Computational Materials Science 92 (2014) 13–21

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Single-grit modeling and simulation of crack initiation and propagation in SiC grinding using maximum undeformed chip thickness

Dahu Zhu [a], Sijie Yan [b,*], Beizhi Li [c]

[a] School of Automotive Engineering, Hubei Key Laboratory of Advanced Technology of Automotive Parts, Wuhan University of Technology, Wuhan 430070, China
[b] State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China
[c] College of Mechanical Engineering, Donghua University, Shanghai 201620, China

ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form 26 March 2014
Accepted 12 May 2014

Keywords:
Numerical simulation
Crack initiation
SiC
Grinding
Undeformed chip thickness
Wheel speed

ABSTRACT

The application of engineering ceramics is often limited due to its low machining efficiency and surface/subsurface damage, of which surface/subsurface micro-crack is one of the major challenges during grinding. Single-grit simulation has been utilized to investigate the initiation and propagation of individual cracks in SiC grinding under controllable maximum undeformed chip thickness (M-UCT). The simulation results indicate that the material removal is dominated by the ductile-regime grinding when M-UCT is kept below 0.29 μm, resulting in the workpiece surface morphologies are less dependent on the wheel speed. Brittle removal mode becomes more significant and transverse cracks are initiated once M-UCT exceeds 0.3 μm. In brittle-regime, wheel speed is found to be a crucial factor of workpiece surface integrity, and median cracks can be effectively inhibited by moderate wheel speed. High speed grinding experiment in conjunction with a high workpiece speed is proposed as a solution for the brittle-to-ductile transition, resulting in desired surface morphologies and residual stress distribution. The M-UCT serves as a basis for users to select optimal process parameters.

1. Introduction

Engineering ceramic is widely employed in cutting tools, automobile engines, spacecraft, optical instrumentation and computer communications with its low density, strong corrosion resistance, wear resistance, high temperature resistance and excellent chemical inertness [1]. Its high hardness, high brittleness and low fracture toughness, however, make such material prone to generation of deformation layer, surface/subsurface micro-cracks, material powder, fuzzy surface, phase transformation zone, and residual stresses, limiting the adoption of great material removal rate. Among these defects, the attention on surface/subsurface micro-cracks is focused. In loading conditions, ceramics are high-risk to generate median/radial cracks [2]. With the removal of loads, cracks further propagate, then the median/radial crack system is generated, and the median/radial problem provides the framework for a complete analysis of crack evolution [3].

Extensive studies have been undertaken to investigate the machining-induced damage in ceramic grinding, and the material removal mechanisms are generally considered to be classified into three categories: brittle removal modes, including grain removal [4], spalling [5], brittle fracture [6], crushing [7]; powder removal mode [8]; and plastic removal mode [9]. For various brittle materials, the grinding feed corresponding to the brittle transition is associated with the material properties, such as fracture toughness, hardness, and elastic modulus [9]. In the case of sufficiently small grinding depth, brittle materials are removed by the plastic flow rather than the brittle fracture mode. Thus the research on brittle-to-ductile transition receives wide concerns and is applied into other materials behaving brittle and ductile properties, such as GaN nanotubes [10], lead-free solder joints [11], bulk metallic glasses [12,13], soda-lime glass [14], nanowires [15], biomaterials and hard tissues [16], and brittle single crystal materials [17,18].

Although ductile-regime grinding is capable of attaining better surface quality, it is inefficient and takes high processing costs owing to either low grinding depth or workpiece speed or both. Thus semi-ductile grinding comes into being [19]. Another approach for higher removal rate has been proposed while maintaining a small chip thickness through the utilization of high wheel speed and an optimum mesh size superabrasive [20,21]. However, the removal mode is not solely determined by the geometrically calculated M-UCT, and limited published work is available on the application of M-UCT to further characterize the crack initiation and propagation in ceramic grinding. In light of the aforementioned limitations, this paper aims to report the viability by using

---

* Corresponding author. Tel.: +86 27 87543437.
E-mail address: sjyan@hust.edu.cn (S. Yan).

http://dx.doi.org/10.1016/j.commatsci.2014.05.019
0927-0256/

the controllable M-UCT to investigate the initiation and propagation of transverse and median cracks in SiC grinding, and an approach based on single-grit simulation is employed in the present work.

2. Critical condition for ductile-regime grinding

The critical depth of cut for brittle-to-ductile transition of hard and brittle materials in grinding may be represented by the following empirical formulae [22]:

$$a_{gc} = K_0 \cot\left(\frac{\alpha_0}{2}\right)\sqrt{\frac{2\lambda_0}{\alpha}}\left(\frac{K_{id}}{H}\right)^2 \tag{1}$$

where K_0 is coefficient to brittle-to-ductile of the coolant, and a value of 1 is selected without coolant [22]; α_0, top angle, $\alpha_0 \approx 120°$, this value is adopted in the later simulation model; λ_0, integrative factor, $\lambda_0 = (1.0\text{–}1.6) \times 10^4$ [22]; α, geometry factor of the indenter, $\alpha = 1.8854$ [22]; H, micro-hardness of the material, $H = 25$ GPa for SiC; K_{id}, dynamic fracture toughness, $K_{id} \approx 30\% K_{ic}$ [22], and $K_{ic} = 5$ MPa m$^{1/2}$ for SiC. According to Eq. (1), a_{gc} for SiC is determined as 0.2–0.27 μm.

