Research on quality control of precision machining straight internal gear by abrasive flow based on large eddy simulation

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Abstract

Traditional finishing technology is difficult to realize the precision machining of complex geometric parts. Abrasive flow machining technology solves this problem well. Taking the spur internal gear as the research object, the wall shear force, static pressure, dynamic pressure, and abrasive velocity vector of the internal channel of the straight internal gear under different inlet velocity, abrasive concentration, and abrasive particle size are analyzed by using the large eddy simulation method, and the action law of different parameters on the machining of straight internal gear by solid–liquid two-phase abrasive flow is discussed. At the same time, the orthogonal test was carried out. The results show that the solid–liquid two-phase abrasive flow machining technology can effectively remove the burrs, pits, and bulges on the tooth surface of spur internal gear, reduce the tooth surface roughness, and improve the surface quality. The optimal combination of processing parameters and the primary and secondary order of various factors affecting processing are obtained by range analysis and analysis of variance. The regression equation is constructed by regression analysis to verify the effectiveness and accuracy of the model, which provides theoretical support and data reference for actual processing and production.

Keywords Abrasive flow · Large eddy simulation · Gear · Orthogonal experiment

1 Introduction

As the most basic mechanical transmission part, the internal gear is widely used in aviation and shipping, rail transit, automobile industry, and other important fields. To ensure the transmission accuracy of internal gear, the tooth surface must be machined through an appropriate finishing process to improve the surface quality [1]. Although traditional finishing processes such as grinding and manual polishing can meet the accuracy requirements of mechanical parts, they have low efficiency and high cost. Even manual polishing is easy to cause tooth surface burns and affect transmission performance, so they are not suitable for machining mechanical parts with complex geometric shapes [2, 3]. Abrasive flow machining (AFM) technology takes the fluid as the carrier, mixes the self-sharpening solid abrasive particles into it, and prepares the abrasive suitable for machining. By squeezing the semi-solid fluid abrasive into the flow channel formed by the workpiece and supporting fixture, it flows back and forth to achieve the purpose of polishing, deburring, rounding, and removing the recast layer, and finally obtain the high-quality workpiece surface [4–6].

In recent years, AFM technology has been continuously improved. Its advantages such as high polishing efficiency, high adaptability, and low workpiece damage rate have made it widely concerned and applied [7–9]. Bremerstein et al. studied the influence of the change of abrasive medium on the abrasive flow machining effect, and found that the tip and edge of large abrasive particles become blunt due to machining, small and sharp particles are cut off, and the rheological behavior and composition of the abrasive medium, as well as the change of particle shape and size, are the reasons for the decline of abrasive efficiency [10]. Fang et al. used the experimental design method to optimize the abrasive flow machining process parameters and analyze the range of experimental results, and proved that the optimized process parameters can significantly improve the abrasive
grinding efficiency and grinding quality [11]. Guo et al. took the Inconel 718 Alloy manufactured by three-dimensional additive as the research goal, analyzed the influence of process parameters such as medium viscosity and temperature on abrasive flow machining effect, and concluded that good surface roughness can be obtained under the conditions of high viscosity and low temperature [12]. Sushil et al. chose the electric discharge machining (EDM) method to process Al/SiC composites, and then used the abrasive flow machining process for surface finishing. The test shows that AFM can effectively remove the surface defects such as cracks, pits, and recast layer during EDM, and effectively reduce the surface roughness [13]. Fu et al. proposed a new prediction method combining numerical simulation and experiment for abrasive flow machining, analyzed the material removal of single and multiple particles, and finally carried out experimental verification on the finishing of Aeroengine Blades, providing basic guidelines for the optimal design of constraint surfaces of complex components [14].

