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A cutting force model for rotary ultrasonic machining of brittle materials

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ABSTRACT

Knowing cutting force in rotary ultrasonic machining (RUM) can help optimizing input variables. RUM of brittle materials has been investigated both experimentally and theoretically. However, there are no reports on cutting force models for RUM of brittle materials. This paper presents a mechanistic model for cutting force in RUM of brittle materials. Assuming that brittle fracture is the primary mechanism of material removal in RUM of brittle materials, the cutting force model is developed step by step. On the basis of this mechanistic model, relationships between cutting force and input variables (such as spindle speed, feed rate, ultrasonic vibration amplitude, abrasive size, and abrasive concentration) are predicted. Experiments are conducted for model verification and experimental results agree well with model predictions.

1. Introduction

Superior properties of some brittle materials, such as high hardness and strength at elevated temperatures, chemical stability, low friction, and high wear resistance, make them attractive for many applications. Machining of brittle materials has gained significant importance over the last two decades [1–10]. Rotary ultrasonic machining (RUM) shown in Fig. 1 is a non-traditional machining process and has been used for brittle materials such as glass [11,12], KDP [13], and ceramics [14]. It is a hybrid process that combines material removal mechanisms of grinding and ultrasonic machining [3]. The rotary core drill with abrasive particles can oscillate at high frequency (typically 20 kHz) while being fed towards the work-piece.

Although there have been some models [14–19] of RUM, most of them were developed for predicting material removal rate (*MRR*) or investigating material removal mechanism, and only one cutting force model for RUM of ductile materials was reported [20]. At present, no publications are available on cutting force models for RUM of brittle materials. Therefore, it is necessary to develop a cutting force model for RUM of brittle materials to help optimizing input variables.

In this paper, a mechanistic model to predict relations between cutting force and input variables for RUM of brittle materials is developed based on the indentation fracture mechanics under pyramidal indenters. In this mechanistic model, a proportionality parameter will be used to describe the ratio between the actual volume of material removed by one abrasive particle in a vibration cycle and the theoretical volume of the fracture zone induced by the abrasive particle. The model is mechanistic in the sense that this parameter for a particular work-piece material is a constant and can be obtained from a few experiments and then used in prediction of cutting force over a wide range of input variables.

The paper is organized into six sections. Following this introduction section, Section 2 describes the cutting force model development step by step. In Section 3, the proportionality parameter for alumina is obtained by experiments. In Section 4, predicted influences of input variables (such as spindle speed, feed rate, ultrasonic vibration amplitude, abrasive size, and abrasive concentration) on cutting force are discussed. Section 5 provides model verification using pilot experiments. Conclusions are contained in Section 6.

2. Development of cutting force model

2.1. Approach to model development

RUM might be considered as a combination of ultrasonic machining process and grinding process [3]. It is a complex process with a large number of input variables, as shown in

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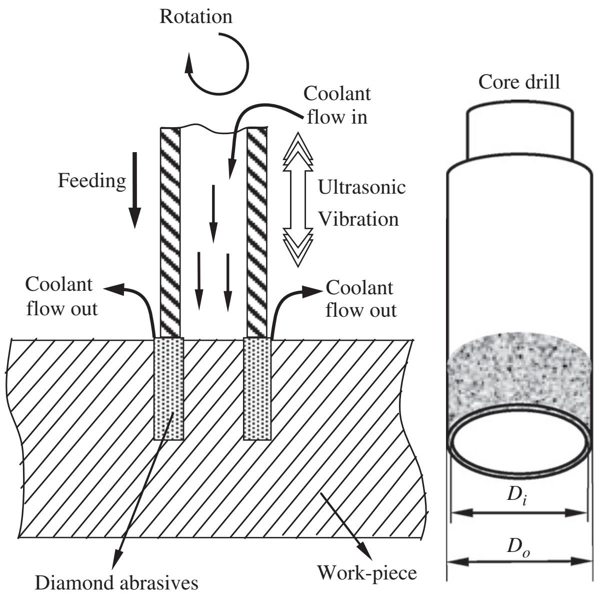

Fig. 1. Illustration of RUM process (after [3]).

