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Shear-thickening polishing method

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ABSTRACT

A shear-thickening polishing (STP) method utilizing the shear thickening mechanism of non-Newtonian power-law fluid based slurry is proposed for curved surface polishing. The STP principle and micro-material removal action are analyzed. The high-performance STP slurry with the shear-thickening rheological behaviors has been prepared. To achieve the material removal mechanism of STP process, based on the Preston formula, fluid dynamics and shear thickening mechanism, the material removal rate (MRR) model is established and the difference of MRR between theoretical and experimental results is 6.12%. The experimental and theoretical tests of STP process are conducted to investigate the influences of polishing velocity, abrasive concentration and grain size on MRR and surface roughness. Compared with Newtonian fluid slurry, STP slurry can achieve much higher MRR and better surface quality due to shear-thickening effect. MRR of Cr12Mo1V1 (die steel) is up to 13.69 μm/h, and surface roughness is reduced from R_a 105.95 nm to R_a 5.1 nm within 0.5 h of processing. This indicates that STP is a promising processing method for precision finishing or polishing.

1. Introduction

The curved surface plays a key role in the wide fields of manufacturing industry, such as blade of aviation engine in mechanics [1], GMT aspherical mirror in optics [2] and artificial hip or knee in biomedical implants [3]. High-performance and rapid growing demand of curved surface requires high surface quality and high efficiency processing technologies. Currently, many technologies have been developed and applied to process the curve surface, such as elastic emission machine (EEM) [4], chemical mechanical polishing (CMP) [5], hydrodynamic polishing (HP) [6], magnetic float polishing (MFP) [7], magnetorheological finishing (MRF) [8], electrorheological fluid-assisted polishing (EFP) [9], magnetorheological abrasive flow finishing (MRAFF) [10]. EEM can obtain the damage free ultra-smooth surface, but the processing efficiency is limited due to several or dozens of atomic level of material removal amount only [4]. Although nanoscale removal of material can be achieved by CMP, the chemical slurry has a certain impact on the environment [5]. MRF by using computer-controlled optical surfacing [11] is considered as the "gentle" ultraprecision processing method for curved surface polishing/finishing. It is reported that the aspherical carbide mold with surface roughness of R_q 0.5–2.0 nm and profile accuracy of $\lambda/10$ were obtained by MRF [12]. Small ultraprecision aspheric surface can be processed by EFP [9]. MRAFF, as a combination of MRF and abrasive flow machining (AFM) [13], is used for complicated geometry nano-finishing [10]. However, the relatively high cost of magnetorheological fluid (MR fluid) in MRF (or MRAFF) and electrode design in EFP limit their potential application in a much broad range. Consequently, new polishing methods with high efficiency, high quality and low cost have been always to seek out. In addition, environment-friendly processing methods also start to draw attention [14].

In this paper, in order to improve rapidly the surface quality, shear-thickening polishing (STP) is proposed by applying the shear thickening mechanism of non-Newtonian power-law fluid slurry (that is a kind of shear thickening fluid (STF)). Sufficient works [15–20] have already been done to research the performance of STF. Galindo-Rosales et al. [15] theoretically described the rate dependent with steady shear viscosity of STF as shown in Fig. 1. Wagner et al. [16] explained the mechanism of shear thickening as presented in Fig. 2, based on the hydroclusters/particle clusters formation. The fundamental performance of STF is that its rheological behaviors under low shear rate or shear stress is similar to that of Newtonian fluid, while the viscosity of STF increases rapidly with shear rate/shear stress, and even leads to a solid-like behavior. Owing to this particular property, STF is applied in many fields, such as the damping medium of buffer system [17], the liquid body armor combined with Kevlar [18]. Crawford et al. [19,20] discovered that the shear thickening performance of slurry

