Study on the characteristics of grinding fluid in extrusion grinding machining

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Abstract. Extrusion grinding machining (EGM) has become a key technology in the post-processing of micro-hole in the injector nozzle. In this paper, the pure slurry prepared from organic bentonite and the pure slurry after adding abrasive as experimental objectives, and the correlation performance has been carried out. Results showed that both pure slurry and slurry abrasive have good shear thinning characteristics, belong to pseudoplastic non-Newtonian fluid, and their rheological properties obey the power-law model. The pure slurry after stirring and shearing can restore the reticular structure in a short time, which proves that it has excellent thixotropy and meets the conditions of circulating processing of grinding fluid. In addition, the pure slurry and slurry abrasive also have good sedimentation stability, suspension capacity, and dispersion properties.

1. Introduction

Micro-hole extrusion grinding is a micro-hole deburring technology, which is continuously developed based on water jet machining and abrasive flow machining technology. For the injector nozzle processed by the Electrical Discharge Machining process [1], this technology has a significant effect on removing the sharp burrs remaining in the nozzle hole, polishing the rough surfaces, and forming a rounded corner at the nozzle hole entrance. After EGM, the nozzle hole diameter of the injector nozzle increases, the flow coefficient is significantly enhanced, and the flow dispersion is reduced, which improves the engine performance and emissions using the injector nozzle [2].

The grinding fluid as the processing tool of EGM flows through the workpiece under high pressure, and the abrasive particles in the grinding fluid collide with the raised burrs and recast layer to cut so that the inner surface of the small hole meet the processing requirements [3]. The performance of grinding fluid prepared by mixing abrasive particles, base fluid, and additives have an extremely significant influence on the processing effect. Among them, the slurry prepared from the base liquid and additives needs to act as a carrier of the abrasive, which can make the abrasive uniformly scattered, and has favorable suspension stability [4].

Huang Ying et al [5] used deionized water, sodium bicarbonate, and sodium polyacrylate to compound suspensions, adding mineral oil and other additives, mixed with brown alumina to form oil-water emulsion as grinding fluid. According to the preparation results, the grinding liquid With good performance in suspension and cutting, and no conspicuous sedimentation within ten days. Tina Bremerstein et al [6] discussed the rheological properties of a new abrasive media consists of
polyborosiloxane and three different sizes of silicon carbide particles with the addition of hydrocarbon oil and metal soap to adjust the viscosity of the mixture, and the effect of abrasive particles on grinding efficiency. They obtained that the increasing viscosity of the abrasive media and progressing rounding of the large abrasive particles as a result of the machining process were the main factors that cause a decreased material removal rate and reduced surface quality. Pure silicone rubber and silicone rubber with additives were chosen as the media by A.C.Wang et al [7]. These silicone gels had low flow property and were mixed uniformly with abrasive particles to become the flexible media, which did not stick on the workpiece surface after contact.

However, in the case of high pressure and high speed, the polymer chain in the slurry prepared by polymer is vulnerable to breakage, and the structure changes accordingly, which affects the suspension stability and rheological properties of the grinding fluid in the processing process. Liu et al [8] investigated that bentonite can substitute the function of polymer compounds in slurry preparation, acting as a suspending agent, thixotropic agent and lubricant. The formulated slurry has wonderful suspensibility, stable structure in the processing process, and can be reused, which can improve work efficiency.

Based on previous studies, bentonite exerts an enormous function on EGM because of its good mineralogical and technological properties. But the performance of the slurry and slurry abrasives prepared by it has not been fully studied, which will impact the processing quality and efficiency of the injector nozzle. Therefore, the rheological properties, thixotropy, and settlement stability of the slurry and the slurry abrasive were studied in this paper, which can provide guidance to make up EGM grinding fluid in engineering works.

2. Experiments

2.1 Fabrication of grinding fluid

The grinding fluid in this study is composed of lubricating oil, organic bentonite, abrasive, and additives in a certain proportion. The details of the preparation ratio are presented in Table 1. Organic bentonite is a kind of product with a sheet structure. Its oil-tend characteristics make it easy to form a thixotropic gel in lubricating oil, so it has the properties of anti-settling, thickening, anti-sagging, and thixotropy [9]. With the help of additives, the dispersion speed of abrasive particles and the pulping speed are enhanced, and the dispersion fineness becomes smaller. Under the same abrasive concentration, the smaller the diameter of the abrasive particle is, the easier it is to be wrapped by the net structure in the slurry. Moreover, a decrease in surface roughness has been observed with the reduction in abrasive particle size because smaller abrasive particles produce a smaller depth of indentation in the workpiece [10]. So silicon carbide of 3000 mesh is selected in this paper.

| Component       | Lubricating oil | Organic bentonite | Additive | Abrasive |
|-----------------|-----------------|-------------------|----------|----------|
| Wt.%            | 77.89           | 4.91              | 8.6      | 8.6      |

2.2 Experimental scheme

Choosing the pure slurry and the slurry abrasive as the experimental objects, as shown in figure 1, this paper carried out three parts of experiments to study their properties.

