Powder Technology 302 (2016) 153–159

Contents lists available at ScienceDirect

Powder Technology

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

Numerical and experimental study on the spiral-rotating abrasive flow in polishing of the internal surface of 6061 aluminium alloy cylinder

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ARTICLE INFO

Article history:
Received 12 May 2016
Received in revised form 15 August 2016
Accepted 20 August 2016
Available online 21 August 2016

Keywords:
Computational fluid dynamics
Spiral-rotating abrasive flow
Particle trajectory
Internal surface
6061 aluminium alloy
Polishing quality

ABSTRACT

A spiral-rotating abrasive flow polishing technology was presented and discussed in this paper to address the issue of precision polishing of internal surface of the cylinder for 6061 aluminium alloy. The effect of the spiral-rotating abrasive flow on the polishing quality, i.e. polishing efficiency and uniformity, was analysed both numerically and experimentally. The relative equations involved in the spiral-rotating abrasive flow were first developed to simulate the particle trajectories by considering the centrifugal force, Coriolis force, Magnus force and Saffman force with Computational Fluid Dynamics method. Numerical simulation shows that the tangential velocity of the abrasive particles near the internal surface increases significantly with an increase of the rotation speed of the constraint module, and due to the spiral-rotating action the near-wall abrasive particles exhibits random direction and uniform magnitude at velocity, such that this technology is expected to enhance the polishing efficiency and uniformity. Experimental study indicates that the line roughness on the target surface decreases with an increase in the rotation speed due to the increased tangential velocity of impacting particles that enhance the micro-cutting action on the target surface, and hence, resulting in a better surface finish. While the material removal rate increases with an increase of the rotation speed due to the larger kinetic energy brought into the process by the rotation of the constraint module, so that the polishing efficiency could be significantly improved. These findings from the experiment are in a good agreement with the corresponding simulation results.

1. Introduction

Due to the rapid developments in aerospace, medicine and chemical industries, the demanding for high-precision devices increases significantly, so that the quality in processing of some key components would affect the overall reliability and performance of these equipment [1]. However, those devices that are in special shapes, such as the internal surface of the cylinder made of 6061 aluminium alloy, cannot be easily machined by the traditional machining technologies [2]. As a non-traditional machining technology, abrasive machining has been widely used to fabricate micro-structures on quartz crystals [3,4], grind of ceramics [5] and polish of fused silica [6]. By introducing the flow characteristics of the fluid into the abrasive machining process, abrasive flow finishing (AFF) has been proven to be a promising approach for precision machining of both internal surface of tubes [7] and other micro-features on a variety of mateirals, but appropriate machining tools and proper carrier medium need to be selected for different machining tasks in this technique, such as the abrasive slurry jet machinig technology which needs to design approprite nozzles and choose relative abrasives in order to controld the particle motions and finish different tasks [8,9]. In addition, magnetic abrasive finishing (MAF) is another technology for processing the internal surface of cylindrical devices with combination of magnetic field and abrasive flow [10]. By employing MAF technology, Wang and Hu [11] investigated the internal surface finishing of aluminium, brass and stainless steel tubes, respectively. It is found that the characteristics of magnetic abrasives and the control of magnetic field are critical factors in affecting the machining quality. Thus, it has been found from the previous studies that it is hard to control the particle trajectories during AFF process that would affect the machining uniformity, and MAF method has critical requirements for the magnetic abrasives and field that would probably affect its machining efficiency, especially, for large-scale parts.

A spiral-rotating abrasive flow machining technology is proposed in this study to overcome the above issues. As shown in Fig. 1, in this method the turbulent abrasive flow can be formed in a short period of time due to the rotation of the constraint module consisting of a grinding rod and a helical flute which is driven by an external motor, and the centrifugal force generated by the rotating motion induces the particles to impact the internal surface of the workpiece frequently and randomly. Compared to the AFF and MAF technologies, this method can achieve surface polishing with relatively small initial pressure and initial

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http://dx.doi.org/10.1016/j.powtec.2016.08.047
0032-5910/

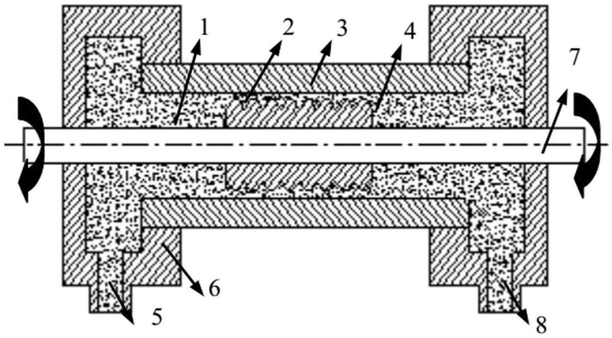

Fig. 1. Schematic representation of spiral-rotating abrasive flow machining: 1. abrasive flow, 2. helical flute, 3. workpiece, 4. confined flow channel, 5. flow outlet, 6. clamp cap, 7. grinding rod, and 8. flow inlet.

velocity due to the spiral-rotating motion induced particle impact erosion, and thus improving the machining efficiency. Moreover, the spiral-rotating motion reduces the inhomogeneous distribution of turbulent kinetic energy and dynamic pressure, and hence improving the polishing uniformity of internal surface as well.

