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Theoretical modelling and analysis of the material removal characteristics in fluid jet polishing

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ABSTRACT

Fluid Jet Polishing (FJP) is a kind of ultra-precision machining technology which not only becomes more widely used for removing tool marks, in order to achieve super finished surfaces while controlling the form accuracy, but also becomes more widely used in superfinishing freeform surfaces made of difficult-to-machine materials. The material removal characteristics, which are described as a tool influence function and assessed in terms of width, maximum depth and material removal rate, play an important role in simulating the surface generation accurately and manufacturing the designed surfaces deterministically in FJP. Due to the multi-factor influence and the complexity of the polishing mechanism, it is difficult to model the material removal characteristics accurately with the consideration of a lot of operational parameters in FJP. In this paper, a ductile-mode erosion model has been built to predict the volume removed by a single particle and a modified Gaussian function was used to describe the spatial distribution of abrasive particles in Fluid Jet Polishing. Hence, an Integrated Computational Fluid Dynamic (CFD)-based erosion model was established which integrates the CFD model, erosion model and experimental study to predict the material removal characteristics in FJP. A series of experiments were conducted by the a Zeeko IRP200 Ultra-precision Computer Controlled Polishing machine so as to validate the predictability of the integrated CFD-based erosion model. The experimental results show a good agreement between the model predicted results of CFD-based erosion modelling.

1. Introduction

With the broad application of freeform surfaces in various areas, the fabrication of these complex surfaces with sub-micrometric form accuracy and nanometric surface finish, especially for the hard and difficult-to-machine materials, has always been a challenge to the optics industry. Currently, numerous ultra-precision machining technology can be potentially applied to produce the complex shaped freeform surfaces, such as ultra-precision diamond machining technologies [1], ultra-precision grinding [2], Magneto-Rheological Finishing (MRF) [3], Ion Beam Figuring (IBF) [4] and Computer Controlled Ultra-precision Polishing (CCUP) [5], etc. However, freeform machining technologies based on diamond machining are susceptible from the significant tool wear problems due to the high hardness and brittle nature of most of the difficult-to-machine materials being cut. Although ultra-precision grinding and milling methods are developed to be suitable for the fabrication of some kinds of freeform optics or materials, they cannot meet the optical surface requirements for a wide variety of optical applications [6]. MRF is unsuitable for the magnetic materials while IBF has a relatively low material removal rate. CCUP is an enable technology which becomes more widely used in superfinishing freeform surfaces made of difficult-to-machine materials [7]. Fluid Jet Polishing (FJP), proposed by Fahnle [8–11], is one of the promising CCUP technologies which pumps the premixed slurry (abrasive particles and water) through an inclined adjustable nozzle to direct towards a target surface at appropriate speeds (see Fig. 1). In recent years, FJP has not only been used for removing tool marks, in order to achieve super finished surfaces, but also has been used for controlling the form accuracy of polished surfaces [12]. Although our understanding of complex mechanisms of material removal are still far from complete, there is a need to establish theoretical model for the determination of the material removal characteristics (see Fig. 2), which plays an important role in simulating the surface generation accurately and manufacturing the designed surfaces deterministically in FJP.

In the FJP system, target surfaces are machined mechanically by the repeated impact of the small abrasive particles in ductile mode to avoid the discernible cracks and achieve the superfinished surfaces [13,14]. In general, the material removal characteristics of the target surface can be controlled by varying process parameters such as the slurry concentration, the particle size, the

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particle type, the slurry pressure, the machining time, the impingement angle, the standoff distance, etc. The material removal depends not only on the material properties of the target surface and the nature of the particles, but also on the conditions under which the particles impact the target surface. Till date, there is still a lack of deterministic models that have been developed considering all these operational parameters, so as to predict the material removal profile accurately in the FJP process. As a result, this paper aims to establish a ductile-mode erosion model which takes into consideration the material removal mechanism of single particle and the spatial distribution of abrasive particles. Hence a theoretical model named integrated CFD-based erosion model has been developed which integrates the computational fluid dynamics (CFD) modelling together with erosion model and experimental research to predict the detail material removal characteristics in FJP.

2. Integrated computational fluid dynamics-based erosion model

Fig. 3 shows the schematic diagram for establishing the integrated computational fluid dynamic-based erosion model which attempts to theoretical modelling of the material removal characteristics in FJP. First, the hydrodynamic conditions and the trajectories of particles in the slurry are determined and simulated using the CFD code. Hence, the data obtained from the CFD simulations are used together with the erosion model to predict the detailed material removal profile, while some empirical constants involved in the erosion models should be determined by the experiments.

