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Study on the system matching of ultrasonic vibration assisted grinding for hard and brittle materials processing

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ABSTRACT

Ultrasonic vibration assisted grinding (UAG) is an effective processing method for hard and brittle materials. Compared with common grinding (CG), both of grinding force and workpiece surface quality is improved by UAG, but the principle of improvement is still unclear. In order to reveal the mechanism of grinding force reduction and grinding quality improvement in UAG, this paper presents a mathematical model for system matching in UAG of brittle materials. Assuming that brittle fracture is the primary mechanism of material removal in UAG of brittle materials, the system matching model is developed step by step. On the basis of this mathematical model, the mechanism of grinding force reduction and surface roughness forming are discussed. The advantage of UAG processing brittle materials is pointed out in theory. Using the model developed, influences of input variables on grinding force are predicted. These predicted influences are compared with those determined experimentally. This model can serve as a useful foundation for development of grinding force models in UAG of brittle materials and models to predict surface roughness in UAG.

1. Introduction

Hard and brittle materials are attractive for many applications due to their superior properties [1]. These properties include high hardness and strength at elevated temperatures [2], chemical stability, low friction, and high wear resistance [3]. Machining of brittle materials has gained significant importance over the last two decades.

Hard and brittle materials were difficult to achieved efficient and high quality machining process by the traditional machining methods. Otherwise, UAG have a small grinding force, high material removal rate (MRR) and high machining quality [4], which plays an important role in hard and brittle materials processing. In UAG, The rotational movement of the grinding tool increases the MRR, improves the machining accuracy, reduces the cutting force [5] and lengthen the grinding tool's life [6].The MRR of UAG is 6–10 times of common grinding (CG) [7], and 4 times of ultrasonic machining [8]. In UAG, thermal burns, physical and chemical properties changes of work piece surface could be avoided [9]. Furthermore, the smaller surface roughness could be obtained and the surface integrity could be improved [10].

Both of grinding parameters and the ultrasonic parameters could be influenced the MRR in UAG [11]. The MRR increases as the spindle speed, feedrate, frequency and amplitude increase [12]. Material removal process both has brittle broken and plastic removal characteristics in UAG processing brittle materials [13]. The experiment shows that as the MRR increase, the surface of workpiece will not damaged [14]. The abrasive grain simplified for different shapes will get different MRR models and different grinding force models [15]. The grinding force and removal rate were influenced by spindle speed, feedrate, grinding depth, ultrasonic frequency, amplitude *etc.* [16].

This paper presented a mathematical model for system matching in UAG; moreover the grinding force model and the MRR model were presented. The paper first described the models development step by step, and then the influence of vibration frequency and amplitude on grinding quality is pointed out. The gaps of grain trajectory are described by the models, and it is used to explain the grinding force reduction and ground surface profiling. The grain trajectory has an important relation to the grinding quality. The relationship between grain trajectory and intergranular trajectory is figured out through the mathematical deduced and simulated. The principle of improvement in grinding force and workpiece surface roughness are clearly described in theory. Afterwards, using these developed models, they can predict influences of input variables (diamond grain number, grinding depth, vibration amplitude, vibration frequency, spindle speed, and feedrate) on grinding force and workpiece surface topography.

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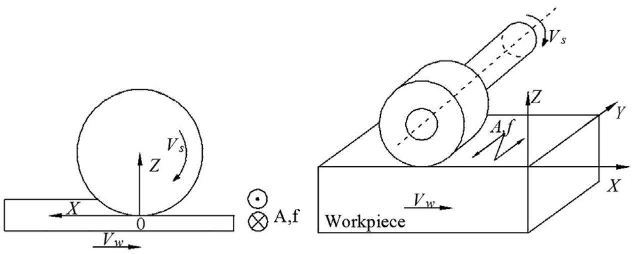

Fig. 1. The motion model of axial ultrasonic vibration assisted grinding.

Finally, these predicted influences are compared with the experimental results.

2. The kinematics analysis of ultrasonic vibration assisted grinding

As shown in Fig. 1, there are three kinds of grain motion such as grinding wheel rotational circular motion, grinding wheel feed movement and the simple harmonic oscillation [17].

For simplicity, make the following assumptions for the object of study and the grinding process:

(1) The grains on the grinding wheel surface distribute equidistantly along the circumference;
(2) Material is ideal brittle material;
(3) Ultrasonic vibration in the machining process keeping a stable condition, Amplitude, frequency remain unchanged;
(4) Abrasive grains are rigid Vickers tetrahedron of the same size, and grain shape is invariable in the grinding process.

