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Research on the Rotary Ultrasonic Facing Milling of Ceramic Matrix Composites

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Abstract

Ceramic matrix composites (CMC) has got increasing importance in many fields of industry, especially in the aerospace. However, due to the special properties, the conventional machining methods are generally very challenging for CMC. The rotary ultrasonic machining (RUM) is a high efficiency processing technology for these advanced materials. This paper carried out research on the rotary ultrasonic facing milling of C/SiC and developed the cutting force simulation software to optimize the cutting parameters. Verification experiments were conducted showing that the efficiency improved by RUM is 5.8 times while the surface quality is improved by 54.4% compared with the conventional milling.

Keywords: Rotary ultrasonic machining; Ceramic matrix composite; Cutting force; Cutting parameters;

1. Introduction

Ceramic matrix composites (CMC) are advanced materials with superior properties like high specific strength, high specific rigidity, high-temperature strength and high wear resistance. At present, these advanced materials has been commonly used in thermal protection systems of space vehicles, hot structures, vanes, nozzles and flaps of rocket motors and jet engines, etc. [1-2]. Even though CMC are often made a near net shape, some cutting processes are unavoidable. In the traditional machining, the cutting tools like polycrystalline diamond (PCD) tools tend to get severe wear in short cutting time causing high processing cost [3]. Moreover, the inhomogeneous and anisotropic properties of CMC usually lead to the processing defects like fiber pullout, which decrease the processing quality and efficiency [4]. Thus it's critical to research for an effective processing technology for such composites to achieve desired accuracy, high efficiency and cost-effective.

Rotary ultrasonic machining (RUM) has been shown to be a very feasible processing technology for hard and brittle materials to lower cutting force, improve surface quality and reduce tool wear [5-11]. Researchers have investigated the machinability and processing effects of advanced materials through RUM. The rotary ultrasonic face milling (RUFM) was first proposed by Pei et al. And a new cutting tool for rotary ultrasonic face milling was designed to get the basic material removal mechanisms of ultrasonic machining [12]. Feng et al. established a theoretical model for the rotary ultrasonic face milling assuming that the diamond grit was closer to the regular octahedron [13]. Li et al. evaluated the cutting force, material removal rate (MRR) and surface quality of CMC finding that RUM has advantages over conventional machining [14]. Zhang et al. established the material removal model based on indentation theory for advanced ceramic and found the particle effective cutting depth is the most significant parameter having effect on surface roughness based on brittle fracture material removal [15]. Wang et al.

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applied rotary ultrasonic drilling on potassium dihydrogen phosphate (KDP) crystal indicating that the spindle speed, ultrasonic power, feed rate, and particular tool shape are the main influential factors in RUM for KDP crystal material [16]. Yuan et al. studied the rotary ultrasonic side milling of C/SiC and developed a cutting force model taking into account the influence of fiber volume fraction and the frictional force between the diamond grits and material substance [17].

From studies and previous research work, it is found that cutting force of C/SiC composites for RUM is a very crucial parameter, therefore the research on the cutting force modelling was normally carried out. However, in the practice, there is a gap between the theory model application and the demand of RUM because of the complexity and specificity [18]. In this research, the brittle fracture material removal mechanism of C/SiC by RUFM was discussed. A cutting force simulation software was developed based on the brittle fracture cutting force model to established the direct relation among the CMC properties, cutting parameters and the cutting force. And the cutting parameters were optimized by the software to reduce the cutting force. A set of RUFM experiments were conducted verifying that the processing efficiency and surface quality were significantly improved compared with the conventional milling.