2.1. Hydrodynamic model

Since direct measurement of particle velocities and visualisation of particle trajectories are very difficult in FJP, computational fluid dynamic (CFD) modelling tends to be an effective means to study the jet dynamic characteristics in the polishing process. This study can provide insights into the forces acting on the abrasive particles which affect particle motion and hence determines the conditions of abrasive particles impact on the target surface. The slurry jetting in the vertical FJP process is assumed as a two-dimensional, incompressible, steady axisymmetric turbulent flow with constant properties and temperature conditions [14]. In this study, the Eulerian–Eulerian–Lagrangian method, which treats the water and air as Eulerian phases and the abrasive particles as Lagrangian particles, is used in the Computational Fluid Dynamics (CFD) software package named FLUENT. After solving the stream flow, the particulate phase is modelled based on a force balance around individual particles to calculate the detail information of the interaction of the particles with the target surface. Due to the low slurry concentration used in the FJP process, particle–particle interactions are considered negligible and the particulate phase does not affect the prevailing flow field. Table 1 presents a summary of the model settings used in the CFD simulations.

2.2. Spatial distribution of abrasive particles

Due to the axisymmetric characteristics in the vertical FJP, The equation of erosion model can be expressed as:

$$V(x) = N(c, u, x) \cdot E(u_p(x), \alpha(x), d_p, k_m) \quad (1)$$

where $V(x)$ is material removal amount at position x, term $N(c, u, x)$ is the abrasive particle spatial distribution that represents the effect of the slurry concentration c, the slurry velocity u, and the impact position x, and the term $E(u_p(x), \alpha(x), d_p)$ is the volume removed by a single particle that describes the effect of the impact velocity $u_p(x)$, the impact angle $\alpha(x)$, the particle size d_p and material property k_m. Generally, the CFD-based erosion modelling does not require a detailed knowledge of instantaneous particle

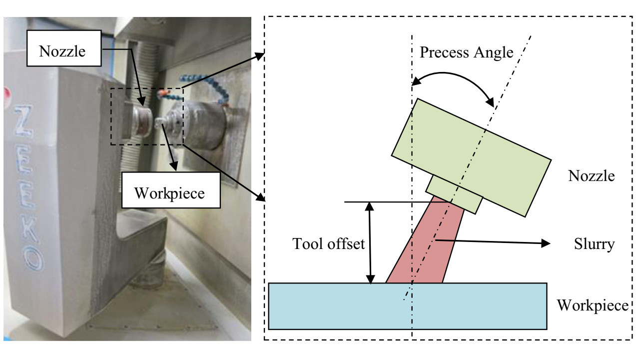

Fig. 1. Configuration of fluid jet polishing.

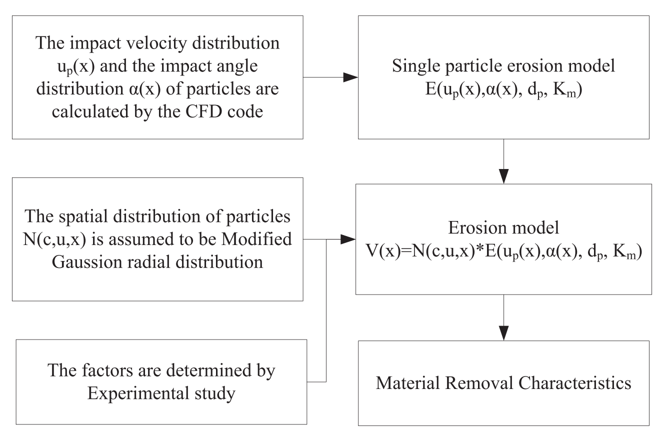

Fig. 3. Schematic diagram of the integrated CFD-based erosion model for theoretical modelling of the material removal characteristics in fluid jet polishing.

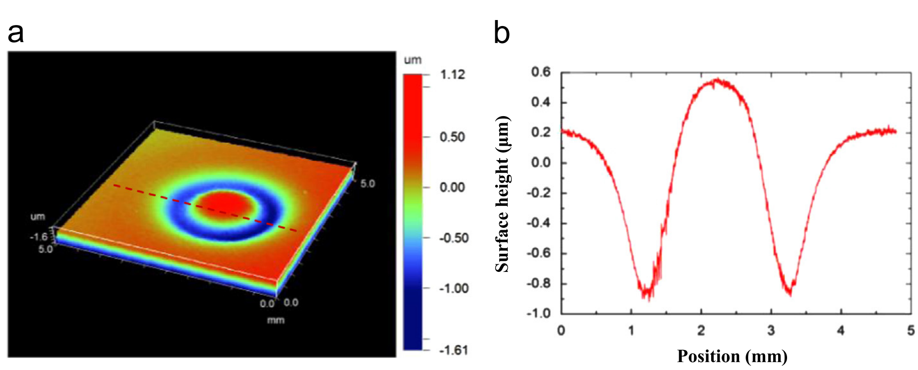

Fig. 2. 3D material removal characteristics and 2D cross-section profile for the vertical fluid jet polishing.