Combining computational fluid dynamics knowledge with finite element analysis software is one of the common technical means in modern engineering. At present, the research methods of turbulent motion are mainly divided into the direct numerical simulation, Reynolds average method and large eddy simulation. The huge amount of calculation of direct numerical simulation makes it difficult to be used in engineering practice, and Reynolds average method is difficult to predict the unsteady characteristics of large eddy motion. Large eddy simulation (LES) changes the fluid into large-scale quantity and small-scale quantity through the filter function, directly simulates the large-scale quantity, and uses an appropriate sub-grid scale model to simulate the small-scale quantity, which can accurately predict the evolution process of vortex body and capture the changes of flow state and vortex [15–17]. Li et al. combined large eddy simulation with experimental machining, studied the impact of the collision between abrasive particles and common machining parameters, concluded that particle size is an important factor affecting machining effect, and verified the effectiveness of large eddy simulation method in assisting actual machining [18, 19]. Ramírez-Cruz et al. conducted large eddy simulation research on the free surface flow in the turbine-driven baffleless stirred tank, and compared it with the experimental research. The results show that the liquid surface shows good consistency [20]. Vashisth and Kumar analyzed the flow and turbulence characteristics in the high shear mixer at constant rotor speed based on the large eddy current simulation method, and verified the reliability and good consistency of the simulation analysis in terms of power number through available numerical and experimental studies [21]. Li et al. scholars calculated the aerodynamic noise generated by 3.0-MW high-power double blades through the large eddy current simulation turbulence model, determined the discrete characteristics of the tip noise spectrum according to the static pressure and flow field distribution of the double blades, and determined the most appropriate location for installing the wind turbine [22].

To explore the effects of inlet velocity, abrasive concentration and particle size on the machining effect of solid–liquid two-phase abrasive flow, taking spur gear as the research object, large eddy numerical simulation and experimental machining analysis were carried out, and the effects of different factors and the best combination of machining parameters in the precision machining of spur internal gear by solid–liquid two-phase abrasive flow were discussed. The rest of the article is organized as follows: Sect. 2 contains theory, Sect. 3 contains numerical simulation analysis, Sect. 4 contains experiments and discussion, and Sect. 5 contains conclusions.

## 2 Large eddy numerical simulation theory

The solid–liquid two-phase abrasive flow fluid machining of spur internal gear is taken as the research object. Aiming at the complex problem of wall-flow of spur internal gear, the large eddy simulation method has high applicability and feasibility, and can well capture the changes of flow state and the characteristics of vortexes.

### 2.1 The basic idea of large eddy numerical simulation

The main idea of large eddy numerical simulation is to decompose turbulence into solvable-scale turbulence (including large-scale pulsations) and unsolvable-scale turbulent motion (including all small-scale motions) through a filter. The solvable-scale turbulence motion is directly carried out by numerical calculation methods. To solve, the effect of small-scale turbulent pulsation energy, momentum, and mass transport on large-scale motion is modeled (called sub-grid model), so that the solvable scale motion equation is closed. Since the flow boundary has little influence on small-scale pulsations, the sub-grid model may have good applicability to a wide range of complex turbulent motions.

### 2.2 Energy equation

The essence of the law of conservation of energy as a basic law that all heat exchange fluid systems must satisfy is the first law of thermodynamics. The expression of the energy equation is:

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\bar{u} (\rho E + p)) = \nabla \cdot (k_{\text{eff}} \nabla T - \sum_j h_j j_j + (\tau_{\text{eff}} \cdot \bar{u})) + S_p
\]

where \( E \) is the total energy of fluid clusters, \( J/kg \) including the sum of potential energy, internal energy, and kinetic energy; \( E = h - p/\rho + u^2/2 \); \( h \) is the enthalpy; \( h_j \) is the enthalpy of the component; \( k_{\text{eff}} \) is the effective heat transfer coefficient, and \( W/(m \cdot K) \); \( k \) is the turbulent

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heat transfer coefficient, which requires specific turbulence. The model is determined; $f_i$ is the diffusion flux of the component $j$; $S_k$ is composed of the chemical reaction heat and the user-defined volume heat source term.

### 2.3 Large eddy simulation control equations

During the processing of solid–liquid two-phase abrasive particle flow, the fluid is usually regarded as an incompressible fluid. Taking the Navier-Stokes equation as the governing equation, the expressions of the continuity equation and the momentum equation are respectively:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x_i} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j} \quad (3)$$

In the tableula: $v$ is the molecular viscosity coefficient.

The assumptions of filtering operation and derivation operation can be exchanged, and the following equations can be obtained by using the Navier–Stokes equation as filtering:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} \quad (4)$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (5)$$

Let $\bar{u}_i \bar{u}_j = \bar{u}_i \bar{u}_j + (\bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j)$, then the tableula (2–4) can be written as:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} + \frac{\partial (\bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j)}{\partial x_j} \quad (6)$$

Equations (2) and (3) has a similar table to the Reynolds equation, with an unclosed term at the right end:

$$\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j \quad (7)$$

Among them, $\tau_{ij}$ called sub-grid stress, sub-grid stress can filter out the momentum transport between small-scale pulsation and solvable-scale turbulence.

