, in which the grain size grows up to 20–200 μm [5]. The increase in grain size results in a reduction of the mechanical strength and hardness. The synthetic Cleartran ZnS is typically a mixture of the cubic (sphalerite)

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Nomenclature

f_1	Feed rate in workpiece coordinate system
f_{2x}	Feed rate along X_2-axis in tool coordinate system
f_{2y}	Feed rate along Y_2-axis in tool coordinate system
f_{2z}	Feed rate along Z_2-axis in tool coordinate system
a_{p1}	Cutting depth in workpiece coordinate system
a_{p2x}	Cutting depth along X_2-axis in tool coordinate system
a_{p2y}	Cutting depth along Y_2-axis in tool coordinate system
a_{p2z}	Cutting depth along Z_2-axis in tool coordinate system
h	Indentation depth
h_f	Residual indentation depth
h_2	Uncut chip thickness in tool coordinate system
h_{c2}	Critical uncut chip thickness in tool coordinate system
m	Fitting coefficient used for modeling the stress–strain curve
n	Strain hardening exponent
r_n	Tool cutting edge radius
d_c	Brittle–ductile transition depth
C_m	Length of medial crack in workpiece coordinate system
C_{m2}	Critical length of medial crack in tool coordinate system
K_{IC}	Quasi-static fracture toughness
K_{ID}	Dynamic fracture toughness
E	Young's modulus
H	Vickers hardness
Q	Indention force
V_1	Cutting velocity in workpiece coordinate system
F_c	Principal cutting force
S_0	Actual cutting area
S_1	Plastic deformation area
S_2	Brittle fracture area
R	Tool nose radius
P_L	Loading force in nanoindentation
P_U	Unloading force in nanoindentation
A	Fitting coefficient used for modeling the stress–strain curve
B	Fitting coefficient used for modeling the stress–strain curve
α	Strengthening coefficient
η	Coefficient
η_0	Coefficient in relation to the dynamic effects
λ	Tool oblique angle
γ	Tool rake angle
σ	Engineering stress
σ_s	Yield strength
σ_b	Fracture strength
ε	Engineering strain
ε_s	Yield strain
φ	Transition angle of triangle used for modeling
θ	Transition angle of triangle used for modeling
ρ	Density
ν	Poisson ratio

and hexagonal (wurzite) crystal structures, as well as a host of polymorphs, which are derived from the former two basic structures [10]. Except for the material properties, it is also essential to enable the ductile regime machining on the Cleartran ZnS crystal, with which a crack-free and low residual stress surface can be achieved. In this field, many previous work concerning the material removal mechanism of brittle materials can be referred.

The first investigation on the plastic deformation characteristics of brittle materials was performed by King et al. [4]. In their work, it was found that the material removal of rock salts presents a ductile manner under a highly hydrostatic pressure during the frictional wear. Lawn et al. reported that there is a critical depth for the plastic deformation of brittle materials in indentation, in which the 'size effect' appears [11,12]. They claimed that from the macroscopic viewpoint the brittle materials, such as glass and ceramics, will exhibit a plastic response at the submicron scale. Subsequently, Marshall et al. validated Lawn's work by conducting indentation trials on various brittle materials, and they finally proposed a brittleness independent perspective, i.e. that the brittle materials always present some ductility as long as the deformation scale is small enough [13]. Blake and Scattergood presented a brittle–ductile transition model in terms of the energy consumption in material removal. Under their theory, the ratio of plastic flow energy to fracture energy is proportional to the uncut chip thickness [14]. Yan et al. reported that the ductile regime machining generates the high enough hydrostatic pressures in the deformed brittle materials, including the compressive and shear stresses, which well suppresses the crack propagation in chip formation. They claimed that the chip formation behaves in a plastic manner ahead of tool cutting edge if the depth of cut is small enough [15].

Furthermore, in order to explicate the removal mechanism in ductile regime machining of brittle materials, some interesting hypotheses had also been made. For example, Fang et al. explored the removal behavior of mono-crystalline silicon in nanometric cutting. As a result, an extrusion induced removal mechanism, rather than the shearing deformation theory, was proposed by using of molecular dynamics simulation and nano-indentation [16]. Goel et al. carried out the cutting experiments on single crystal 6H–SiC to elucidate the microscopic origins of ductile-regime machining. They found that the occurrence of brittle–ductile transition is responsible for the ductile-regime machining, in which the structural phase transformation of workpiece associated with the diamond turning process is a prerequisite [17]. Venkatachalam et al. proposed a fracture toughness-dependent model to predict the uncut chip thickness for brittle–ductile transition in diamond turning of single crystal brittle materials, in which the cutting edge radius effect and ploughing were considered. They found that the brittle–ductile transition takes place when the fracture toughness is equal to the stress intensity factor [18]. Wang et al. found that the specific cutting energy can be considered as a criterion to distinguish the removal mode in scribing the hard and brittle materials [19]. Arif et al. presented a specific cutting energy related model to predict the critical brittle–ductile transition condition in diamond turning of brittle materials, into which the effects of material properties of workpiece, tool geometries and cutting parameters were integrated [6]. Bifano et al. thought that if the resolved shear stress at any point of the deformed brittle materials exceeds the critical value of plastic yield stress, the deformation mechanism will transform from elastic stretching to energy dissipation, which inevitably leads to the crack propagation [20]. Nakasuji et al. raised a new viewpoint that the brittle–ductile transition phenomenon depends on the cleavage fracture due to the presence of defect, e.g. dislocation. The critical condition for transformation from cleavage fracture to plastic deformation is related to the defect density in the deformed brittle materials. Since the defect density has a limitation in the brittle materials, the stress field size will heavily affect the critical condition. They declared that the cleavage fracture can be suppressed if the stress field size is smaller than the uncut chip thickness [21].