Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2013, 5(9):278-285

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Mechanism research and experimental study of viscoelastic magnetic abrasive tools finishing

W. H. Li, S. Q. Yang, X. H. Li, H. F. Zhai and J. T. Shi

College of Mechanical Engineering, Taiyuan University of Technology, Taiyuan, Shanxi, P. R. China

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ABSTRACT

Based on the characteristics of solid magnetic abrasive and abrasive flow finishing, a new technology of viscoelastic magnetic abrasive finishing is presented. The theoretical micro model of viscoelastic magnetic abrasive tools is established, and influencing factors of a positive pressure are determined by force analysis. Finishing mechanism of micro-grinding, slipping, rolling and so on is analyzed theoretically and verifying experimentally. Experiments also show that all burrs are removed, the edges are rounded off and the surface is smooth, the surface roughness value Ra of hole surface drops from 0.53μm to 0.05μm. Its successful application will effectively solve the practical difficulty of deburring and surface finishing for special shapes such as groove, keyway, etc., and fulfil the quantitative finishing of complex surfaces. Results can provide the theoretical basis for the preparation of viscoelastic magnetic abrasive and further experimental study of this process.

Keywords: Finishing, Magnetic Abrasive Tools, Viscoelastic, Finishing Mechanism

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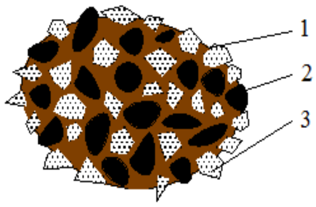
INTRODUCTION

An important development direction of modern manufacturing technology is precision and ultra precision, fine and ultra-fine processing technology. Surface finishing technology is the main methods to improve the surface quality and surface integrity of the part as a very important part of the precision and ultra-precision processing technology, being widely studied and applied. There are many surface finishing problems such as pipeline of engine, oil and gas transmission pipeline, various valves of the hydraulic components, bearings retainer and other parts in actual production, as well as the development of new composite materials presents new subjects and challenges for surface finishing technology. Developing practical surface finishing technology will provide a more efficient means for solving the finishing problems of composite materials, difficult to cut materials and special-shaped surface[1].

Solid magnetic abrasive has special advantages in finishing effect, finishing efficiency and application range, etc., occupying the important position, having the huge potential application value, where the magnetic abrasive grains directly influence the finishing effect and efficiency. The existing problems of solid magnetic abrasive are easy to disperse and spatter during finishing, complicated preparing processes, high cost, etc.[2-5]. Because the abrasive flow has good fluidity and viscoelasticity, it is helpful to realize the deburring and finishing of special-shaped hole surface, but the equipment requires high pressure (approximately 20MPa), and the special machine and fixture must be designed according to the different parts[6-8]. For this reason, integrating effectively the advantages of solid magnetic abrasive and abrasive flow finishing, a new technology of viscoelastic magnetic abrasive finishing is presented, which provides a more effective method for solving the surface finishing problems of long-thin tube, narrow groove surface and special-shaped surface[9-10].

Viscoelastic Magnetic Abrasive Finishing

As Fig.1 shows that viscoelastic magnetic abrasive tools(VMAL) are prepared from matrix, magnetic medium phase and abrasive phase by the certain process. Matrix is prepared from carrier (viscoelastic polymer) and many auxiliary additives, and magnetic medium and abrasive phase disperse evenly in the matrix. The abrasive phase surrounded by the magnetic medium phase would be pressed against the workpiece surface because of the magnetic force of magnetic medium phase in magnetic field, thus realizing the finishing of the workpiece. The abrasive phase play a major role in finishing, the magnetic medium providing force for the finishing of abrasive phase, and improving significantly the finishing effect of abrasives under rheological property of the matrix.