### 3 Numerical simulation analysis

#### 3.1 Establishment of numerical model

This paper takes a spur internal gear as the research object, and the specific basic parameters are shown in Table 1.

The three-dimensional geometric model and three-dimensional section view of the spur internal gear are shown in Fig. 1.

#### 3.2 Fixture design

The purpose of this fixture is to guide the fluid to flow through the tooth surface of the internal gear and assist in the precision machining of the tooth surface of the gear. The fixture is mainly composed of a guide device, clamp, and fluid guide. The assembly drawing and explosion drawing are shown in Figs. 2 and 3. In the exploded view, 1 is the diversion device of the fixture, which connects the machine tool and the fixture through the thread at the entrance; 2 and 7 are hex bolts and hex nuts respectively, which connect the various parts of the fixture into a whole through connection and cooperation; 3 and 5 are soft-sealing rings, which are used to prevent abrasive leakage due to excessive pressure during processing; 4 is the workpiece to be processed; 6 is the workpiece to be processed; 6 is the clamping body, its function is to cooperate with the guide device to fix the internal gear, and table a closed flow channel between the machine tool and the fixture; 8 is a drainage part, its function is to table a narrower flow path environment between the abrasive and the tooth surface of the internal gear through the cylinder at the upper end of the fluid, which is conducive to the finishing of the tooth surface.

#### 3.3 Numerical simulation analysis of spur internal gears

Combined with the actual processing conditions of abrasive flow machining machine tool and the size of the flow channel, set the inlet velocity of abrasive flowing into the inner surface of the workpiece (30 m/s, 40 m/s, 50 m/s, and 60 m/s), the concentration of solid particles in abrasive (10%, 20%, 30%, and 40%) and the particle size of abrasive

### Table 1 Basic parameters of spur internal gear

| Name                      | Parameter value | Name              | Parameter value |
|---------------------------|-----------------|-------------------|-----------------|
| Number of teeth $z$       | 18              | Modulus $m$       | 3 mm            |
| Pressure angle $\alpha$   | 20°             | Helix angle $\beta$ | 0               |
| Addendum height coefficient $h_a^*$ | 1            | Tooth width $B$   | 50 mm           |
| Head clearance coefficient $c^*$ | 0.25         | Addendum circle diameter $D_a$ | 48 mm          |
| Tooth root circle diameter $D_r$ | 61.5 mm     | Diameter of index circle $D$ | 54 mm          |
solid particles (400 mesh, 600 mesh, 800 mesh, and 1000 mesh), and the static pressure and the dynamic pressure, wall shear force, and cogging velocity are numerically simulated and analyzed.

### 3.3.1 Numerical analysis of the entrance velocity on the machining of spur internal gears

The reason why the abrasive can flow through the workpiece surface to be machined is that the upper hydraulic cylinder of the abrasive flow machine tool can provide sufficient pressure for the abrasive to generate speed, so as to promote the abrasive to pass through the surface to be machined and finish the workpiece surface. Therefore, it is necessary to explore the influence of abrasive inlet velocity on the machining effect.

1. Static pressure analysis of different inlet velocities

Select the above four different inlet velocity parameter values, and the other settings are consistent with the variables. The cloud diagram of static pressure distribution is given below, as shown in Fig. 4.

Figure 4 is the static pressure cloud diagram obtained by using the large eddy simulation method under different inlet velocities. Obviously, under the conditions of four different entrance velocities, the static pressure cloud map of the spur internal gear wall shows the same changing characteristics, and the wall color changes from light to dark, showing a stepped distribution. This shows that the pressure at the inlet is the largest and the pressure at the outlet is the smallest, and the processing effect of the abrasive flow is gradually weakened.

2. Analysis of wall shearing force on different inlet velocities

When the abrasive flows through the workpiece surface, it is necessary to overcome the viscous resistance, resulting in shear force. The effect of abrasive flow machining depends on the influence of abrasive flow on the wall of the workpiece. The wall shear force can fully reflect the influence of abrasive flow machining on the wall of the workpiece. The wall shear stress nephogram under different inlet velocities is shown in Fig. 5.
It can be seen from Fig. 5 that the wall shearing force at the entrance is the largest. The number of abrasive particles in contact with the wall becomes smaller, the wall shearing force is also decreasing, and the processing effect also changes weakly. But as the entrance velocity increases, the wall shear force of the workpiece also increases; the light blue area in the middle increases, which shows that the increase in the entrance velocity can effectively improve the uniformity of processing.