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Nomenclature

F_{shear}	shear force (N)
F_D	dynamic force (N)
F_R	abrasive resistance force (N)
h_1,h_2,h_3,h'	thickness of shear elastic layer at different conditions
u_0	relative velocity of fluid flow (m/s)
d	average grain size (μm)
τ	shear stress ($\times 10^3$ Pa)
K	consistency index (Pa s^n)
n	viscosity index
u_0	velocity of fluid flow (m/s)
$\dot{\gamma}$	shear rate(or velocity gradient) (s^{-1})
ε	second invariant of the deviatoric stress tensor
υ	kinematic viscosity (Pa s)
ρ	density of fluid (g/mm^3)
u_i, u_j	velocity components
τ_{ij}	viscous shearing stress (Pa)
X_i	mass force
u, v, w	velocity components on x, y, and z direction
MRR	material removal rate
k	Preston coefficient
k_0	Preston modified coefficient
$\bar{k}_0$	average value of k_0
k_1	coefficient related with the workpiece material hardness number
k_2	polishing velocity coefficient related with the abrasive grain size
k_3	coefficient influenced by other factors
U	fluid velocity or velocity of potential flow provided by the polishing plate (m/s)
Φ	stream function
k'	permeability
p'	pressure of the fluid at the capillary wall
h	clearance between the fluid and workpiece surface (mm)
p	pressure of non-Newtonian fluid on the workpiece (Pa)
p_d	dynamic pressure (Pa)
p_f	buoyancy (Pa)
ρ_s	density of dispersion medium (g/mm^3)
η	viscosity (Pa s)
ρ_a	density of Al_2O_3 (g/mm^3)
T	temperature (°C)
v,ω	abrasive velocity (m/s) and rotation speed (r/min), respectively
l	distance between Spindle I axis center and polishing surface (cm)
ρ_w	density of Cr12Mo1V1 die steel (g/mm^3)
E	elastic modulus of Cr12Mo1V1 die steel (GPa)
$D(R),L'$	diameter (or radius) and length of the cylindrical workpiece (mm)
R_a	surface roughness (nm)
$w\%$	concentration (wt%)

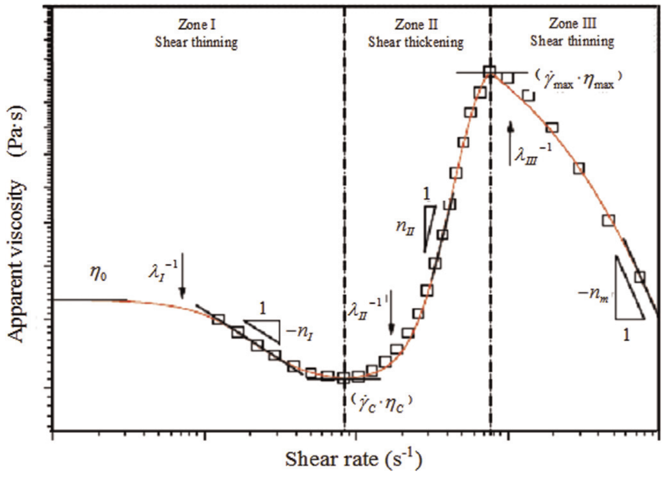

Fig. 1. Three typical regions of the viscosity curve of STF [15].

under high shear conditions affected the surface quality in the CMP process, and analyzed its mechanism, then tried to avoid it. On the contrary, this “defect” is utilized in STP. It is worth mentioning that STP slurry has very good shape adaptability for certain mobility of fluid, and has shear thickening properties to meet the requirements of material removal, besides, the polishing slurry can be recycled without causing pollution.

Setting up the model of material removal rate (MRR) is the wide and critical approach to understand the mechanism of polishing process. Much valuable works [21–32] have already been done to research the MRR model of various processing methods. Preston [26] proposed the Preston equation, an empirical formula to calculate MRR, which has been widely used in precision polishing or grinding process; Runnels et al. [27,28] established the wear model of material removal for correcting the Preston equation by analyzing the fluid dynamic pressure of CMP in tribology. Sundararajan et al. [29] calculated the thickness of polishing liquid film and hydrodynamic force by solving the Reynolds equation.

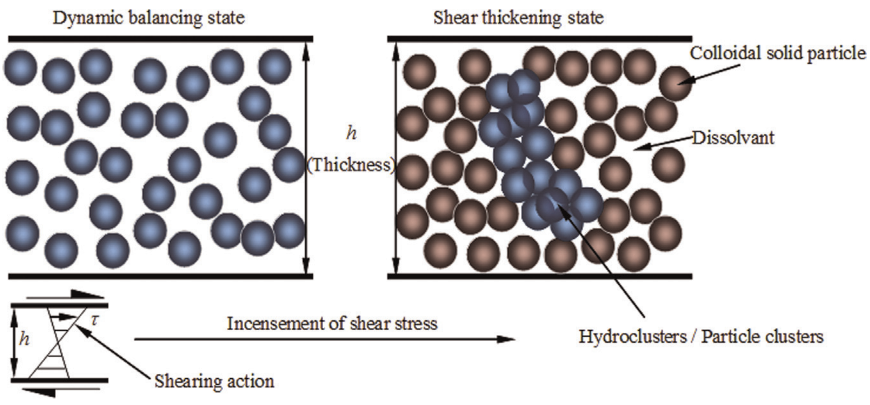

Fig. 2. Schematic illustration of shear thickening mechanism [16].