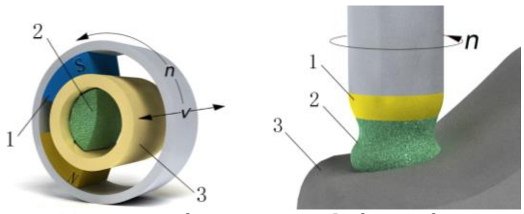


1.Matrix 2.Magnetic medium phase 3.Abrasive phase

Fig. 1. VMAL Schematic Diagram

VMAL is semi-solid in appearance, having a certain viscoelasticity. It can adapt to different workpiece surfaces or any part of the workpiece surface because of its own fluidity. It has a certain magnetic, producing a certain force on the workpiece surface in magnetic field. The viscoelastic magnetic abrasive tool would form complex motion with respect to the surface of workpiece under the action of relative rotational motion, reciprocating linear motion and vibration, etc., realizing the finishing of the workpiece surface by micro-grinding, collision, rolling, electrochemical corrosion, etc., under the action of force and relative motion.

Cavity surface finishing such as grooves with VMAL as shown in Fig.2 (a). The amount of viscoelastic magnetic abrasive was placed on the inner cavity of workpiece, realizing the finishing and deburring of the whole surface under the action of relative rotation and axial rectilinear motion between the magnetic pole and the workpiece. When finishing free surface as shown in Fig.2 (b), the amount of viscoelastic magnetic abrasive was placed between the workpiece and the magnetic pole, the abrasive tools forming a “fretting flexible tools” under the control action of the magnetic field, realizing finishing of the whole by the pole rotary motion and the shaping motion of the free surface (by means of NC machine used in the former surface shaping process, using viscoelastic magnetic abrasive as cutting tools).



(a) groove surface (b) free surface
1.Magnetic pole 2. Viscoelastic magnetic abrasives 3. Workpiece

Fig. 2. VMAL Finishing Schematic Diagram

VMAL Microcosmic Model

Flow morphology of the viscoelastic abrasive tools depends on the solid phase volume fraction in abrasive tools. Because they are uncompatible between the magnetic medium phase, abrasive phase and the matrix, without considering the porosity, according to volume additivity principle:

$$\frac{V_x}{m_x} = \frac{V_g}{m_x} + \frac{V_y}{m_x} \tag{1}$$

Where, V_x is the volume of suspension(L), m_x is the mass of suspension(kg), V_g is the volume of solid phase(L), V_y is the volume of the fluid phase(L).

Two methods of suspension solid are mass fraction ω_g and volume fraction ϕ_g of the solid phase, respectively:

$$\omega_g = m_g/m_x \quad \phi_g = V_g/V_x \tag{2}$$

When m_x =1kg, there is:

$$\frac{\omega_g}{\rho_g\phi_g} = \frac{\omega_g}{\rho_g} + \frac{1-\omega_g}{\rho_y} \tag{3}$$

Where, ρ_g and ρ_y are density of the solid and fluid phase(kg/m^3).

Thus the relationship between the mass fraction and the volume fraction is:

$$\phi_g = \frac{\omega_g/\rho_g}{\omega_g/\rho_g + (1-\omega_g)/\rho_y} \tag{4}$$

Referring to the calculation method of mixed slurry solid phase volume fraction in the sticky slurry flow[11], there is:

$$\frac{\omega_c}{\rho_c\phi_c} = \frac{\omega_m}{\rho_m\phi_m} = \frac{\omega_c}{\rho_c} + \frac{\omega_m}{\rho_m} + \frac{1-\omega_c-\omega_m}{\rho_j} \tag{5}$$

Where ω_c and ω_m are mass fraction of the magnetic medium and abrasive phase, ρ_c and ρ_m are density of the magnetic medium and abrasive phase (kg/m^3), ϕ_c is volume fraction of the magnetic medium phase, ρ_j is density of the matrix(kg/m^3).

The volume fraction of magnetic medium phase and abrasive phase can be derived from formula(5):

$$\phi_c = \frac{\omega_c}{\omega_c + \frac{\omega_m\rho_c}{\rho_m} + \frac{(1-\omega_c-\omega_m)\rho_c}{\rho_j}} \tag{6}$$

$$\phi_m = \frac{\omega_m}{\omega_m + \frac{\omega_c\rho_m}{\rho_c} + \frac{(1-\omega_c-\omega_m)\rho_m}{\rho_j}} \tag{7}$$

According to the suspension viscosity calculation formula with wider application range put forward by Chong[12]:

$$\eta = \eta_0\left[1+0.75\frac{\phi_g/\phi_{vc}}{1-\phi_g/\phi_{vc}}\right]^2 \tag{8}$$

Where η and η_0 are viscosity of the suspension and matrix (cp), ϕ_g is volume fraction of the solid fraction, ϕ_{vc} is maxium volume fraction of the solid fraction in fluid.