Combining Figs. 6 and 7, it can be seen that at the same inlet velocity, the tooth surface wall shear force presents a trend of decreasing first and then stable. Under different inlet speeds, the wall shear force increases with the increase of the inlet speed, indicating that increasing the inlet speed is beneficial to the finishing of the tooth surface.

### 3.3.2 Numerical analysis of abrasive concentration on straight-tooth internal gear machining

In the process of abrasive flow processing, if the concentration of abrasive is too high, the surface of the workpiece will be scratched and even the flow channel will be blocked; if the concentration of abrasive is too low, the processing effect of the surface of the workpiece is not obvious. Select the abrasive concentration value as the variable, set four groups of different abrasive concentrations of 10%, 20%, 30%, and 40%, the inlet velocity is 40 m/s, and the abrasive particle size is 600 mesh for numerical simulation.

1. Dynamic pressure analysis of abrasive concentration

Figure 8 is a cloud diagram of the axial dynamic pressure distribution of one of the tooth grooves under different abrasive concentrations. It can be seen from Fig. 8 that under the same abrasive concentration, the upper wall of the tooth groove and the middle part of the tooth groove show different trends. The dynamic pressure at the middle position of the cogging shows a gradually increasing trend, the dynamic pressure at the inlet end is the smallest, and the dynamic pressure at the outlet end is the largest. The upper wall surface of the tooth groove shows the opposite trend to the middle part of the tooth groove. With the inflow of abrasive, the dynamic pressure on the upper wall surface becomes smaller and smaller, reaching a minimum at the outlet. Under different abrasive concentrations, with the increase of abrasive concentration, the dynamic pressure in the tooth groove gradually increases. When the abrasive concentration reaches 40%, the value of dynamic pressure becomes significantly larger, the color of the dynamic pressure cloud image on the upper wall becomes lighter and becomes closer, and the distribution of the various colors of the cloud image in the middle of the tooth groove is more unitable, which shows that the appropriate increase abrasive concentration can not only improve the surface finish of the wall surface, but also effectively improve the unitableity of the wall surface processing.

2. Wall shear force analysis of different abrasive concentrations

Figure 9 shows the wall shear force cloud diagram of the spur internal gear under different abrasive concentrations. The abrasive particles enter the flow channel from the left and flow out from the right. It can be seen from Fig. 9
that as the concentration of abrasive increases, the overall wall shear force of the spur internal gear can be effectively increased.

To more intuitively analyze the influence of different concentrations on the wall shearing force of the tooth tip, tooth root, and tooth surface, a tooth slot in the spur internal gear is extracted, as shown in Fig. 10.

When the abrasive concentration is constant, the shear force on the tooth surface generally decreases first and then remains stable. The wall shearing force of the tooth surface at the entrance is the largest, and the wall shearing force of the 0–4 mm section has the fastest decline. The wall shear force decreases gently after 4 mm of the tooth surface until the latter half remains unchanged. It shows that the surface quality at the entrance of the tooth surface is the best, and the machining of the middle and rear sections is more unitable. When using abrasives with concentrations of 10%, 20%, and 30%, the maximum wall shearing force at the entrance is not much different, and the variation range of the wall shearing force of the tooth surface from 0 to 4 mm is basically the same. The 20% and 30% change curves even coincide after 12 mm, which shows that the effect of the first three concentrations of abrasives in processing the tooth surface is very close. When the abrasive with a concentration of 40% is used for processing, although the wall shearing force at the entrance increases significantly, the subsequent wall shearing force is only slightly higher than the wall shearing force of the first three concentrations. In general, the relationship between the four abrasives with different concentrations in the numerical simulation on the tooth surface machining effect is $40\% > 30\% \approx 20\% > 10\%$ (Fig. 11).
3.3.3 Numerical analysis of abrasive particle size on the machining of spur internal gears

In abrasive flow machining, in addition to the inlet speed and abrasive concentration, abrasive particle size is also one of the important factors affecting the machining effect. Therefore, this section will numerically analyze the effect of abrasive particle size on the machining of spur internal gear. Set the inlet speed as 40 m/s and the abrasive concentration as 10%. Take the abrasive particle sizes of 400 mesh (38 μm), 600 mesh (25 μm), 800 mesh (18 μm), and 1000 mesh (15 μm) for numerical analysis.

