Surface quality and geometric accuracy control of fuel nozzle single-pass honing

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Abstract
Fuel nozzle is a key part of aero-engines. Due to the particularity of fuel nozzle’s working environment, the high machining requirements for the surface quality and geometric accuracy of nozzle hole were put forward. The existing process is difficult to meet the machining requirements, so a new process is proposed, which is called the flexible single-pass honing. For the novel single-pass honing tool with diameter less than 1 mm, the laws are not very clear, so studies were carried out. Firstly, a novel cutting force model of single-pass honing was established, which explains the relationship between force and machining parameters. Based on the cutting force model, the influence laws of honing parameters on surface roughness, bore diameter, and shape accuracy were explored detailedly. Finally, according to the machining requirements of fuel nozzles, the honing process optimization was carried out, and the optimal parameters were obtained. Furthermore, precision control of surface quality and geometric accuracy for fuel nozzle single-pass honing was realized.

Keywords Surface roughness · Geometric accuracy · Single-pass honing · Cutting force

1 Introduction
Fuel nozzle is a key unit of aero-engines, which directly affects aero-engine performance [1]. The atomization of fuel nozzle is affected by the surface roughness and geometric accuracy of the hole [2, 3]. Poor surface roughness results in the fluctuation of flow, especially the deviation is large when rate of flow is small. Therefore, the surface roughness is extremely an important evaluation index of quality. Besides, poor geometric accuracy will not only affect the stability of fuel flow, but also affect the uniformity of fuel atomization.

The traditional honing mainly relies on the liquid pressure or the motor to push the straight-line movement of the wedges, so as to realize the radial expansion of the oilstone [4–6]. The oilstone will gradually expand with the removal of the material, and the hole diameter will reach the required size after the repeated reciprocating of honing rod in the hole [7]. The advantage of honing is that it can obtain the better shape accuracy and surface quality [8–10]. However, there are still some problems such as low material removal rate and low processing efficiency [11–13]. Due to the limitation of tool structure, the minimum hole diameter of traditional honing tool is about 3 mm. The diameter of the fuel nozzle is less than 1 mm, so the traditional honing cannot meet the machining requirements. Therefore, a new technology which can retain the original honing accuracy and adapt to smaller hole machining needs to be proposed.

A novel super-abrasive tool of fixed dimension has been employed in single-pass honing. When the tool rotates, the tool passes through the hole to remove some material at the same time [14–16]. Combining the advantages of reaming and honing, the single-pass honing is a kind of abrasive process, which can achieve higher dimension consistency and shape accuracy. Therefore, it has been widely used in the finish process of holes in the hydraulic field [17, 18]. The process capacity of single-pass honing is perfectly matched with the requirements of fuel nozzles, which has great application potential in high efficiency and high consistency machining of nozzles.

In order to fully tap the potential of single-pass honing and improve the efficiency and quality of single-pass honing, many researchers have put much effort into this problem and several methods have been proposed. Arunachalam designed
the orthogonal test, and systematically studied the influence of honing process parameters, abrasive particle size, and tool length, on the cylindricity and surface roughness of single-pass honed hole [19, 20]. It is pointed out that most of the workpiece materials in honing are removed by ploughing of grains. The orthogonal tests of single-pass honing for steering gear valve sleeve were carried out [21]. The results showed that the spindle speed and feed speed were the decisive factors of roundness, while the surface roughness mainly depended on the particle size. The straightness of the hole was determined by the positioning accuracy of the machine tool and the fixture system. Through single-pass honing tests, the influence of honing parameters and workpiece material on tool wear and machining accuracy was established, and the selection principle of honing tool and process parameters was given [22]. The machining parts of the foregoing researches are all holes larger than 10 mm, and the honing tool has good rigidity, which is different from the fuel injection nozzle processing with small bore diameter.

The diameter of fuel nozzle is generally less than 1 mm, so the diameter of the honing tool used is smaller. In the early stage, the studies have been carried out on the preparation and life prediction of small diameter flexible honing tools [23]. The diameter of the honing tool is small, in which rigidity is poor. Single-pass honing is a kind of flexible machining, which is quite different from that of the honing tool with better rigidity. Therefore, it is necessary to study the surface quality and geometric accuracy of honed hole for flexible honing tool. In this paper, the surface quality and geometric accuracy of single-pass honing are made a profound study, combining the influence of process parameters on axial force and torque. Finally, taking the surface quality and geometric accuracy as the optimization objects, the appropriate honing parameters are determined to realize the high-efficiency and precision machining of fuel nozzle.