The viscosity of VMAL may be derived by substituting the variables of the formula (6) and (7) into the formula(8):

$$\eta_1 = \eta_0\left[\left[1+0.75\frac{\phi_c/\phi_{vc}}{1-\phi_c/\phi_{vc}}\right]^2 + \left[1+0.75\frac{\phi_m/\phi_{vc}}{1-\phi_m/\phi_{vc}}\right]^2\right] \tag{9}$$

Where η_1 is VMAL viscosity(cp).

Although the shear stress increases non-linearly with the shear deformation rate in the non-Newtonian fluid experiment, but can be expressed by a power function. The VMAL is the power-law fluid, its constitutive equation is[13]:

$$F_\tau = K\dot{\gamma}^{n} \tag{10}$$

Where F_τ is VMAL shear stress, *K* is the viscosity, $\dot{\gamma}$ is the shear rate, *n* is the value of power exponent.

The shear stress of the VMAL is:

$$F_\tau = \eta_0\left[\left[1+0.75\frac{\phi_c/\phi_{vc}}{1-\phi_c/\phi_{vc}}\right]^2+\left[1+0.75\frac{\phi_m/\phi_{vc}}{1-\phi_m/\phi_{vc}}\right]^2\right]\dot{\gamma}^{n} \tag{11}$$

It can be found from formula(11) that the shear stress of the VMAL is not only related to the viscosity of the matrix, but also the maximum volume fraction, the volume fraction of the magnetic medium and abrasive medium phase. Fig.3 shows the variation in shear stress with the volume fraction of magnetic medium and abrasive medium phase under certain conditions.

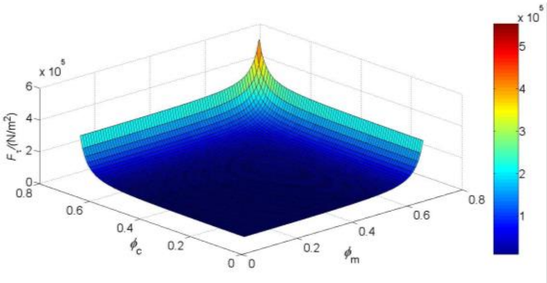


Fig. 3. Variation in shear stress with the volume fraction of magnetic medium and abrasive medium phase

Force Analysis

The force analysis of the VMAL is shown in Fig.4. In Fig.4, F_N is the normal force of the workpiece on the abrasive tools, F_m is the magnetic force, F_z is the finishing resistance, *m* is the mass of abrasive, θ is the angle between F_m and normal direction, α is the angle between gravity and normal direction, β is the angle between F_z and tangential direction, *M* is the viscous torque of the abrasive subjected to the matrix.

The tangential direction:

$$F_1 = F_m\sin\theta - F_z\cos\beta - mg\sin\alpha \tag{12}$$

The normal direction：

$$F_2 = F_m\cos\theta - F_z\sin\beta + m\,g\cos\alpha + F_C - F_N = 0 \tag{13}$$

$$F_z = fF_N/\cos\beta \tag{14}$$

$$F_N = \frac{F_m\cos\theta + mg\cos(2\pi nt) + F_C}{1+f\tan\beta} \tag{15}$$

Where F_1 and F_2 are the resultant force in tangential and normal direction(N), f is the friction coefficient between magnetic medium phase and workpiece(r/min), *t* is the finishing time(min).

