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Modelling and characterization of surface generation in Fluid Jet Polishing

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ABSTRACT

Fluid Jet Polishing (FJP) has the advantages of localized force and cooling of the debris, and of a stable and controllable material removal function with very little tool wear. Due to the complex machining mechanism, it is still difficult to model the material removal characteristics and simulate the surface generation for FJP. In the present study, an attempt has been made to better understand the material removal and surface generation mechanisms in the FJP process. Hence, a theoretical model is built for predicting and characterizing the material removal characteristics and surface generation in FJP based on computational fluid dynamic modelling. A series of spot and pattern polishing tests, as well as simulation experiments by the theoretical model, were conducted. The results show that the theoretical model satisfactorily predicts the surface generation under different polishing conditions and enables a better understanding of the polishing process in FJP.

1. Introduction

Nowadays, ultra-precision freeform surfaces are widely used in various applications, such as optics, photonics, opto-mechanics-electronics and biomedical engineering [1]. To meet the optical surface requirements for a wide variety of freeform optics, these surfaces are usually fabricated by ultra-precision machining technologies with sub-micrometer form accuracy and nanometric surface finish [2]. However, geometrical complexity introduces considerable challenges to the precision manufacturing of freeform surfaces. An ultra-precision machining technology based on Fluid Jet Polishing (FJP) is a sub-aperture polishing and shaping process that bears a resemblance to the kinetic process engaged in abrasive water jet machining that guides a premixed slurry (water and abrasive particles) to the surface at low pressures [3]. FJP has the advantages of localized force and cooling of the debris, and of a stable and controllable material removal function with very little tool wear [4]. As a result, FJP is a promising technology which is becoming more widely used for superfinishing complex optical lenses, mirrors and moulds in a number of materials, from glass to nickel [5–7].

According to the literature review, most of the research work in the field of Fluid Jet Polishing was seen to have been focused on the following areas: (1) Process modelling, such as computational fluid dynamics (CFD) simulation [8–10] and surface characterization [11,12]; (2) Introducing new techniques such as integrating FJP with bonnet polishing for optimizing the polishing process chain [13], selecting polishing parameters to optimize the FJP process [14] and finishing difficult-to-machine materials [15]; (3) Developing new systems such as the stable pressure system [9], on-line monitoring systems [16] and nozzle optimization [17]; (4) Developing new applications for the FJP process such as Jules Verne [18] and submerged jet polishing [19]. Although much research has been carried out in an attempt to improve the surface finish of polished surfaces and to fundamentally understand the polishing process [20–22], research work on the polishing mechanism is still far from complete, and relatively little attention has been focused on the theoretical modelling of surface generation in FJP.

Nowadays, the generation of the desired surface integrity of a high performance optical surface still largely depends on the expensive trial-and-error approach. As the optimal machining conditions and polishing strategy for ensuring good surface quality depend largely on the polishing environment, the work materials and the geometry of surfaces being polished, there is a need for modelling and simulation methods and tools which can simulate and predict the effect of different factors on the surface generation in the FJP process. Therefore, an attempt has been made to understand the material removal and surface generation mechanisms in the FJP process. Hence, a surface generation model for FJP is proposed and explained. A series of experiments has been conducted

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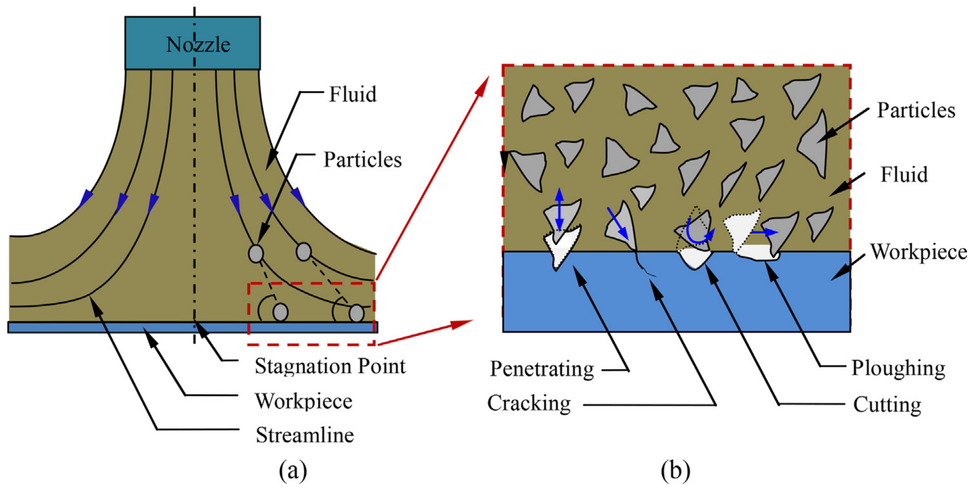

Fig. 1. Material removal mechanism in the FJP process: (a) fluid conditions in the case of perpendicular impact and (b) abrasive particles' erosion conditions.