In this study, Computational Fluid Dynamics (CFD) method is first employed to develop a bi-phase abrasive flow, i.e. water and abrasive particles, to simulate the particle trajectories under complex spiral-rotating flow field using Euler multiphase flow model, and then it is to explore the effect of the rotation speed on the characteristics of the spiral-rotating abrasive flow, including the distributions and values of the tangential velocity and pressure near the internal surface of the cylinder. Finally, experimental work will be conducted to validate the simulation results by analysing the effect of the rotation speed on the polishing performance, such as the material removal rate and average line roughness on the internal surface of the cylinder.

2. Models of spiral rotating abrasive flow

As can be seen from Fig. 1 that the motion of the device was performed by the rotation of the constraint module, and hence, resulting in a spiral-rotating abrasive flow field near the internal surface of the workpiece. The polishing quality is associated with the pressure applied by the abrasive flow and its relative velocity. Therefore, mathematical models are needed to be developed in order to calculate the pressure and relative velocity of the abrasive particles near the wall region during the polishing process. The CFD code used for this study is Fluent 14.5 (ANSYS Inc., Canonsburg, Pennsylvania, United States).

2.1. Governing equations of spiral-rotating abrasive flow

The Euler multiphase flow model was used to simulate the bi-phase abrasive flow, i.e. water and abrasive particles, in which the water was considered as the Euler phase and particle was considered as the Dense Discrete Phase, and here the incompressible water was assumed to be chemically inactive and physically stable [12]. The mass equation for the fluid phase can be taken from:

$$\frac{\partial}{\partial t}\left(\alpha_f\rho_f\right)+\nabla\cdot\left(\alpha_f\rho_f\vec{v}_f\right)=\sum_{p=1}^{n}(m_{pf}) \tag{1}$$

where ρ_f is the density of the fluid phase, $\vec{v}_f$ is the velocity vector of the fluid phase, and α_f is the volumetric concentration of the fluid phase, and m_{pf} is the mass of material transferred from solid phase to fluid phase.

By considering the centrifugal force caused by the rotation of constraint module with rotation speed of ω, the momentum equation of fluid phase can be obtained by [13]:

$$\frac{\partial}{\partial t}\left(\alpha_f\rho_f\vec{v}_f\right)+\nabla\cdot\left(\alpha_f\rho_f\vec{v}_f\right)=-\nabla\left(\alpha_f p_{\mathrm{m}}-\frac{1}{2}\rho_f\omega^2 r^2\right)+\nabla\cdot\overline{\overline{\tau_f}}+\alpha_f\rho_f\vec{F}_f+\sum_{p=1}^{n}\left(\vec{R}_{pf}+\dot{m}_{pf}\vec{v}_{pf}\right) \tag{2}$$

where p_m is the static pressure of the bi-phase mixture, r is the rotation radius, $\vec{R}_{pf}$ is the interactive force between phases, $\vec{F}_f$ is the external mass force, and $\overline{\overline{\tau_f}}$ is the stress-strain tensor.

It is assumed that abrasive particles are considered as rigid spheres with a uniform size and the interactions between abrasive particles can be negligible as the volume fraction of abrasive particles in the mixture is small. In this study the rotation speeds are relatively high, in which the rotation of the module may affect the particle trajectories, so that the centrifugal force and the Coriolis force on the particles is taken into consideration. In addition, the Magnus force (F_{ML}) and Saffman force (F_{SL}) are not negligible in this study due to the transverse velocity gradient. Therefore, the equation for predicting the particle motion based on Newton's Second Law can be obtained as follows [14]:

$$m_p\frac{dv_p}{dt}=m_p g+F_D+F_{ML}+F_{SL}+F_X \tag{3}$$

where m_p is the mass of a single particle, v_p is the particle velocity, g is the gravitational acceleration, F_D is the resistance experienced by the particles, and F_X is other force applied on the particles consisting of centrifugal force and the Coriolis force.

In Eq. (3), the forces of F_D, F_{ML}, F_{SL} and F_X can be, respectively, given by [15]:

$$F_D=C_d\frac{1}{2}\rho_f\left(v_f-v_p\right)\left|v_f-v_p\right|S_p \tag{4}$$

$$F_{ML}=\frac{3\rho_f}{4\rho_p}\omega\left(v_f-v_p\right) \tag{5}$$

$$F_{SL}=\frac{3\sqrt{\rho_f\mu_f}}{4\pi\rho_p r_p}\sqrt{\left|\nabla v_f\right|}\left(v_f-v_p\right) \tag{6}$$

where v_f is the fluid velocity, S_p is the front face area of the particle, r_p is the average radius of the particles, and C_d is the resistance coefficient which depends on the Reynolds number, Re_p, of the particles.

By considering the rotation of the constraint module, F_X can be considered as a sum of the centrifugal force and the Coriolis force that can be given by:

$$F_X=\left(1-\frac{\rho_f}{\rho_p}\right)\omega^2 r_x+2\omega\left(v_p-\frac{\rho_f}{\rho_p}v_f\right) \tag{7}$$

where r_x is the distance from the particle to the rotating axis.

2.2. Turbulent model of spiral rotating abrasive flow

As the abrasive moves in a complex spiral-rotating filed, the RNG k-ε turbulent model was employed to represent this complicated situation due to its enhancing accuracy for rapidly strained and swirling flows. This turbulent model considers the effects of both the vortex with large curvatures and turbulence, which was proven to be suitable for the simulation of flow with high strain rates and large curvature streamlines [16,17]. Further, the enhanced wall function that was affected by the baric gradient was also employed to consider the