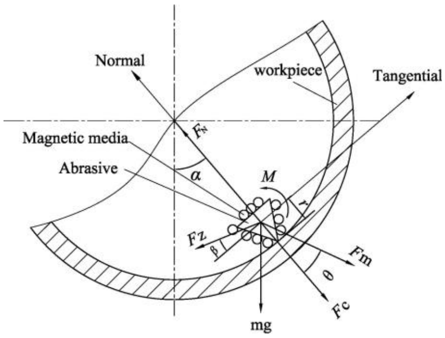


Fig. 4. The force analysis diagram of the viscoelastic abrasive tools

Assuming that the magnetic fields distribute evenly, according to the circuit design and practical calculation, the formula of the magnetic field force can be simplified as follows[14]:

$$F_{\mathrm{m}} = \frac{\pi B^2 r^2}{2\mu_0} \tag{16}$$

Then, F_{N} can be calculated as:

$$F_{\mathrm{N}} = \frac{\pi B^2 r^2 \cos\theta + 2\mathrm{g}m\mu_0\cos(2\pi nt) + 2\mu_0 F_C}{2\mu_0(1+f\tan\beta)} \tag{17}$$

Where μ_0 is the permeability of vacuum(H/m), *B* is the magnetic induction intensity(T), *r* is the simplified radius of single abrasive(mm).

The overturning moment of workpiece acting on the abrasive in the tangential direction can be calculated as:

$$T = F_1 \cdot r = (F_{\mathrm{m}}\sin\theta\text{-}F_{\mathrm{z}}\cos\beta\text{-}mg\sin\alpha)\cdot r \tag{18}$$

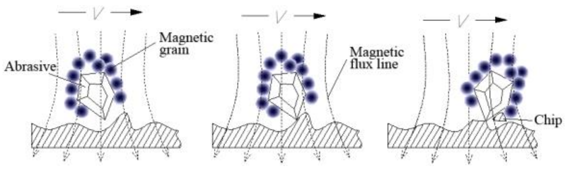
Where *T* is the overturning moment(N·mm).

When *M* is larger than *T*, the VMAL viscoelasticity is relatively large, thus abrasive does not roll, but sliding relatively to the workpiece surface, the major roles are grinding and sliding at this time; when *M*<*T*, the abrasive would roll, thus producing collision and rolling action; when *M*≈*T*, it would produce grinding, rolling and slipping.

Finishing Mechanism

Micro- Grinding and Sliding

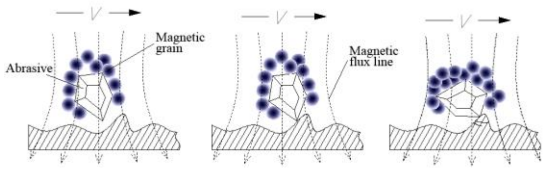
Without considering gravity, magnetic abrasive grain in machining region could be pressed into the workpiece surface under the centrifugal force and normal component force of magnetic force. Because the magnetic fields drive abrasives moving, thus producing the relative sliding between the abrasive and the workpiece surface, the workpiece surface atoms would be removed if thrust force of magnetic force and interaction force of magnetic particles is greater than the machining resistance. The action process is shown in Fig.5.



(a) Abrasives approaching to the surface peak (b)Abrasives grinding the surface peak (c) The chip peeling off
Fig. 5. Surface grinding and sliding of VMAL acting on the surface of workpiece

Rolling

The abrasives could be pressed to the workpiece surface under the action of the centrifugal force and normal component force of magnetic force. If the tangential component force of the magnetic field force and the interaction force between particles is less than the finishing resistance, the abrasives would not produce grinding action on the workpiece surface. According to mechanical analysis, there is relative rolling besides relative sliding. If the kinetic energy of abrasives rolling on the workpiece surface is greater than the energy for elastic deformation and plastic deformation of the workpiece, the surface micro peak would produce plastic deformation and flat under the rolling action of the abrasives, thus realizing rolling finishing. When the kinetic energy of abrasives is not enough to make the micro peak producing plastic deformation, but only elastic deformation, under the alternate effect of a large number of abrasives, micro peak would harden or break because of fatigue, forming chip, thus realizing the surface finishing. The action process is shown in Fig.6.



(a) Abrasives approaching to the surface peak (b)Abrasives colliding , rolling and sliding the surface peak (c) Plastic deformation of the peak stacking

Fig. 6. Collision, rolling and sliding process of abrasive magnetic tools acting on the surface of workpiece

EXPERIMENTAL SECTION

The experiment device and abrasives is shown in Fig.7. The experimental parameters are as shown in Table 1.