1. Velocity vector analysis of different abrasive particle size

The above four kinds of abrasive grains are used to numerically simulate the spur internal gear, and the velocity vector cloud diagram in the tooth groove is obtained, as shown in Fig. 12.

The velocity vector cloud diagram mainly reflects the changes in the direction of the abrasive particle flow trajectory and the size of the abrasive particle velocity, which can be seen from Fig. 12: (1) when the workpiece is processed with abrasives of the same particle size, the velocity of the abrasive particles at the entrance changes from red to gold and then to green, indicating that the abrasive enters the flow channel after friction with the wall, and the velocity drops rapidly. The direction of the abrasive particles at the entrance changes from horizontal to right to diagonally downward, indicating that the abrasive particles enter the flow channel and collide with the wall surface and have a...
tendency to rebound to the middle of the flow channel. (2) When the abrasive grain size is different, the larger the number of abrasive grains, the finer the abrasive grains, and the smaller the mass of a single abrasive grain, the smaller the energy carried, which shows that the velocity is lower and the processing effect is slightly insufficient.

To show the velocity difference of different abrasive particle sizes more intuitively, the maximum and minimum data tables for different abrasive particle sizes at the outlet of the tooth groove are listed, as shown in Table 2.

According to Table 2, it can be seen that with the increase of abrasive particle size, the maximum and minimum velocities both show a slight decrease trend. Abrasive velocity and processing effect can be said to have a proportional relationship within a certain range. The higher the velocity, the more severe the abrasive friction on the surface of the workpiece, and the better the processing effect. It can also be found from Table 2 that the difference in the decrease in the maximum velocity between the abrasive particle sizes is much smaller than the decrease in the minimum velocity. That is to say, the larger the abrasive particle size, the smaller the difference between the maximum and minimum abrasive velocities, and the more unitable the processing. From the processing effect, the order of selection should be 400mesh > 600mesh > 800 mesh > 1000 mesh. From the point of view of the unitableity effect of processing, the order of selection should be 1000 mesh > 800 mesh > 600 mesh > 400 mesh.

Draw the maximum velocity comparison curve in Fig. 13. It can be seen from Fig. 13 that with the increase of the abrasive
particle size, the maximum and minimum abrasive velocities at the outlet of the tooth groove show a decreasing trend, and the difference between the maximum velocity and the minimum velocity under each abrasive particle size is also decreasing. Therefore, when the abrasive particle size is selected to be 400 mesh, the processing effect of the workpiece wall is the best; when the abrasive concentration is selected to be 1000 mesh, the overall processing effect of the workpiece wall is the best.

2. Wall shear force analysis of different abrasive particle size

Figure 14 is the wall shear force cloud diagram of the same tooth groove with different abrasive particle sizes. It can be seen from the figure that with the increase of the abrasive mesh, although the wall shearing force of the tooth groove gradually decreases, the uniformity of the tooth groove is gradually improved.

Figure 15 is the comparison curve of the maximum wall shear force and the minimum wall shear force of the tooth surface under different abrasive particle sizes. The effect of different abrasive particle sizes on the tooth surface processing is slightly different, and the 400 mesh abrasive processing effect is better.

4 Test processing and result analysis

4.1 Preparation for abrasive flow machining test

In order to more accurately predict the actual abrasive flow production and processing, the straight internal gear is used as the research object for numerical simulation analysis and experimental processing respectively. The specific physical drawing of the workpiece is shown in Fig. 16.

4.1.1 Design of the test plan

Combined with the numerical analysis results and actual processing conditions, considering the influence of inlet velocity, abrasive concentration, abrasive particle size, and processing times on abrasive flow machining straight internal gear, the level table of design factors is shown in Table 3. According to Table 3, the orthogonal test of four factors and four levels shall be designed, and the test times shall not be less than 13. Therefore, L16 (4^4) shall be considered to design the test scheme, and the test times shall be 16. The orthogonal test table is shown in Table 4.
4.2 Detection of abrasive flow processing results

4.2.1 Detection of the surface topography of spur internal gears

In order to visually observe the surface morphology of the tooth surface in the tooth groove, a scanning electron microscope is used for inspection. According to Table 4, the samples under different test conditions are named 01# to 16# workpieces in sequence, and the original workpiece without test process is named 00#. Samples are taken every three times from the original 00# to the test piece 16#. The scanning results are shown in Fig. 17.

