International Journal of Machine Tools & Manufacture 101 (2016) 18–27

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Modeling the dependency of edge chipping size on the material properties and cutting force for rotary ultrasonic drilling of brittle materials

Jianjian Wang [a,c], Pingfa Feng [a,c,*], Jianfu Zhang [a,c], Chenglong Zhang [b], Zhijian Pei [d]

[a] Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
[b] Beijing Institute of Electronic System Engineering, Beijing 100854, China
[c] Beijing Key Lab of Precision/Ultra-precision Manufacturing Equipment and Controls, Beijing 100084, China
[d] Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

ARTICLE INFO

Article history:
Received 8 July 2015
Received in revised form
14 October 2015
Accepted 20 October 2015
Available online 22 October 2015

Keywords:
Rotary ultrasonic machining
Edge chipping
Subsurface crack
Brittle material

ABSTRACT

Edge chipping induced by rotary ultrasonic drilling (RUD) restricts the applications of brittle materials. It should be possible to reduce or eliminate edge chipping by optimizing the process parameters based on efficient theoretical modeling of the size of the edge chip. However, to date, no publications are available on the predictive modeling of edge chipping during RUD of brittle materials. This paper presents an analytical model for predicting the edge chipping size during RUD of brittle materials by considering both effects of cutting force and subsurface cracks induced by machining on the occurrence of edge chipping. The relationships between the edge chipping size, processing variables (material properties and ultrasonic amplitude), and the cutting force were established theoretically. The coefficients in the model were obtained by conducting RUD tests on K9 optical glass specimens. Subsequently, the model was validated by conducting RUD tests on sapphire specimens. Using this model, the edge chipping size can be predicted during RUD of brittle materials. The experimental and predicted results were in good agreement.

1. Introduction

Brittle materials, such as advanced engineering ceramics and optical glass, are widely used in various fields owing to their superior physical, mechanical, optical, and electronic properties, such as high hardness and strength at elevated temperatures, chemical stability, high wear resistance, and low friction [1–5]. However, because of their high hardness and low fracture toughness, brittle materials are classified as the most difficult-to-machine materials [6–8]. Improving the efficiency and reducing the cost of machining these materials without compromising the quality remains a major challenge [9]. In the past two decades, various conventional and unconventional technologies have been introduced to improve machining, such as cutting [10], grinding [11], drilling [12], lapping [13], electrolytic in-process dressing grinding [14], electrical discharge machining [15], abrasive water jet machining [16], ultrasonic machining [17], and ultrasonic vibration-assisted machining [18]. Rotary ultrasonic drilling (RUM) is an unconventional, hybrid machining process that combines the material removal mechanisms of diamond grinding and ultrasonic machining [19,20]. In RUM, a rotating tool with diamond abrasives is ultrasonically vibrated in the axial direction with a very low amplitude while being fed towards the workpiece at a constant feed rate. As illustrated in Fig. 1, the machining process is drilling when the tool is fed parallel to the direction of ultrasonic vibration and is milling when the tool is fed perpendicular to the direction of ultrasonic vibration. RUM has been successfully applied in the manufacturing of many brittle materials, such as K9 optical glass [21], KDP crystal [22], and engineering ceramics [23], because of its low cutting force, high surface quality, and fast rate of material removal [24].

Holes are a commonly required feature in products made from brittle materials [25]. As shown in Fig. 2, in the hole manufacturing of brittle materials employing RUD, edge chipping at the hole entrance and especially at the hole exit can be observed [26]. The edge chipping size is an important criterion to evaluate the quality of a hole because it greatly influences the performance of the component and the positioning accuracy in an assembly. Several investigations, both experimental and numerical based on the finite element method, have concentrated on the mechanism of edge chipping during RUD of brittle materials [27–31]. Experimental studies have also focused on reducing or eliminating edge chipping by optimizing the process parameters [27]. However, optimization should be established based on theoretical modeling

* Corresponding author at: Department of Mechanical Engineering, Tsinghua University, 100084 Beijing, China. Fax: +86 10 62782351.
E-mail address: fengpf@mail.tsinghua.edu.cn (P. Feng).