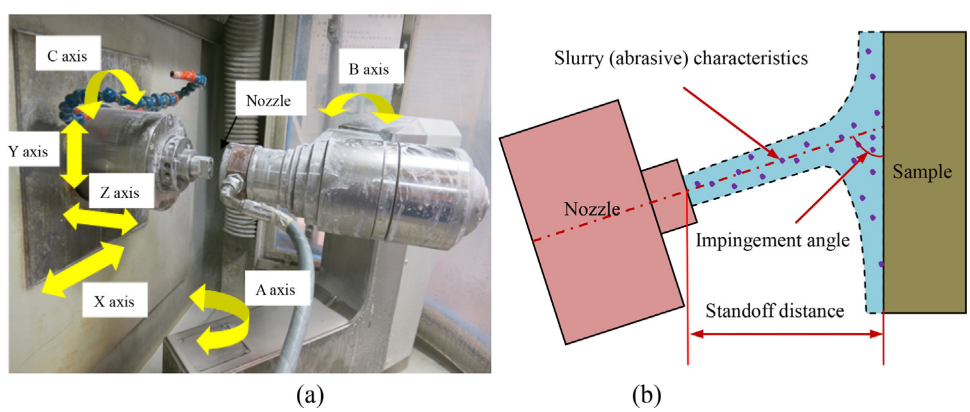

Fig. 2. (a) Real set-up and (b) schematic illustration of Fluid Jet Polishing.

for validating the surface topography simulation model, and the results are discussed.

2. Polishing mechanism

2.1. Material removal mechanism

In the FJP system, abrasive particles are accelerated by the drag force of water to impact on the workpiece and then initiate material removal at the nano-scale. The mechanism of material removal is a complex process, which is affected by various parameters such as the abrasive particle concentration, the particle size, the particle type, the slurry pressure, the machining time, the impingement angle, the standoff distance, etc. While the FJP process bears some similarities with abrasive water jet machining, it operates at much lower slurry pressure and with smaller particle size [9]. As a result, the particle energy is insufficient to immediately perform a cut, but rather erodes the material at a small rate [23]. More generally, target surfaces are machined mechanically by the repeated impact of the small abrasive particles in the ductile mode. The amount of material removed by the fluid jet depends on the flow conditions of the jet slurry and on the abrasive particles' erosion mechanism, as can be seen in Fig. 1. It seems clear that an understanding of the material removal that occurs in FJP may be divided into two major parts. The first part involves the determination of the relative motion between the workpiece and the particles, which can be solved by multiphase fluid theory. With such information available, the second part is the modelling of the erosion rate caused by abrasive particles. In the FJP process, the material removal characteristics represent the distribution of the material removal rate across the surface of the polishing tool [24,25]. They are referred to as the Tool Influence Function (TIF) which is assessed in terms of width, maximum depth and volumetric material removal rate.

2.2. Surface generation mechanisms

Fluid Jet Polishing (FJP) is a type of computer controlled ultra-precision polishing (CCUP) technology that is illustrated in Fig. 2. In the present study, it is operated on an ultra-precision polishing machining system with three linear axes (*X*, *Y* and *Z* axis), and three rotational axes (*A*, *B* and *C* axis). The slurry nozzle is mounted on the *B* axis and the fluid jet is released from the slurry nozzle. The workpiece is mounted on the *C* axis. The machining process of FJP is quite different from that of other diamond machining technologies, such as single point diamond turning and ultra-precision raster milling. The surface generation in FJP is dominated by the polishing Tool Influence Function (TIF) rather than the geometry of the cutting tool [26]. It turns out that the material removal distribution on the polished surface in FJP can be viewed as the convolution of the tool influence function and polishing tool path planning. Hence, there are two ways to control the surface generation: (a) controlling the tool influence function through changing polishing process conditions and (b) controlling the polishing path generator with a constant tool influence function. The former method can achieve non-uniform material removal and shows high polishing efficiency, while it tends to introduce waviness, texture or other non-neligible