2.1. The grain trajectory model of single abrasive

Based on the UAG kinematics analysis, establish the single abrasive grain trajectory model.

$$x=(v_w+v_s)t_1 \tag{1}$$

$$y=A\ \sin(2\pi f t_1+\varnothing_0) \tag{2}$$

$$z=R-R\ \cos\ \omega t_1 \tag{3}$$

where v_s is grinding wheel speed, t_1 is grinding time of single grain, ω is grinding wheel angular velocity, v_w is feed rate, f is ultrasonic frequency, R is grinding wheel radius, $\varnothing_0$ is ultrasonic vibration initial phase, A is ultrasonic amplitude.

Assume the ultrasonic vibration initial phase $\varnothing_0=0$, the trajectory length of single grain contact with material in single rotation period can be defined:

$$L=\int_0^{t_1}\sqrt{(v_w+v_s)^2+(2\pi f A\ \cos(2\pi f t_1))^2+(v_s\ \sin\ \omega t_1)^2}dt_1 \tag{4}$$

3. UAG material removal rate and grinding force modeling

The crack mechanism of brittle material:

(a) The initial loading: Contact region produce a permanent plastic deformation, there is no crack damage. Deformation zone increases with load increase.
(b) Load reaches critical value: the region of stress concentration produced media crack.
(c) Loading increase: the media crack grows bigger.
(d) The initial unloading: the media crack began to close.
(e) Further unloading: due to the contact area elastic-plastic stress unmatched, a tensile stress in the stress field has been produced, and then produces series of transverse crack.
(f) Unloading completely: transverse crack continue to expanding, finally detached from the work piece as abrasive dust.

As Fig. 2 shown, there are two kinds of brittle material removal modes: One is the plastic removal below the critical load; another is brittle removal over the critical load.

3.1. The plastic removal below the critical load

By the material removal mechanism, large load resulted in plastic deformation, then abrasive dust detached from the work piece along the grinding wheel feed direction. The relationship between load P (N) and indentation size $2a$ (mm) can be described by following equation [18]:

$$P=\xi H_v a^2; \tag{5}$$

where ξ is the geometrical factor of the grain, and $\xi=2\times H_v$ (Gpa) is Vickers hardness.

With the increase of pressure load P, the plastic deformation area will further increased. When the P exceeds its critical load P^*, media crack will produced. The critical load P^* can be obtained by the following equation:

$$P^*=54.5\left(\frac{\alpha}{\eta^2\gamma^2}\right)\frac{K_{IC}^4}{H_v^3} \tag{6}$$

where a, η, γ are dimensionless constants. For the Vickers indenter, $a=2/\pi$, $\eta\approx 1$, $\gamma=0.2\times K_{IC}$ (MPa/m$^{1/2}$) is the fracture toughness.

The dynamic fracture toughness K_{ID} is only 30% of static fracture toughness K_{IC} for hard and brittle material. Ultrasonic vibration excitation changed material mechanical properties. Material surface hardness can be reduced by 30%, and the critical cutting thickness a_{gc} of the grain is effectively increased [19]. According to Eq. (6), Dynamic critical load P_{cd} can be deduced:

$$P_{cd}=54.5\left(\frac{\alpha}{\eta^2\gamma^2}\right)\frac{K_{ID}^4}{H_v^3} \tag{7}$$

The above equation means when the load is smaller than P_{cd}, the material is in the ductile removal mode.

As Fig. 3 shown, indentation feature size $a=a_g\tan\theta$, θ is cone top half angle of grinding grain. According to Eq. (5), P can be obtained by following equation:

$$P=k\xi\tan^2\theta H_v a_g^2. \tag{8}$$

where a_g (mm) is abrasive cutting thickness, k is area proportion of load bearing grain area and grain area, $0\leq k\leq 1$.When $P=P_{cd}$, the

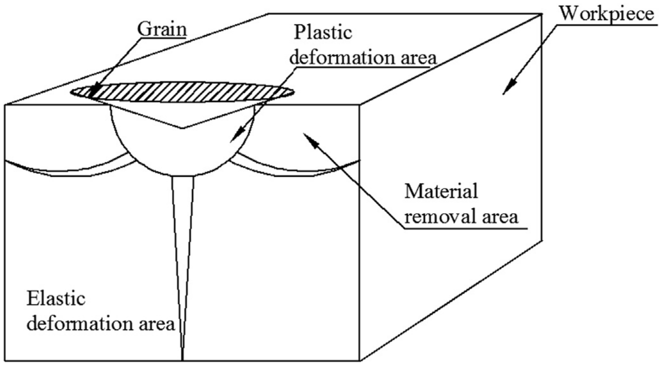

Fig. 2. Indentation fracture model.