In addition, a well-known equation for calculating the M-UCT of single-grit is given by [23]:

$$a_{gmax} = \left[\frac{4}{Cr}\left(\frac{v_w}{v_s}\right)\left(\frac{a_p}{d_e}\right)^{1/2}\right]^{1/2} \tag{2}$$

where v_w is workpiece feed rate; v_s, tangential speed of the wheel; C, number of cutting points per unit area and $C = 3.2$ grits/mm^2 for the 50/60 grit wheel is estimated from micrographs of wheel surface by using the optical microscope [21]; r, chip width-to-thickness ratio and a value of 10 is chosen arbitrarily by Mayer and Fang [24], a_p, depth of cut; d_e, equivalent diameter of the wheel.

Consequently, the material removal mode is judged by the relationship between M-UCT and critical depth of cut, as shown below [22]:

$$a_{gmax} > a_{gc} : \text{Fracture mode} \tag{3}$$

$$a_{gmax} \leqslant a_{gc} : \text{Ductile mode} \tag{4}$$

3. Dynamic constitutive relation and failure model

Two important aspects, the dynamic constitutive equation of materials and the separation criteria of wear debris and workpiece (material failure model) must be solved when clarifying the removal mode of SiC through finite element method. In this paper, JH-2 constitutive model, proposed by Holmquist and Johnson [25], is utilized to describe the fracture damage of ceramic grinding. Notice that one of the key technologies in finite element simulation is to establish the constitutive relation for materials. Ceramic can be treated as an elastic material prior to destruction. When such material appears destruction, its intact strength will change with the damage. Therefore, the strength of ceramics can be described with intact strength, crushing strength, strain rate and damage variables. The JH-2 constitutive equation is given by Eq. (5) [26].

$$\sigma^* = \sigma_i^* - D(\sigma_i^* - \sigma_f^*) \tag{5}$$

where σ_i^* and σ_f^* denote the standardized strength of intact material and failure material, respectively, and D is material damage coefficient. Standardized equivalent strength of material (σ^*, σ_i^* and σ_f^*) is expressed by: $\sigma^* = \sigma/\sigma_{HEL}$, where σ is true equivalent stress for material, and σ_{HEL} is equivalent stress at Hugoniot. Then the standardized strengths both for intact material and failure material can be described by variables such as pressure and strain rate using Eqs. (6) and (7) [26].

$$\sigma_i^* = A(P^* + T^*)^N(1 + C\ln\dot{\varepsilon}) \leqslant \sigma^i_{\max} \tag{6}$$

$$\sigma_f^* = B(P^*)^M(1 + C\ln\dot{\varepsilon}) \leqslant \sigma^f_{\max} \tag{7}$$

where A, B, C, M, N are undetermined parameters of the material, P^* is standardized hydrostatic pressure and can be defined as $P^* = P/P_{HEL}$, P is hydrostatic pressure, P_{HEL} is hydrostatic pressure at HEL, T^* is standardized maximum hydrostatic tensile strength and can be defined as $T^* = T/P_{HEL}$, T is maximum hydrostatic tensile strength, and σ^f_{max} is maximum failure strength.

The hydrostatic pressure of intact material is given by Eq. (8) [27].

$$P = \begin{cases} K_1\mu + K_2\mu^2 + K_3\mu^3, & \text{if } \mu \geqslant 0 \\ K_1\mu, & \text{if } \mu \leqslant 0 \end{cases} \tag{8}$$

where $\mu = \rho/\rho_0 - 1$, and K_1, K_2, K_3 are material constants.

When the brittle material appears damage ($D > 0$), there will be volume expansion, and it is equivalent to the increase in pressure ΔP, thus the hydrostatic pressure of the material to produce damage is written as Eq. (9) [25].

$$P = K_1\mu + K_2\mu^2 + K_3\mu^3 + \Delta P \tag{9}$$

Seen from the perspective of energy loss, the pressure increment is given by

$$\Delta P_{t+\Delta t} = -K_1\mu_{t+\Delta t} + \sqrt{(K_1\mu_{t+\Delta t} + \Delta P_t)^2 + 2\beta K_1 \Delta U} \tag{10}$$

where β is conversion factor of elasticity loss energy and hydrostatic pressure potential ($0 \leqslant \beta \leqslant 1$).

Both the geometrical and physical separation criteria are the two main criteria for separation of the debris and workpiece. Separation criterion of JH-2 constitutive equation belongs to the physical separation criterion, which is used to determine the failure of brittle materials. Material failure parameter ω is defined as Eq. (11)[27].

$$\omega = \sum \frac{\Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_f^{pl}(P)} \tag{11}$$

where $\Delta\bar{\varepsilon}^{pl}$ is increment of equivalent plastic strain, $\bar{\varepsilon}_f^{pl}(P)$ is failure strain under the pressure P and is written as Eq. (12)[27].

$$\bar{\varepsilon}_f^{pl} = D_1(P^* + T^*)^{D_2}, \quad \bar{\varepsilon}^{pl}_{f,\min} \leqslant \bar{\varepsilon}_f^{pl} \leqslant \bar{\varepsilon}^{pl}_{f,max} \tag{12}$$

where D_1, D_2 are model constants, set $D = \omega$ when JH-2 model is employed. Suppose that the brittle material appears failure when $D > 1$, and then the failure element is removed from the mesh to achieve the debris separation.

4. Numerical simulation procedures

Single-grit simulation has been performed in accordance with the following procedures: geometry modeling, material modeling, kinematic modeling and process modeling. A two-dimensional model is utilized in this paper to reduce the computation time. Axinte et al. [28] have experimentally verified that circular base frustum grit leads to greater specific cutting force than those grits with square shape and triangular shape in grinding of brittle materials, however it produces extensive plastic deformation. With the advantage of circular grit, in the present work the geometry of single-grit is further improved and assumed as an ideal cone with a top cone angle of 120° coupled with the height of 0.12 mm and tip radius of 0.015 mm. Here the cone angle corresponds to the top angle in Eq. (1). SiC with dimension of 4 × 4 mm is to be