http://dx.doi.org/10.1016/j.ijmachtools.2015.10.005
0890-6955/

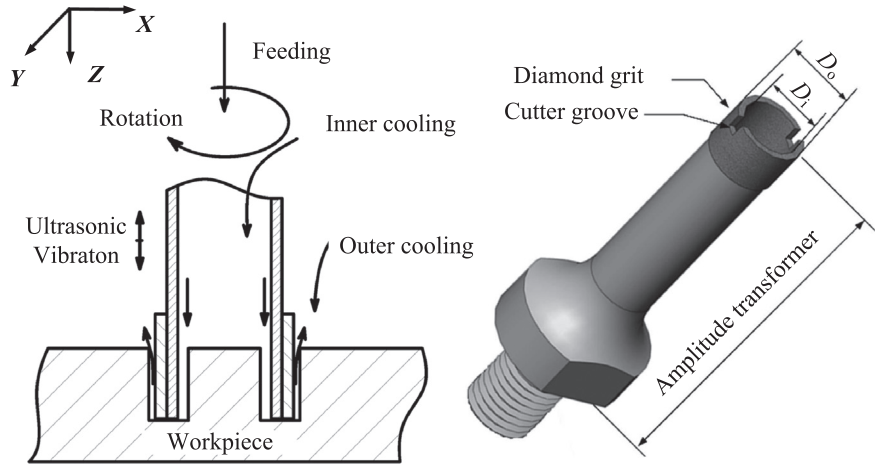

Fig. 1. Illustration of rotary ultrasonic drilling.

of the edge chipping size. Although some models have been applied to RUD, most were developed for predicting the material removal rate or the cutting force [32–34]. At present, no publications are available on predictive modeling for edge chipping during RUD of brittle materials. Therefore, it is necessary to develop such a model to help reduce or eliminate edge chipping defects.

In this paper, an analytical model is developed based on indentation fracture mechanics under sharp indenters to ascertain the dependence of the edge chipping size on the material properties and processing conditions. In this model, a criterion for edge chipping was proposed. A series of experiments were performed to determine the coefficients and validate the model.

2. Development of the edge chipping size model

2.1. Kinematic characteristics of an abrasive particle in rotary ultrasonic drilling

RUD can be regarded as a combination of ultrasonically vibrated machining and conventional diamond grinding. As shown in Fig. 1, the motion of the diamond particle during RUD combines rotational motion, longitudinal feed motion, and ultrasonic oscillation in the direction of the tool axis. Therefore, the trajectory of the diamond particle during RUD can be expressed as

$$S_{\text{RUM}}(t) = \begin{bmatrix} r\cos\left(\frac{2\pi n}{60}t\right) \\ r\sin\left(\frac{2\pi n}{60}t\right) \\ A\sin(2\pi ft) + v_f t \end{bmatrix} \quad (1)$$

where r is the rotational radius of the diamond particle, A is the ultrasonic vibration amplitude, f is the ultrasonic vibration frequency, n is the spindle speed in rpm, v_f is the feed rate in the direction of the z axis, and t is the processing time. Fig. 3 shows the trajectory of a diamond particle obtained from Eq. (1).

Because the tool vibrates at the ultrasonic frequency, the diamond sintered on the end face of the tool is not in continuous contact with the workpiece. As shown in Fig. 4, in each vibration cycle, the diamond particles on the end face of the diamond tool penetrates into the workpiece for a certain period of time, namely the effective cutting time (Δt), with a maximum depth of δ.

The relationship between Δt and δ can be expressed as

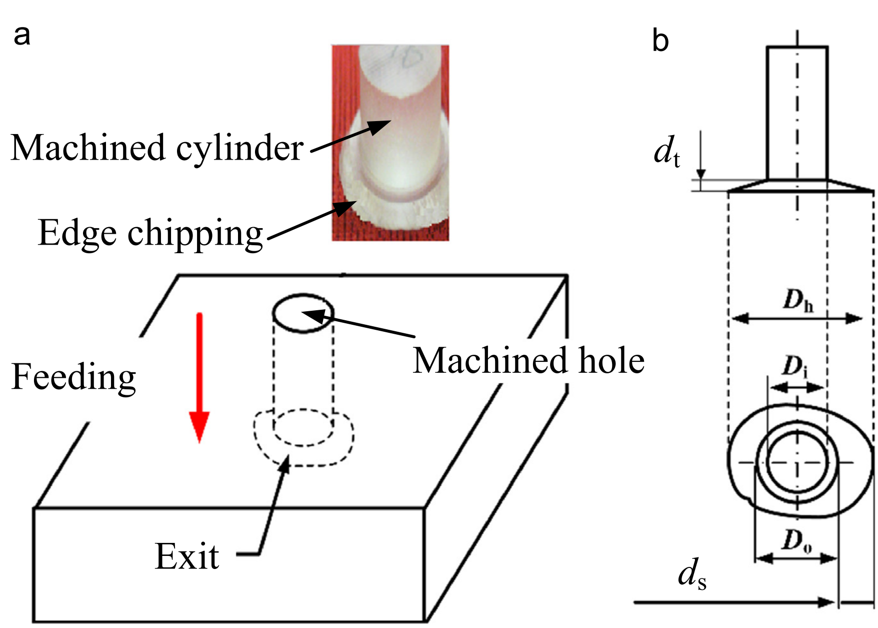

Fig. 2. Illustration of (a) a machined hole and (b) measurement of an edge chip.