It can be seen from Fig. 17 that there are obvious spot-like protrusions and pits of various shapes on the tooth surface of the original. The surface is not only uneven, but also has poor gloss. After the solid–liquid two-phase abrasive flow processing, the quality of the tooth surface is significantly improved. With the change of processing parameters, the protrusions on the inner surface of the test piece become less and less, and the surface becomes more and more flat and smooth. When the electron microscope is magnified...
500 times, the fine scratches left on the inner surface of the test piece after abrasive processing can be observed. These scratches are lines generated by abrasive flow processing.

4.2.2 Surface roughness detection of spur internal gears

The surface roughness of the tooth surface of the tooth groove is measured by the Marl LD120 surface roughness profile measuring instrument, and the test results are drawn in a table, as shown in Table 5.

In order to see the changes of the surface roughness values of different tooth surfaces more intuitively and clearly, draw a line graph of the tooth surface roughness of the spur internal gear according to Table 5, as shown in Fig. 18.

Combining Fig. 18 and Table 5, it can be found that the tooth surface roughness of the spur internal gear without solid–liquid two-phase abrasive flow processing reaches 3.918 μm. After the processing is completed, the minimum value of the spur internal gear tooth surface roughness is one order of magnitude smaller, reaching 0.380 μm, which effectively improves the quality of the spur internal gear tooth surface, reduces the surface roughness, and improves the working performance of the spur internal gear.

Fig. 10 Clouds of shear force on the tooth groove wall under different abrasive concentrations. (a) 10%, (b) 20%, (c) 30%, and (d) 40%
4.3 Analysis of processing results

4.3.1 Range analysis of orthogonal test

According to the designed orthogonal test table and the corresponding roughness value, it is summarized and calculated, and the orthogonal range analysis table shown in Table 6 is obtained.

In Table 6, the tooth surface roughness is used as the test index, and the influence of four factors on the effect of processing the tooth surface of the straight tooth internal gear is analyzed. It can be seen from Table 6 that the tooth surface roughness generally shows a decreasing law, the highest is the tooth surface roughness of test piece 01# is 2.423 μm; the lowest is the tooth surface roughness of test piece 16# is 0.380 μm. In order to analyze the influence of different factors on the processing effect, it is necessary to calculate and compare the 16 sets of test data in order to find the more important processing factors and the best level value of each factor. The “Kj” in the table is the sum of the test data at the same level in the corresponding column. The larger the Kj value, the greater the roughness value of the tooth surface at this level. Take the inlet velocity as an example: the Kj values corresponding to the inlet velocity of 30 m/s, 40 m/s, 50 m/s, and 60 m/s are 8.789, 5.641, 3.642, and 2.132 respectively, namely K1 > K2 > K3 > K4. The smaller the

**Table 2** Numerical table of velocity at different abrasive particle size at the outlet of the tooth groove

| Abrasive particle size (mesh) | Velocity (m/s) | Max   | Min   |
|------------------------------|----------------|-------|-------|
| 400                          | 47.01          | 4.683 |       |
| 600                          | 46.99          | 4.667 |       |
| 800                          | 46.97          | 4.649 |       |
| 1000                         | 46.90          | 4.626 |       |

Fig. 11 Change curve of tooth surface wall shear force under different abrasive concentration

Fig. 12 The velocity vector cloud diagram of the tooth groove axial cross-section under different abrasive particle sizes. (a) 400 mesh, (b) 600 mesh, (c) 800 mesh, and (d) 1000 mesh
tooth surface roughness, the better the working performance. It can be judged that when the inlet velocity is 60 m/s, a better surface quality can be obtained. Similarly, the optimal levels of the other three factors are 40%, 400 mesh, and 40 times. The “Rj” in the table is the range of the factor in the corresponding column; the range is large, and it has a large impact on the test results, and is the main factor; the range is small, and the impact on the test results is small, and it is a secondary factor. The R values corresponding to the inlet velocity, abrasive concentration, abrasive particle size, and processing times are 1.6643, 0.2573, 0.0520, and 0.2705, respectively. It can be seen that the inlet velocity has the greatest influence on the processing effect, and the abrasive particle size has the smallest effect on the processing effect.