Fig. 1 Single-pass honing platform and tool structure

Fig. 2 Maximum contour distribution of tool

2 Experimental procedures

As shown in Fig. 1(a), the test was carried out on machining center produced by DMG MORI. The maximum speed of the spindle is 42,000 rpm, and the runout is within 5 μm. The workpiece material is 4Cr13 with HRC55 after heat treatment. The diameter and length of original holes are from 0.744 to 0.750 mm and 1.5 mm obtained by drilling and reaming, respectively. The single-pass honing tool has five parts, which are guide part, cutting part, finishing part, retracting part, and clamping part. The single-pass honing tool was dressed, which had 270/325 mesh electroplated CBN grains, as shown in Fig. 1(c). The maximum profile obtained by simulation is distributed along the axial direction as shown in Fig. 2. From the actual measured tool contour, there is no obvious boundary between cutting part and finishing part. The Kistler 9272 dynamometer was used to measure the axial force and torque during machining. The high-precision compound CMM produced by Werth was used to measure the bore diameter. The honed hole was cut along the axis, and the machined surface morphology and surface roughness was observed by Sensofar. The factors and levels were shown in Table 1.
3 Analysis of cutting force

Force is an important process parameter during hole machining, which directly reflects the interaction between tool and workpiece, and the stability of the machining process. Through the analysis of micro cutting process, the cutting force model in single-pass honing was established. On this basis, the influence of process parameters and tool profile on cutting force was analyzed.

3.1 Modeling of axial force and torque

During single-pass honing, the relative position and contact state of tool and workpiece change all the time, and the micro cutting load at each position of tool is different. Therefore, to calculate the change of cutting force with time $t$, it is necessary to define the micro cutting load at each position of the single-pass honing tool. The force analysis diagram of single abrasive is shown in Fig. 3. The material deformation resistance and friction force of a single abrasive due to the main cutting motion can be divided into tangential force $F_{st}$ along the cutting speed direction and normal force $F_{sn}$ along the radial direction. In addition, the feed resistance force caused by the tool axial feed movement along the hole axis is recorded as the axial force $F_{sa}$. The cutting force of a single abrasive is approximately proportional to the undeformed chip cross-sectional area $A_{cs}$ [24–26]:

$$F_{st} = k_t A_{cs}$$

$$F_{sn} = k_n A_{cs}$$

$$F_{sa} = k_a A_{cs}$$

where $k_t$, $k_n$, and $k_a$ are cutting coefficients, which depend on the material properties and the grain morphology. During single-pass honing, the relative position of tool and workpiece is shown in Fig. 4. If $t=0$, the tool overlaps with the left end of the workpiece at $x=0$. When the axial feed rate is $v_a$, the position $x(t)$ of the workpiece left end in the tool axis can be expressed as

$$x(t) = v_a t$$

At a certain time $t$, the tool at axial section $[x(t), x(t)+L]$ contacts the workpiece with length $L$. Assuming that the cutting force coefficients of different effective grains on the tool surface are the same, the axial force and torque can be expressed as

$$F_a(t) = \int_{x(t)}^{x(t)+L} k_a A_{cs} dx = k_a A_c(t)$$

$$M_a(t) = \int_{x(t)}^{x(t)+L} k_t A_{cs} r_d dx = k_t r_d A_c(t)$$

where $r_d$ is the diameter of the tool in contact with the workpiece at time $t$, and $A_c(t)$ is the sum of the undeformed chip cross-sectional area that the effective grains contact the workpiece at time $t$, which can be expressed as

$$A_c(t) = \frac{\Delta V_u(t)}{S_L}$$

where $\Delta V_u(t)$ is the sum of the undeformed chip volume that the effective grains contact the workpiece at time $t$, and $S_L$ is the cutting distance of a single abrasive on the workpiece surface, which can be expressed as

$$S_L = \frac{L}{\sin \alpha}$$

where $\alpha$ is an angle between the direction of cutting speed and the tangential direction of hole.