Table 1. Experimental Parameters

Parameters	Value
Arrangement angle of magnetic poles	90 °
Rotational speed of magnetic poles	0.55m/s
Feed speed of magnetic poles	10mm/s
Abrasive phase	Green SiC, Size 240#
Magnetic medium phase	Iron power
Filling amount of viscoelastic magnetic abrasive	20g
Inner diameter of Workpiece	32mm
External diameter of Workpiece	36mm
Material of Workpiece	YL12
Finishing time	20min

Fig. 7. Photo of experimental device and abrasives

The relation curve between surface roughness value *Ra* and finishing time *T* is shown as Fig.8. From Fig.8, *Ra* sharply declines at the initial phase and drops about 2 levels in 5 min, *Ra* drops from 0.53μm to 0.07μm after 10 min. With the prolonging of finishing time, *Ra* declines slowly, and to 0.05μm after 15min. It indicates that this new process has high efficiency and an optimal finishing time *T*.

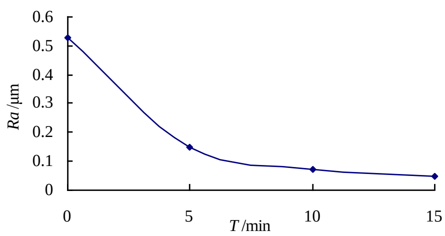
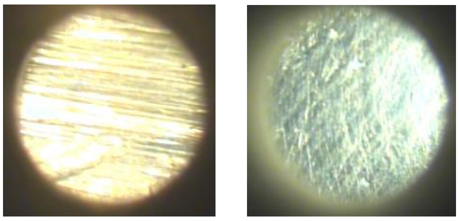


Fig. 8. Relation curve between surface roughness value *Ra* and finishing time *T*

After finishing, the machined surface is smooth and bright, comparison photos are shown in Fig.9.

(a) Before finishing (b) After finishing
Fig. 9. Comparison photos of aluminium hole surface

The image contrast of hole surface acquired by SW01 keyhole video instrument before and after finishing is shown in Fig.10.



（a）Before finishing （b）After finishing 20min
Fig. 10. Microscopy of hole surface before and after finishing(40X)

It can be seen from Fig.10 that cutting markers are visible on the workpiece surface before finishing, exhibiting isotropy, the surface being rough. After finishing 20min, the surface exhibits anisotropy due to the random motion of abrasives under the action of rotation and moving of the magnetic poles, the surface quality improving greatly. It can be seen from the finishing texture that the trajectory of abrasives is crossing reticulate clay, mainly caused by micro-grinding and sliding of abrasives, and micro-pits of the workpiece surface are mainly caused by rolling of abrasives.

CONCLUSION

⑴VMAL finishing is advanced on the basis of analyzing synthetically the advantages and disadvantages of the solid magnetic abrasive tools and abrasive flow finishing, and the composition of viscoelastic composition and realization way of the technology are analyzed.

⑵The micro mathematical model has been developed for VMAL, the shear stress formula having been deduced, the simulation having been carried out, the influencing factors having been determined for the shear stress, which was not only related to the viscosity of the matrix, but also the maximum volume fraction of solid phase in the matrix and the volume fraction of magnetic medium and abrasive phase. This provides theoretical basis for VMAL preparation.

⑶The mechanism of VMAL finishing has been analyzed in theory; the formula of normal force and overturning moment having been deduced; the finishing mechanism having been determined, which has been validated experimentally. This provide theoretical basis for experimental study of the technology.

⑷Experiments show that all burrs are removed, edges are rounded off, the surface is smooth, *Ra* drops from 0.53μm to 0.05μm. Its successful application will effectively solve the practical difficulty of deburring and surface finishing of special shapes and fulfil the quantitative finishing.

Acknowledgments
This research is financially supported by specialized research fund for the doctoral program of higher education of China (2011 1402120003) and provincial natural science foundation of Shanxi (2011021021-4).

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