In order to show the influence of different factors and levels on the test processing results more intuitively and clearly, the relationship between different factors and test indicators is drawn, as shown in Fig. 19.

It can be seen from Fig. 19 that different factors have different effects on the test indicators as the level changes. The slope of the broken line in the figure indicates the degree of influence of the factor on the test index. The
larger the slope, the more significant the effect; the lower the mean value, the better the processing effect at this level. Therefore, the optimal combination of processing parameters is the inlet velocity is 60 m/s, the abrasive concentration is 40%, the abrasive particle size is 400 mesh, and the number of processing is 40 times.

**Fig. 14** Clouds of shear force on the tooth groove wall under different abrasive particle sizes. (a) 400 mesh, (b) 600 mesh, (c) 800 mesh, and (d) 1000 mesh

**Fig. 15** Comparison curve of tooth surface wall shear force under different particle diameters. a) Maximum wall shear force. b) Minimum wall shear force
4.3.2 Analysis of variance in orthogonal test

The optimal conditions have been obtained by the range analysis method of orthogonal experiment. This method only needs to do a small amount of calculation and analysis on the obtained test data, but the accuracy of the analysis cannot be grasped. The analysis of variance is a mathematical method that decomposes the sum of squares of the total variation according to various factors giving dispersion, and then makes statistics and testing. It can well make up for the deficiencies of the range analysis method. The analysis of the variance table shown in Table 7 can be obtained by using the analysis of variance method.

According to the variance detection method, when the $P$-value is less than 0.05, it means that this factor has a significant impact on the test results. It can be seen from Table 7 that the $P$-value of the entrance velocity is 0, indicating that the influence of the entrance velocity on the experimental results is significant. The $P$-values of processing times and abrasive concentration are 0.053 and 0.059, respectively, indicating that the processing times and abrasive concentration have a significant influence on the test results, and the processing times have a greater influence. The $P$-value of the abrasive particle size is 0.796, indicating

| Table 3  | Test factors-level table |
|----------|--------------------------|
| Factor   | A | B | C | D |
| Level    | Inlet velocity (m/s) | Abrasive concentration (%) | Abrasive particle size (mesh) | Processing times |
| 1        | 30 | 10 | 400 | 10 |
| 2        | 40 | 20 | 600 | 20 |
| 3        | 50 | 30 | 800 | 30 |
| 4        | 60 | 40 | 1000 | 40 |

| Table 4  | orthogonal table |
|----------|------------------|
| Test number | Experimental conditions |
|            | Velocity(m/s) | Concentration(%) | Particle size (mesh) | Times |
| 1          | 30             | 10              | 400                  | 10    |
| 2          | 30             | 20              | 600                  | 20    |
| 3          | 30             | 30              | 800                  | 30    |
| 4          | 30             | 40              | 1000                 | 40    |
| 5          | 40             | 10              | 600                  | 30    |
| 6          | 40             | 20              | 400                  | 40    |
| 7          | 40             | 30              | 1000                 | 10    |
| 8          | 40             | 40              | 800                  | 20    |
| 9          | 50             | 10              | 800                  | 40    |
| 10         | 50             | 20              | 1000                 | 30    |
| 11         | 50             | 30              | 400                  | 20    |
| 12         | 50             | 40              | 600                  | 10    |
| 13         | 60             | 10              | 1000                 | 20    |
| 14         | 60             | 20              | 800                  | 10    |
| 15         | 60             | 30              | 600                  | 40    |
| 16         | 60             | 40              | 400                  | 30    |
Fig. 17 Tooth surface profile of spur internal gear. (a) 00#, (b) 04#, (c) 08#, (d) 12#, and (e) 16#
that the abrasive particle size has no significant influence on the test results. Combining the above analysis and the data in the table, it can be seen that the order of the influence degree of the four factors on the experimental processing results is inlet velocity > processing times > abrasive concentration > abrasive particle size; it is consistent with the conclusion obtained by the range analysis, which also verifies the correctness of the range analysis.

4.4 Analysis of optimal parameters for machining straight internal gears

After the above orthogonal test analysis, the optimal combination of processing parameters under the four factors of inlet velocity, abrasive concentration, abrasive particle size, and processing times is inlet velocity of 60 m/s, abrasive concentration of 40%, abrasive particle size. It is 400 mesh, and the number of processing is 40 times. But there is no combination of this set of parameters in the orthogonal test table, so it is necessary to add a set of tests. The operation of the test and the method of testing are the same as before, and the testing diagrams are shown in Figs. 20 and 21.