2.2.1 Experimental scheme of rheological properties

To obtain the non-Newtonian category and constitutive equations of pure slurry and slurry abrasives, at a constant temperature of 25°C, the apparent viscosity values were continuously measured by the NDJ-8S viscometer at 8 kinds of rotational speeds, and the rotor rotational speed was converted into the shear rate by equation (1) [11].
\[ \dot{\gamma} = \frac{\pi n}{15} \cdot \frac{r_2^2}{r_2^2 - r_1^2} \]  \tag{1}

Where \( \dot{\gamma} \) is shear rate, \( n \) speed of the rotor, \( r_1 \) radius of the rotor, and \( r_2 \) measuring cup radius of the pure slurry or slurry abrasive.

2.2.2 Experimental scheme of thixotropy
Since the specific structure and processing requirements of the injector nozzle, the grinding method of spray holes is One-way EGM rather than Two-way EGM [12]. After processing, the slurry abrasive returns to the material box from the pipeline. Then before filling the working tank, it is indispensable to start the mixer in the material box to agitate the mixed liquid at a low speed, so that the slurry can quickly restore the continuous spatial network structure and re-wrap the abrasive to meet the working viscosity requirements. This requires that the prepared slurry should have superior thixotropy.

Because of this case, the Stirring experiment of the pure slurry is carried out separately. Choose a cup of pure slurry and stir 20min at the low speed of 50 r/min in a small mixer every two days, then sit still for 1 hour. Before stirring and after standing, the apparent viscosity is measured by viscometer, and the 10min viscosity value is selected to draw the curve.

2.2.3 Experimental scheme of sedimentation stability
The definition of sedimentation stability means that the abrasive particles are uniformly dispersed in the slurry, and there is no phenomenon of abrasive agglomeration. Besides, the settling of the abrasive particles and oil precipitation can not occur in a long time [11]. The stability of sedimentation is confirmed by static settlement experiments, that is, the total height of precipitated oil layer and suspension are measured at regular intervals. The evaluation index is expressed by the relative settlement height (RSH) of abrasive [13]. The equation is as follows:

\[ RSH = \frac{H - H_0}{H} \]  \tag{2}

Where \( H \) is the total height of the slurry abrasive, and \( H_0 \) represents the distance from the top of the slurry abrasive to the interface between the precipitated oil and the lower turbid layer, which includes a stable slurry abrasive layer and a settling layer. The higher the RSH value is, the better the stability of the slurry abrasive is, which proves that there is no apparent settlement of the abrasive and less oil is precipitated. The newly compounded pure slurry and slurry abrasive were observed at rest, the heights of the two positions were measured once a week, and the apparent viscosity of both was measured at the same time.

3. Results and discussion

3.1 Rheological properties of pure slurry and slurry abrasive

3.1.1 Non-Newtonian fluid category of pure slurry and slurry abrasive
Figure 2 shows the apparent viscosity of pure slurry and slurry abrasive at different shear rates. The apparent viscosity declines with the increase in shear rate, which illustrates that both pure slurry and
slurry abrasive are pseudoplastic non-Newtonian fluids and demonstrate a good shear thinning effect. And with the increase of shear rate, the decreasing trend of their apparent viscosity continuously slows down. This is because the molecules in the two link each other through molecular bonds, forming a net structure finally with mechanical entanglement between molecular bonds [14]. At a low shear rate, the net structure destroyed by the rotor will recover in a short period so that the apparent viscosity can be maintained at a higher level. However, at a high shear rate, the damaged net structure cannot be recovered in time, so that the apparent viscosity of both measured is intensely small.

The apparent viscosity of the pure slurry is lower than that of the slurry abrasive, because there is only the interaction between polymer molecules in the pure slurry. After filling silicon carbide particles, interactions between abrasive particles as well as between abrasive particles and polymer are introduced into the filling system, which leads to the increase of the viscosity of the slurry abrasive [15].

3.1.2 Non-Newtonian fluid constitutive equation of pure slurry and slurry abrasive
To explore the rheological properties and get the non-Newtonian constitutive equation of pure slurry and slurry abrasives, the power-law model is used to non-linearly fit the experimental data based on both of them are pseudoplastic non-Newtonian fluids. The power-law model is shown in equation (3).

\[ \tau = K\gamma^n \]

Where \( \tau \) is shear stress; \( k \) is a consistency coefficient, which represents the average viscosity of the fluid; \( n \) is a flow index, which is a measure of the deviation of fluid from Newtonian.

| Equation | K   | n   | \( R^2 \) | RMSE |
|----------|-----|-----|-----------|------|
| Pure slurry | 5.345 | 0.3616 | 0.9933   | 0.2878 |
| Slurry abrasive | 9.242 | 0.2179 | 0.9693   | 0.7614 |