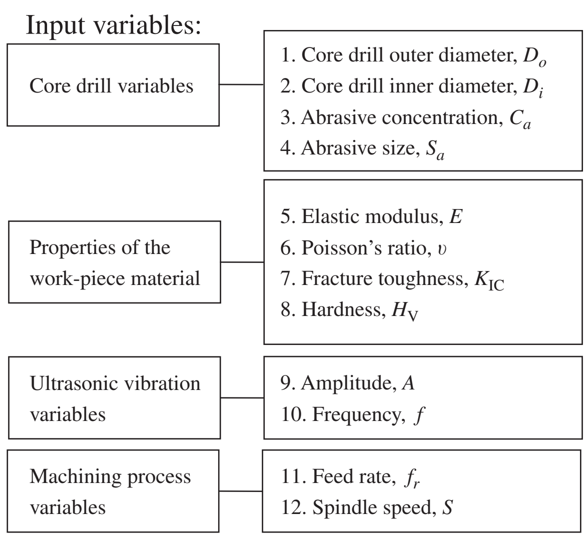

Fig. 2. Input variables in development of cutting force model for RUM.

Fig. 2. Many abrasive machining models [17–24] began with an analysis of one abrasive particle. The models were then derived by summing up the effects of all active abrasive particles taking part in cutting. A similar approach is used in this paper to develop the cutting force model for RUM of brittle materials. To develop the model, the following steps are carried out:

(1) Establish a relation between cutting force and maximum depth that abrasive particles penetrate into the work-piece.
(2) Estimate V, the actual volume of material removed by one abrasive particle in a single ultrasonic vibration cycle.
(3) Establish a cutting force model by aggregating the effects of all active abrasive particles.

Several major assumptions and simplifications on abrasive particles are as follows:

(1) The diamond abrasive particles are assumed to be rigid octahedrons of the same size. Some researchers [14–20] took diamond abrasive particles as spheres (like blunt indenters).

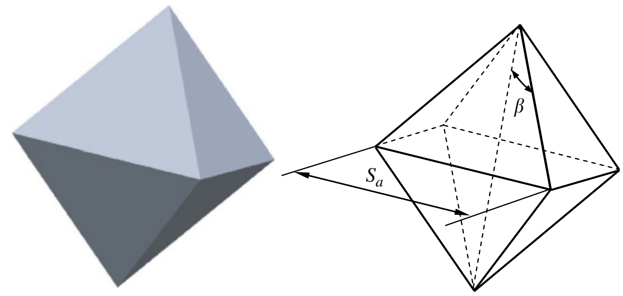

Fig. 3. Illustration of abrasive particle simplified as an octahedron.

However, diamond abrasive particles are more like polyhedron in shape (like sharp indenters). Indentation crack patterns are different between "blunt" and "sharp" indenters [25,26]. In order to establish a more accurate model in this paper, diamond abrasive particles are taken as octahedrons instead of spheres. Every four adjacent triangles have a common vertex, forming a pyramid, as shown in Fig. 3. Only one pyramid of each octahedral particle takes part in cutting.
(2) The semi-angle (β) between two opposite edges of an abrasive particle, as shown in Fig. 3, is 45° before it wears down. Since the lengths of its 12 edges are assumed to be the same (regular octahedron), the size of an abrasive particle (S_a) can be expressed by the length of its edges. If an abrasive particle wears down (by attritious wear not grain fracture), its semi-angle will increase.
(3) All diamond abrasive particles on the end face of a core drill have the same height and all of them take part in cutting during each ultrasonic cycle.

Other assumptions and simplifications will be presented later when they are used.

2.2. Relation between cutting force and maximum penetration depth

When a core drill feeds into the work-piece during RUM, an abrasive particle on the end face of the core drill is not in continuous contact with the work-piece due to ultrasonic vibration of the drill. In each ultrasonic cycle, the abrasive particle on the end face of the core drill will make contact with the work-piece for a certain period of time (Δt—effective cutting time). The maximum impact force between the abrasive particle and the work-piece is produced while the penetration of the active abrasive particle reaches the maximum depth.

If w is the maximum depth that an abrasive particle penetrates into the work-piece, as shown in Fig. 4, then, according to the definition of Vickers hardness, w can be calculated approximately by the following equation [25]:

$$w = \frac{d}{2\tan\beta} = \left(\frac{1}{2\tan\beta\sqrt{\tan^2\beta + 2}} \frac{F_n}{H_V} \right)^{1/2} \tag{1}$$

where w is the maximum penetration depth of an abrasive particle, mm; F_n is the maximum impact force applied to one abrasive particle, N; H_V is the Vickers hardness of the work-piece material, MPa; d is the length of the diagonal of indentation, mm, as shown in Fig. 4. β is the semi-angle between two opposite edges of an abrasive particle. F_n can be obtained by the following equation:

$$F_n = \frac{F_m}{N_a} \tag{2}$$