Study on the correlation between grain size and processing limit in abrasive flow machining

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Abstract: The influence of particle size on the abrasive flow machining mechanism and processing limit was studied by establishing the processing model of different particle size. When many scholars studied the mechanism of abrasive flow machining in the past, they only established a machining model and ignored the effect of abrasive particle size. By comparing the size of different granularity abrasive particles and the workpiece surface in contact with each other, the large granularity abrasive particle processing model and the small granularity abrasive particle processing model were put forward, and their processing mechanism was analyzed respectively. On this basis, the reason of machining limit in different particle size abrasive processing process is explained. Finally, the theoretical analysis and experimental results were compared to verify the correctness of the processing mechanism and theoretical analysis of processing limit of abrasive with different granularity, and an optimal experimental scheme was proposed to break through the original processing limit.

1. Introduction
Abrasive Flow Machining (AFM for short) is a semi-solid fluid Abrasive made by mixing viscoelastic polymer material and Abrasive particles and then extruding through the surface to be machinated to achieve the effects of polishing, deburring and ferreting, so it is particularly suitable for surface finishing of narrow cracks, micro-holes and special-shaped holes [1-3]. Abrasive flow machining technology was developed in the 1960s to solve the processing problems of complex aerospace parts [4-5]. It was introduced into China in the 1980s, which caused the research of many scholars and made many achievements [6].

V.K.Jain et al. established a machining result prediction model where the initial surface contour was considered as an equilateral triangle [7]. Wang Shiying et al. analyzed the mechanical principle of abrasive flow machining by treating the abrasive particle as an irregular polygon with multiple cutting edges and the workpiece surface to be machined as a plane [8]. Hu Jinglei analyzed and studied the mechanism of removing workpiece burr by using abrasive flow technology [9]. Tina et al. considered the influence of abrasive wear in the machining process [10]. But these articles in processing model is established considering the effects of grinding abrasive, only use a kind of mechanism analysis processing model, and found in the previous experimental research and application research on AFM number or time limit [11], and is directly related to the grinding abrasive, processing more than limit, processing effect will be worse, the surface roughness is not. Therefore, this paper takes the abrasive
particle size as the starting point, through the establishment of different particle size abrasive processing model to carry on the processing mechanism analysis, and then studies the abrasive particle size in the abrasive flow processing and processing limit of the correlation.

2. Mechanism study
Before studying the processing mechanism of different granularity abrasive particles, it is necessary to determine the surface morphology of the workpiece. Through the contact relationship between different granularity abrasive particles and the workpiece surface, the processing model of different granularity abrasive particles can be established. Then the influence of particle size on the processing mechanism and processing limit can be analyzed.

2.1 Microstructure of workpiece surface
For the surface morphology of the workpiece, the inner surface of the stainless steel capillary with an initial surface roughness of Ra=1.97μm is taken as an example. The surface morphology of the longitudinal profile is shown in Fig. 1, and the measured surface morphology is shown in Fig. 2.

Figure 1. Surface morphology of the inner wall of stainless steel capillary

Figure 2. stainless steel capillary surface topography measurement curve

Figure 2 with conventional measurement of surface roughness curve expression, vertical and horizontal axis different magnification. According to the measured data will be one of the curve of the vertical and horizontal coordinates are expressed in microns, wall surface microstructure, as shown in figure 3.

Figure 3. stainless steel microstructure of capillary curve

2.2 Influence of particle size on processing mechanism and processing limit
The particle size and corresponding particle size of abrasive particles usually selected in abrasive flow processing technology are shown in Table 1.
Table 1. Corresponding relation between particle size and particle diameter of commonly used abrasive particles

| Particle size/mesh | 70 | 120 | 150 | 180 | 200 | W5 | W3.5 |
|--------------------|----|-----|-----|-----|-----|----|------|
| Particle diameter /μm | 220 | 125 | 100 | 88  | 74  | 5  | 3.5  |

After processing for a period of time, the edges and corners of the edge of the abrasive particles will be worn and become relatively smooth \cite{2}, so the abrasive particles can be regarded as spherical.

2.2.1 Processing models of abrasive particles with different particle sizes

Different from macroscopic scale and microscopic scale, in the field of machining, the geometrical characteristic size of mesoscopic scale is between 0.01 and 1mm. According to the data in Table 1, it can be seen that the abrasive particles with 70-200 mesh size belong to mesoscopic scale, and are greatly different from the micro-morphology of the inner wall of stainless steel capillary, and belong to large-size abrasive particles. Abrasives with the size of W5 and W3.5 are small-size abrasives within the range of microscopic scale. Therefore, large-size abrasives with 180 mesh and small-size abrasives with micro powder W5 are taken as representatives. Based on the micro-morphology curve of the inner wall of stainless steel capillary in figure3, the contact relationship is shown in figure4.