Figure 3 exhibits the rheological properties curves of pure slurry and slurry abrasive, which illustrates the relationship between the shear stress and the shear rate. The shear stress increases sharply at the lower range of the shear rate, whereas it increases slowly at the higher range. Table 2 manifests the model coefficients and evaluation index values of pure slurry and slurry abrasives after fitting. \( R^2 \) is the fitting confidence of the constitutive equation of pure slurry and slurry abrasive, whose values are more than 0.96. RMSE is the root mean square error, and the values of them are less than 1. The higher value of \( R^2 \) is, and the smaller value of RMSE is, which indicates that the experimental data have better consistency with the fitting results, and more veritably reveal the rheological properties of the fluid. The fitting results determine that the rheological properties of pure slurry and slurry abrasive fit the power-law model.
3.2 Thixotropy of pure slurry and slurry abrasive

Figure 4 shows that the apparent viscosity of pure slurry and slurry abrasive decrease with the increase of time at constant rotational speed (60r/min). It can be seen that the pure slurry and slurry abrasive composed of organic bentonite belong to the thixotropic system of non-Newtonian fluid, which has a similar trend as the gel constituted by organic bentonite [16].

When the pure slurry and the slurry abrasive are stationary, the organic bentonite molecules assemble to form a spatial network structure, and the oil and abrasive of fluid are wrapped in it, resulting in the viscosity of the system increases intensely. However, this structure is vulnerable and easy to be destroyed as long as a small shear force is applied to it. Furthermore, the material wrapped in it is re-released, the system returns to fluidity, and the apparent viscosity decreases. The greater the shear force, the faster the apparent viscosity decreases. Once the shear force stops acting, the destroyed structure will slowly recover, the particles will re-gather to form a continuous network structure, and the viscosity of the system will gradually increase. Therefore, this structural characteristic makes the pure slurry and slurry abrasives have superior thixotropy.

Figure 5 shows that although the apparent viscosity measured before each stirring constantly declines with the increase of stirring times, the apparent viscosity measured after stirring and then standing for one hour shows a stable inclination. It is demonstrated that the pure slurry can quickly restore the net structure after stirring, and the values of viscosity measured fluctuate petty each time, which also illustrates that the thixotropy of it is so good to meet processing demand. However, with the extension of the standing time after the measurement, the molecular entanglement points with weak binding force will gradually separate, resulting in a decline in the stability of the system, which is also the reason why the viscosity measured before each stirring is always smaller than the last one.

3.3 Sedimentation stability of pure slurry and slurry abrasive

In the case of the pure slurry without adding abrasive, the spatial structure formed by organic bentonite is stable, which can wrap the oil well, and there will be no oil precipitation after standing for a long time. While in the power-law fluid, as long as there is a difference between the density of the
abrasive and the slurry, under the action of gravity, the abrasive particles will migrate in the slurry and sink or float at a certain speed [17].

As shown in Figure 6 and Figure 7, the apparent viscosity of pure slurry increases with the increase of standing time and then conduces to be stable without oil precipitation. During the standing time after preparation, the electrostatic interaction between bentonite molecules is close to each other so that the spatial network structure becomes more compact, the range of it is wider, and its stability is also enhanced. Moreover, the viscosity increases gradually and finally tends to be stable. The apparent viscosity of slurry abrasives rose at first and then declined with the increase of standing time. The value of RSH in the first two weeks was more than 0.98, which means that only a little oil was precipitated. The reason for the difference in slurry abrasive is that with the further extension of the standing time, some molecules get closer together and create some independent dense aggregates, which makes their reticular structures begin to separate or aggregate. The separation of the network structure also leads the oil and abrasive re-released. The abrasive begins to settle under the action of gravity. On the contrary, the oil starts to rise to the top of the fluid. In addition, when the value of RSH of the slurry abrasive is less than 0.9, the apparent viscosity starts to decrease, which determines that a certain amount of abrasive has precipitated, and the suspension capacity of it gradually becomes worse. In a word, the stability of pure slurry is exceedingly superior. The Sedimentation stability and suspension capacity of slurry abrasive are good within two weeks, which can satisfy the demands of storage and processing.

4. Conclusions
In this paper, a series of experiments were carried out on the slurry and slurry abrasives prepared by organic bentonite, which are commonly used in EGM, and whether their rheological properties, thixotropy, and sedimentation stability meet the processing requirements were discussed. Specific experimental results are shown as follows:

(1) Both pure slurry and slurry abrasive are pseudoplastic non-Newton fluids, and their apparent viscosity decreases as the shear rate is increased, exhibiting a remarkable characteristic of shear-thinning, which greatly meets the injector nozzle processing requirements.

(2) The rheological properties of both pure slurry and slurry abrasive fit the power-law model. And their specific non-Newtonian fluid constitutive equations can be obtained through nonlinear fitting calculations for experimental data.

(3) The pure slurry and slurry abrasive prepared from organic bentonite also belong to the thixotropic system of non-Newtonian fluid and have good thixotropy. The net structure after stirring and shearing can recover quickly in a short time, and the values of viscosity measured fluctuate petty each time, which can meet the conditions of grinding fluid cycle processing.

(4) The stability of pure slurry is exceedingly superior, and there is no precipitation for a long time. The Sedimentation stability and suspension capacity of slurry abrasive are good within two weeks, which can satisfy the demands of storage and processing.
The results and conclusions of this paper can be used to study the formulation optimization of EGM, which also can provide guidance for the engineering application of EGM.

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