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Curvature-adaptive multi-jet polishing of freeform surfaces

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ABSTRACT

This paper presents a curvature-adaptive multi-jet polishing (CAMJP) method that can achieve high efficiency and cater for adaptation of the variation of the material removal rate (*MRR*) to the curvature of freeform surfaces. CAMJP makes use of a purposely designed multi-jet nozzle incorporated with a pressure control system. The effect of surface curvature on the *MRR* is analysed by computational fluid dynamic modelling. The fluid pressure of each jet is controlled independently to vary the *MRR* according to the curvature of freeform surfaces. Experimental results show that CAMJP is effective in improving the accuracy of polishing freeform surfaces.

1. Introduction

Due to the superior functionality of freeform surfaces, they have been widely applied in many fields such as imaging, illumination, aerospace, biomedical engineering, green energy, etc. [1]. Fluid jet polishing (FJP) [2] is one of the promising machining methods for the precision manufacture of freeform surfaces due to its unique advantages such as high machining accuracy, suitability for polishing various kinds of materials, no heat generation during polishing, etc. [3,4]. A multi-jet polishing (MJP) [5] process was proposed to largely enhance the polishing efficiency of FJP, and further extend its applications to medium- to large-sized surfaces.

However, the curvature effect generates considerable residual errors, especially in the FJP of freeform surfaces. Yang et al. [6] investigated the effect of surface curvature on polishing on an aspheric lens die, and it was found that the polishing area and the central removal depth vary with the surface curvature. Recently, Song et al. [7] analysed the effect of surface curvature on the polishing parameters in bonnet polishing. Wan et al. [8] built a tool influence function (*TIF*) model of the small tool polishing process considering the effect of surface curvature. However, research on the effect of surface curvature on the material removal in FJP has received relatively little attention.

To address the problems, this paper first investigates the effect of surface curvature on the material removal characteristics in FJP and a pressure dependent curvature adaptive (PDCA) control method is then proposed to compensate for the error induced by the effect of surface curvature in the MJP of freeform surfaces. Hence, a curvature-adaptive multi-jet polishing (CAMJP) system was established and experiments were conducted to validate its performance in the precision polishing of freeform surfaces.

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2. Investigation of the effect of surface curvature on the material removal characteristics in FJP

To analyse the effect of surface curvature which refers to the mean curvature [9], the *TIF* on different designed surfaces was determined by a computational fluid dynamic (CFD) model [10] using the FLUENT 17.2 software package. The experiments were divided into five groups according to different impinging angles (see Table 1). There were concave and convex surfaces with different radii of curvature (r). The diameter of the nozzle was 0.5 mm, the stand-off distance was 4 mm, and the polishing slurry was 10 wt. % 1000# silicon carbide (SiC). The workpiece material was S136 mould steel and the fluid pressure of the inlet was 6 bar.

Table 1
Surface design for analysing the curvature effect in FJP ('−' signifies convex surface, and '∞' means flat surface).

α (deg)	Radius of curvature r (mm)
90	10,20,30,40,50,75,100, ∞,−100,−75,−50,−40,−30,−20,−10
80	10,20,30,40,50,75,100, ∞,−100,−75,−50,−40,−30,−20,−10
70	10,20,30,40,50,75,100, ∞,−100,−75,−50,−40,−30,−20,−10
60	10,20,30,40,50,75,100, ∞,−100,−75,−50,−40,−30,−20,−10
50	10,20,30,40,50,75,100, ∞,−100,−75,−50,−40,−30,−20,−10

As shown in Fig. 1, the material removal rate (*MRR*), which refers to the material volume removal rate of each *TIF*, was determined after simulation. κ is the surface curvature, i.e.

$$\kappa = 1/r \tag{1}$$

It is found that the *MRR* varied from 4.6×10^{-3} mm^3/min to 8.2×10^{-3} mm^3/min with various surface curvature and impinging angles. The variation was significant as a critical factor in regard to compensation of the polishing of freeform surfaces.