![Figure 4](image1)

(a) 180 mesh              (b) W5

Figure 4. The contact relationship between different particle sizes and workpiece surface profile

By figures 4, the big size of abrasive and the workpiece surface micro uneven size is large, the analysis of the processing mechanism when the workpiece surface can be seen as plane; The surface of the workpiece should be regarded as an undulating surface when analyzing the machining mechanism of small particle size abrasive.

2.2.2 Causes of processing limit of large-size abrasive

Stress analysis diagram of large-size abrasive particles is shown in Figure 5:

![Figure 5](image2)

(a) Initial state     (b) In extrusion polishing

Figure 5. Analysis force diagram of large particle size abrasive

Wherein the pressure of the abrasive particles

\[
F_{a1} = \frac{P_{g1} + P_{g2}}{2} \cdot \frac{\pi}{4} \cdot d_{g}^{2} \cdot k_{e} \tag{1}
\]

Where: \( P_{g1} \) -- the upstream pressure of the abrasive grain; \( P_{g2} \) -- pressure downstream of the abrasive grain; \( d_{g} \) - particle size of abrasive particles; \( k_{e} \) -- coefficient of elastic loss.
In Figure 5(b): $t_1$ -- the depth of the abrasive particles pressed into the workpiece during processing, which is related to the material hardness of the workpiece, the hardness of the abrasive materials, and the material flow pressure, etc. $F_p$ -- Thrust generated by pressure difference, calculated by Equation (2):

$$F_p = (p_{g1} - p_{g2}) \frac{\pi}{4} d_g^2$$

In addition, $v_g$ -- the grinding speed of the abrasive grain forward, that is, grinding speed; $M_{g1}$ -- Rolling moment of abrasive particles.

When the abrasive particles are in contact with the workpiece, under the action of force, the abrasive particles are pressed into the workpiece surface at a certain depth $t_1$ to grind the workpiece, and at the same time, rolling will occur under the action of A point torque $M_{g1}$.

According to Figure 3, 4 and 5 and Equations 1 and 2, the large size of abrasive particle size relative to the workpiece microstructure of large size, large size of abrasive will be at a certain depth "mountain" to remove the workpiece surface contour convex, not processing to the bottom of the outline, but due to the workpiece surface topography ups and downs, micro result in some places after the removal of micro rough, some local processing has yet to be completed, to continue processing after a period of time, but began to destroy the part has been processed surface, make the surface roughness can be increased, leading to large size abrasive machining limit.

### 2.2.3 Causes of processing limit of small particle size abrasive

The force analysis diagram of small particle size is shown in Figure 6:

$$F_{n2} = \frac{p_{g1} + p_{g2}}{2} \frac{\pi}{4} d_g^2 . k_e$$

It can be seen from Figure. 3, 4, 6 and Equation 3 that, compared with the large-size abrasive particles, the particle size of the small-size abrasive particles is smaller relative to the microstructure of the workpiece, and the small-size abrasive particles will carry out cutting action along the undulating microscopic surface of the workpiece. Due to the different removal amount required for each section of the workpiece surface, the machining continues until the processed part of the surface is destroyed, so that the surface roughness eventually increases and reaches its processing limit. As the particle size of the small-size abrasive is small, it can be seen from Equation 2 that the pressure is smaller and the removal amount is smaller each time, which indicates that the small-size abrasive needs more processing times to reach its processing limit.

### 3. Processing limit experiment

Workpiece: Stainless steel capillary, inner diameter $D$ =1.0mm, tube length $L$=150mm, initial surface roughness $Ra$=1.3μm.
Processing mode: the principle of clamping method in reference is adopted for one-way processing, and 1kg of abrasive is used for a single processing (mass ratio of carrier and abrasive is 1:1).

### 3.1 Processing limit experiment of small particle size abrasive

In order to verify the processing limit of small-size abrasives, small-size abrasives of W5 size are arranged for experiment, and the results are shown in Table 2.

| Serial number | Processing times | Processing result |
|---------------|-----------------|-------------------|
|               | Small-size abrasive (micro powder W5) /time | Ra/μm | Rq/μm | Rz/μm |
| X1            | 5               | 0.739             | 0.876 | 3.602 |
| X2            | 10              | 0.476             | 0.579 | 2.919 |
| X3            | 15              | 0.474             | 0.586 | 2.740 |
| X4            | 20              | 0.475             | 0.595 | 2.744 |

Its surface roughness change curve is shown in Figure 7.

According to the processing results of X1 -- X4, Ra, Rq and Rz decrease with the increase of processing times when the workpiece with initial surface roughness Ra=1.3μm is processed in the small particle size abrasive of micro powder W5, but they slow down gradually. Continuing processing to 20 times will increase Ra, Rq and Rz, reaching the processing limit.