2. The material removal mechanism and cutting force model

The CMC material removal mechanism in RUFM is based on the indentation fracture theory. The cutting tool used for the C/SiC in RUFM is specially designed to match the frequency (20 KHz) of longitudinal ultrasonic vibration system. Fig. 1 illustrates the diamond abrasive grits of the cutting tool interact with the workpiece material as hammering, abrasion and extraction along with the ultrasonic vibration. There will be a plastic deformation area first on the surface when the diamond abrasive grits penetrates into the substrate of the material. As shown in Fig. 2, with the increase of penetration depth, the median crack will grow and generate the lateral cracks. The lateral cracks then extend and intersect with each other inducing the peeling off of the workpiece material [19-21]. All of the diamond abrasive particles can be assumed rigid octahedron with the angel of 45° and have the same size [13]. The trajectory of the abrasives ploughing in the target materials is the combination of the tangential rotation and axial ultrasonic vibration, thus the longer cutting length can be obtain in the RUFM resulting in the lower cutting force. That may be one of the basic reasons that RUFM is better for hard and brittle materials.

Based on the brittle fracture material removal mechanism, the maximum penetration depth is a key factor to establish the relationship between the cutting parameters (spindle speed, feed rate, cutting depth) and cutting force. According to Chong Zhang [3], the relationship between the normal force of a single diamond abrasive grit and the penetration depth w can be obtain by the indentation theory:

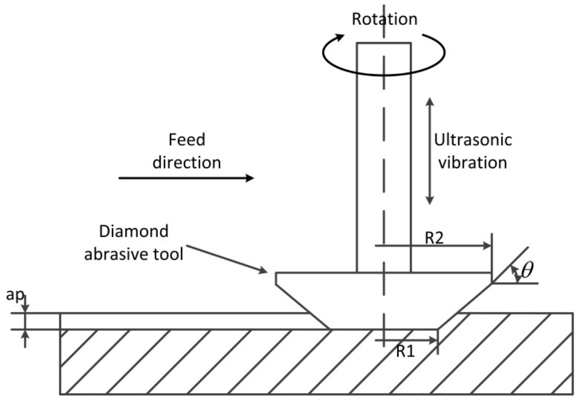

Fig. 1 The RUFM process with the diamond abrasive tool

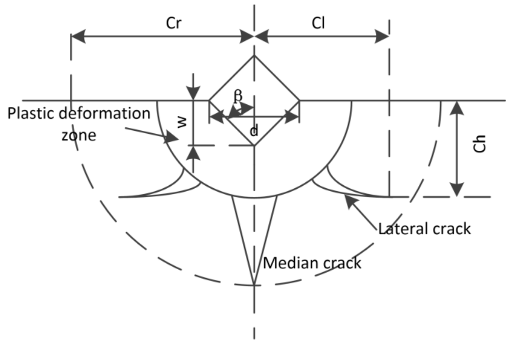

Fig. 2 Crack generation in brittle fracture material removal

$$w = \sqrt{0.051 \cdot \frac{cos^2\beta}{sin\beta} \cdot \frac{Fn}{Hv}} \quad (1)$$

Where Fn is the normal force on the surface of the workpiece; Hv is the Vickers hardness of the workpiece material; β is the half angle of diamond abrasive grains.

In the RUFM, based on the diamond abrasive concentration definition: per cubic centimeter volume of abrasive grains containing 4.4 karats is defined as 100, the total number of active diamond abrasive grits involved in the cutting can be expressed as:

$$\mathrm{N\alpha} = \left(\frac{0.88\times10^{-3}}{\left(\sqrt{2}/3\right)Sa^3\cdot\rho} \cdot \frac{C\alpha}{100} \right)^{2/3} \cdot A_0 = C_1 \cdot \frac{C\alpha^{\frac{2}{3}}}{Sa^2} \cdot A_0 \quad (2)$$

$C\alpha$ is the concentration; A_0 is the cutting area in relation to the cutting depth and the cutting tool geometric parameters; Sa is the side length of the diamond abrasive .

Summarizing for all the active abrasive grits, the relationship between penetration depth and total cutting force can be obtain as follows:

$$w = \sqrt{0.051 \cdot \frac{cos^2\beta}{sin\beta} \cdot \frac{1}{Hv} \cdot \frac{\pi \cdot F \cdot cos\theta}{N\alpha \cdot \left[\frac{\pi}{2} - arcsin\left(1 - \frac{w}{A}\right) \right]}} \quad (3)$$