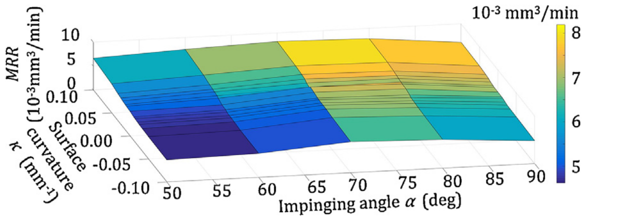

Fig. 1. Material removal rate in FJP of a workpiece with different surface curvature and impinging angles.

To compensate for the variation of *MRR* induced by the variation of the surface curvature and gradient, the relationship among *MRR*, surface curvature and surface gradient was determined first. Besides, a reference *MRR* was needed for comparison. In this study, the *MRR* of the case when the fluid pressure was 6 bar and the impinging angle was 90°, was considered as the reference *MRR* while other polishing conditions were the same. The *MRR* under different situations divided by the reference *MRR* is defined as the removal rate ratio η. The relationship among η, surface curvature and impinging angle is determined as $\eta(\alpha, \kappa)$. Cubic polynomial fitting was used to fit the parametric surface based on the raw data of the *MRR* as deduced from Fig. 1, and the fitted surface is shown in Fig. 2. The fitted $\eta_{Fit}(\alpha, \kappa)$ is given below:

$$\begin{aligned}\eta_{Fit}(\alpha,\kappa) &= c_{00} + c_{10}\alpha + c_{01}\kappa + c_{20}\alpha^2 + c_{11}\alpha\kappa + c_{02}\kappa^2 + c_{30}\alpha^3 \\ &+ c_{21}\alpha^2\kappa + c_{12}\alpha\kappa^2 + c_{03}\kappa^3; c_{00} = 6.505; c_{10} \\ &= -0.3043; c_{01} = -0.5136; c_{20} = 0.005321; c_{11} \\ &= 0.1272; c_{02} = 22.44; c_{30} = -0.00002911; c_{21} \\ &= -0.001049; c_{12} = -0.2421; c_{03} = -128.1\end{aligned} \tag{2}$$

Experiments were conducted on six spherical surfaces specified in Table 2. A comparison between the experimental removal rate ratio η_{EX} and calculated removal rate ratio based on the fitted function η_{Fit} was made. Their difference was less than 10%, which validates the fitted function in Fig. 2.

Table 2
Results of the verification of the fitted function $\eta_{Fit}(\alpha,\kappa)$.

α (deg)	κ (mm^{-1})	η_{Ex}	η_{Fit}
70	−1/20	1.233	1.160
77	−1/30	1.338	1.239
80	−1/40	1.364	1.241
82	−1/50	1.285	1.225
83	−1/60	1.259	1.214
85	−1/80	1.175	1.173

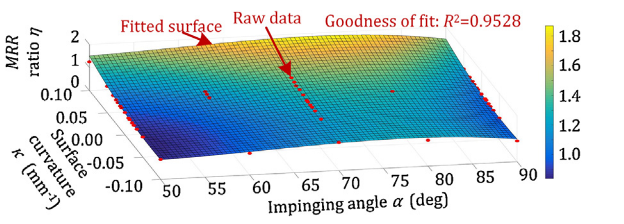

Fig. 2. *MRR* ratio varies with surface curvature and impinging angle.

3. Curvature-adaptive multi-jet polishing method

3.1. Simulation of FJP with and without curvature effect

To further realize the effect of the surface curvature on the material removal characteristics in the FJP of freeform surfaces, a series of simulation experiments was undertaken to simulate the polishing process with and without surface curvature effect. It was assumed that the initial surface form $H_0(x, y)$ was a F-theta surface with no surface form error, and the size was 20 mm × 40 mm. The polished region was 20 mm × 32 mm, and edge parts were left for reference. The *TIF* was generated by a 0.5 mm diameter nozzle under 6 bar fluid pressure. The material removal depth distribution in a unit time within the *TIF* was defined as the removal function $R(x, y)$. A raster tool path with a pitch size of 0.1 mm was adopted in the FJP. The feed rate of 20 mm/min was used, which means that the dwell time $T(x, y)$ for each dwell point was 0.3 seconds when the distance between them was 0.1 mm. When the target surface is a flat surface corresponding to no surface curvature effect, the distribution of material removal $E_{Flat}(x, y)$ is derived by Eq. (3) in the discretized form [11],