It can be seen from Figs. 20 and 21 that the combination of optimized processing parameters has significantly improved the processing effect of the spur internal gear, which is manifested by good surface gloss and smooth surface. According to the surface roughness profile measuring instrument, the tooth surface roughness value has been increased from 0.380 to 0.361 μm, and the ideal surface quality has been obtained.
### Table 6 Orthogonal range analysis table

| Test number | Experimental conditions | Test index |
|-------------|--------------------------|------------|
|             | Inlet velocity(m/s)     | Abrasive concentration(%) | Abrasive particle size(mesh) | Times | Roughness(μm) |
| 1           | 30                       | 10         | 400          | 10    | 2.423        |
| 2           | 30                       | 20         | 600          | 20    | 2.305        |
| 3           | 30                       | 30         | 800          | 30    | 2.193        |
| 4           | 30                       | 40         | 1000         | 40    | 1.868        |
| 5           | 40                       | 10         | 600          | 30    | 1.450        |
| 6           | 40                       | 20         | 400          | 40    | 1.280        |
| 7           | 40                       | 30         | 1000         | 10    | 1.611        |
| 8           | 40                       | 40         | 800          | 20    | 1.300        |
| 9           | 50                       | 10         | 800          | 40    | 0.873        |
| 10          | 50                       | 20         | 1000         | 30    | 1.051        |
| 11          | 50                       | 30         | 400          | 20    | 0.894        |
| 12          | 50                       | 40         | 600          | 10    | 0.824        |
| 13          | 60                       | 10         | 1000         | 20    | 0.655        |
| 14          | 60                       | 20         | 800          | 10    | 0.671        |
| 15          | 60                       | 30         | 600          | 40    | 0.426        |
| 16          | 60                       | 40         | 400          | 30    | 0.380        |
| K1          | 8.789                    | 5.401      | 4.977        | 5.529 | Σ = 20.204   |
| K2          | 5.641                    | 5.307      | 5.005        | 5.154 |             |
| K3          | 3.642                    | 5.124      | 5.037        | 5.074 |             |
| K4          | 2.132                    | 3.954      | 5.185        | 4.447 |             |
| kj1         | 2.1972                   | 1.3503     | 1.2443       | 1.3822|             |
| kj2         | 1.4103                   | 1.3268     | 1.2512       | 1.2885|             |
| kj3         | 0.9105                   | 1.2810     | 1.2593       | 1.2685|             |
| kj4         | 0.5330                   | 1.0930     | 1.2963       | 1.1118|             |
| Ri          | 1.6643                   | 0.2573     | 0.0520       | 0.2705|             |

**Excellent level**

Ri  60  40  400  40

Rank 1  3  4  2

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**Fig. 19** Relationship between different factors and test indicators
Conclusion

Given the insufficient accuracy of internal gear tooth surface machined by traditional finishing technology, numerical simulation and experimental research are carried out in combination with large eddy simulation and abrasive flow machining technology. The conclusions are as follows:

1. Properly increasing the inlet velocity of abrasive flow, abrasive concentration and abrasive particle size can effectively improve the overall wall shear force and pressure of spur internal gear, respectively, so as to improve the polishing efficiency and polishing quality.

2. The effects of inlet velocity, abrasive concentration, abrasive particle size, and processing times on abrasive flow polishing are inlet velocity > processing times > abrasive concentration > abrasive particle size.

3. The optimized abrasive flow machining parameters are as follows: the inlet velocity is 60 m/s, the abrasive concentration is 40%, the abrasive particle size is 400 mesh, and the machining times are 40 times. The tooth surface roughness of spur internal gear can be reduced to 0.361 μm. The tooth surface quality of spur internal gear is effectively improved.

Author contribution Tiangang Zou designed and performed the experiment, analyzed the data, and drafted the manuscript. Qingdong Yan and Lixiong Wang analyzed the data and supervised this study. Yuanyuan An conceived the project. Jiyong Quand Junye Li organized the paper and edited the manuscript. All authors read and approved the manuscript.

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Declarations

Ethical approval Not application.

Consent to participate Not application.

Consent to publication All presentations of case reports have consent for publication.
Conflict of interest  The authors declare no competing interests.

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