### 3.2 Processing limit experiment of large-size abrasive

In order to verify the processing limit of large-size abrasive, the experimental arrangement and results are shown in Table 3.

| Serial number | Processing procedures and times | The processing results |
|---------------|--------------------------------|------------------------|
|               | Small particle size abrasive (W5) / time | Large particle size abrasive (180 mesh) / time | Ra/μm | Rq/μm | Rz/μm |
| XB1           | 3 | 3 | 0.418 | 0.502 | 1.924 |
| XB2           | 5 | 5 | 1.111 | 1.337 | 4.690 |
| XC1           | 10 | 2 | 0.328 | 0.410 | 1.673 |
| XC2           | 10 | 3 | 0.556 | 0.652 | 2.260 |

Its surface roughness Ra changes as shown in Figure 8.
Figure 8. Surface roughness of 180-mesh abrasive varies with processing times

From the processing results of XB1-XB2 and XC1-XC2, it can be concluded that the processing limit of large-size abrasive can be achieved after less processing times compared with small-size abrasive. From table 3, 10 times after granularity abrasive processing artifacts, is smaller than 5 times after granularity abrasive processing after the fewer the number of times will reach its processing limit, this shows that the smaller the surface roughness, surface more smooth, large-grained abrasive reached its machining limit need number is less, it can be used as a face different surface roughness of workpiece in the process of production, number of large-grained abrasive machining selection basis.

4. Optimization Experiment

Under the same experimental conditions, the stainless steel capillary with the original surface roughness of $Ra=1.97\mu m$ was taken as the experimental processing object, and the experimental results of the alternating use of small-size abrasive and large-size abrasive are shown in Table 4.

| Serial number | Processes and Numbers | Ra/μm | Rq/μm | Rz/μm |
|---------------|-----------------------|-------|-------|-------|
| H1            | Small size abrasive 3 times + large size abrasive 2 times + small size abrasive 2 times | 0.310 | 0.351 | 1.320 |

By comparing the data in Table 4 with those in Table 2 and 3, it can be seen that the alternating use of small-size abrasive and large-size abrasive can ensure the processing quality and achieve better processing effect, breaking through the original processing limit.

5 conclusion

1) Due to the size relationship between different particle sizes and the surface topography of the workpiece, different particle sizes have different processing mechanisms.

2) Processing limit is the consequence that abrasive particles begin to destroy the surface of the workpiece after removing a certain amount of microscopic unevenness on the surface of the workpiece.

3) The removal of large-size abrasive material is large, and it takes less times to reach its processing limit; the removal amount of small particle size abrasive is small, and the effective processing times are more before reaching the processing limit.

4) Alternate use of small particle size abrasive and large particle size abrasive can break through the limitations of the original processing limit, to obtain better processing effect.
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References
[1] Li Yuanzong, Yan Mulian, Yang Shuguo. Abrasive Flow Machining Technology [J]. Electronic Process Technology, 1987(7):10-12.
[2] Song Guizhen. Theoretical Analysis and Experimental Research on Abrasive Flow Machining Technology [D]. Taiyuan: Taiyuan University of Technology, 2010.
[3] V K Jain, A Sidpara, M R Sankar, and M Das. Nano-finishing techniques: a review. Proc. IMechE Part C: J. Mechanical Engineering Science. 2011, 226: 327–346.
[4] Flowing abrasive deburr parts[J]. American Machinist. March 18, 1974:53-55.
[5] David E. Siwert. Edge and Surface Finishing with Abrasive Flow[J]. Manufacturing Engineering. December 1975:37-40.
[6] Gao Hang, Wu Mingyu, Fu Youzhi, et al. Development of Theory and Technology of Fluid Abrasive Finishing [J]. Journal of Mechanical Engineering, 2015,51 (7): 174-187.
[7] V.K. Gorana; V.K. Jain; G.K. Lal. Prediction of surface roughness during abrasive flow machining[J]. International Journal of Advanced Manufacturing Technology,2006,Vol.31: 258-267
[8] WANG Shiying, LYU Ming, JIA Gang. Mechanical Principle and Application of Abrasive Flow Machining [J]. Journal of Taiyuan University of Technology,1998, 29 (3): 272-276.
[9] Hu Jinglei. Research on Mechanism of Abrasive Flow Polishing and Material Removal Based on Discrete Element Method [D]. Changchun University of Science and Technology,2018.
[10] Tina Bremerstein, Annegret Potthoff, Alexander Michaelis, Christian Schmiedel, Eckart Uhlmann, Bernhard Blug, Tobias Amann. Wear of abrasive media and its effect on abrasive flow machining results[J]. Wear, 2015(342-343):44–51.
[11] Gong Sheng, Song Guizhen, Li Yuanzong. Influence of Cycle Number on Abrasive Flow Machining Effect [J]. Machine Management Development, 2009, 24 (2) :82~83. (in Chinese)