$$E_{Flat}(x,y) = \sum_i\sum_j R(x - x'_i, y - y'_j)T(x'_i, y'_j)\Delta x'_i \Delta y'_j \tag{3}$$

where x' and y' determine the centre position of the removal function during the polishing process. With the effect of the surface curvature of the freeform surface, the distribution of material removal can be expressed as:

$$E_{Freeform}(x,y) = \sum_i\sum_j \eta(x,y)R(x - x'_i, y - y'_j)T(x'_i, y'_j)\Delta x'_i \Delta y'_j \tag{4}$$

where $\eta(x, y)$ is the removal rate ratio as deduced from $\eta_{Fit}(\alpha, \kappa)$. Hence, the final polished surface H_{Flat} and $H_{Freeform}$ can be expressed as Eqs. (5) and (6), respectively.

$$H_{Flat} = H_0 - E_{Flat} \tag{5}$$

$$H_{Freeform} = H_0 - E_{Freeform} \tag{6}$$

As shown in Fig. 3, the difference between the polished surfaces with and without the surface curvature effect was observed. The difference of the surface form between them was about 0.7 μm when the total removal depth was about 2.4 μm. Hence, the surface curvature should be considered and compensated for in the polishing of freeform surfaces.

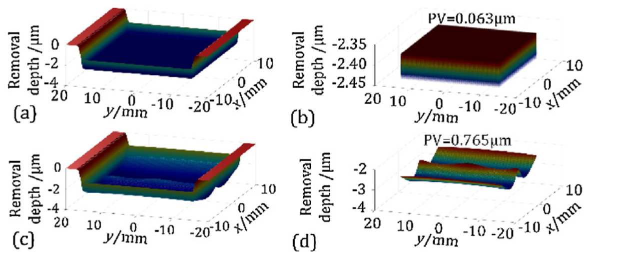

Fig. 3. Simulation results of the polished surface. (a) Whole surface with no curvature effect, (b) central part of the surface with no curvature effect, (c) whole surface with curvature effect, and (d) central part of the surface with curvature effect (Removed F-theta surface form).

3.2. Pressure-dependent curvature adaptive (PDCA) control method

Since there exists a variation of the *MRR* under different surface curvatures, there is a need to compensate for such variation so as to obtain a high accuracy freeform surface. In fact, the fluid pressure is one of the key factors affecting the *MRR* of FJP [10]. The fluid pressure is real-time controlled by pressure control valves. Hence, the compensation of the effect of curvature variation on *MRR* is accomplished by a real-time control of fluid pressure at different locations of the freeform surfaces.

A pressure-dependent curvature adaptive (PDCA) control method was developed in which the pressure distribution along the polishing path is obtained by the steps: (1) Determine the surface curvature distribution $\kappa(x, y)$ of the freeform surfaces. (2) Determine the surface gradient distribution of the freeform surface through the calculation of the surface normal vector adopting the function '*surfnorm*' in the *MATLAB* software, so as to obtain the impinging angle distribution $\alpha(x, y)$. (3) Calculate the distribution of η on the freeform surface based on the fitted function $\eta_{Fit}(\alpha, \kappa)$, refer to Eq. (2). (4) Establish the relationship between the fluid pressure p and η, which is denoted as $p = f(\eta)$, where η is calculated in step 3. (5) The fluid pressure distribution is obtained by the function $p = f(\eta)$ and the tool path information, where $\eta = \eta(\alpha, \kappa)$. As mentioned in step 4, the

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