The tool is discretized along the axial direction with the interval of $l = 0.5$ mm. The undeformed chip volume on each segment of the tool is calculated respectively. Under the condition that the bearing ratio distribution of the tool in the current wear state and the bearing ratio of the workpiece in the

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Table 1 Experimental conditions

| Factors         | Levels               |
|-----------------|----------------------|
| Spindle speed (rpm) | 2000, 3000, 4000, 5000 |
| Feedrate (mm/min)    | 20, 30, 40, 50, 60, 70, 80, 90, 100 |
| Retracting speed (mm/min) | 10, 20, 30, 40, 50, 60, 100, 150, 200, 500 |
initial state are known, the undeformed chip volume on the segment \( i \) of the tool can be expressed as [27]

\[
\Delta V_{ui} = \pi d_i L_{c,\text{max}}^\text{f} T_a(y_i) W_i(y_i) dy
\]  

(9)

Therefore, \( \Delta V_d(t) \) can be expressed as the sum of the undeformed chip volume that the tool contacts the workpiece at time \( t \).

\[
\Delta V_d(t) = \sum \Delta V_{ui}(t)
\]  

(10)

According to the test, the workpiece length \( L = 1.5 \text{ mm} \), which is 3 times of the tool discrete interval \( l \). Therefore, at discrete time \( t \), \( \Delta V_d(t) \) can be expressed as

\[
\Delta V_d(t) = \Delta V_{ui} + \Delta V_{ui(t+1)} + \Delta V_{ui(t+2)}
\]  

(11)

where \( i \) satisfies

\[
i = \frac{x(t)}{l} + 1
\]  

(12)

### 3.2 Influence of machining parameters on cutting force

When the tool speed \( n = 5000 \text{ rpm} \), the feed rate per revolution \( f = 0.01 \text{ mm/r} \), and the chip forming coefficient \( k_g = 0.1 \), the variation of axial force \( F_d(t) \) measured by test and the sectional area \( A_c(t) \) of undeformed chip by theory calculation with time are shown in Fig. 5(a). With the honing process, \( F_d(t) \) and \( A_c(t) \) firstly increase and then decrease, showing a good consistency in the change trend.

In the honing process, the lowest point of the workpiece surface, \( y_w \), firstly interferes with the tool, as shown in Fig. 6. Due to the influence of surface roughness and cylindricity error of original surface, the bearing ratio at the first cutting position of workpiece surface is small, and the cutting load of tool is also small. With single-pass honing, the cutting layer height increases, and the bearing ratio of the workpiece at the cutting position increases gradually, which leads to the increase of the cutting load. When the finishing part starts cutting the workpiece, the bearing ratio of the workpiece gradually decreases, resulting in the reduction of cutting load.

Therefore, the axial force and undeformed chip cross-sectional area increase first and then decrease. It can be seen from Fig. 2 that the maximum contour of the tool is not smooth. When the height of the tool contour increases suddenly, the cutting load will increase suddenly, which leads \( A_c(t) \) appearing a peak value. On the contrary, when the tool contour height suddenly decreases, \( A_c(t) \) will appear a valley value. The peak and valley of \( A_c(t) \) are basically synchronous with that of \( F_d(t) \), as shown in Fig. 5(a).

When \( f = 0.02 \text{ mm/r} \), the variation of \( F_d(t) \) and \( A_c(t) \) with time are shown in Fig. 5(b). Comparing Fig. 5(b) with Fig. 5(a), the values of \( F_d(t) \) and \( A_c(t) \) increase significantly when \( f \) is increased. To sum up, \( A_c(t) \) calculated by simulation can better reflect cutting force in the actual honing process. Therefore, in the follow-up analysis, the influence of honing parameters on \( A_c(t) \) is studied, and then the influence of honing parameters on cutting force is revealed.

When tool speed is 5000 rpm and initial bore diameter is 0.75 mm, \( A_c(t) \) under different \( f \) is shown in Fig. 7. With the
increase of $f$, the honing time is shortened, thus $A_c(t)$ is significantly increased. When $f$ increases from 0.005 mm/r to 0.02 mm/r, the maximum value of $A_c(t)$ increases from 48.96 $\mu m^2$ to 195.8 $\mu m^2$. The cutting distance $s_L$ of a single grain decreases with the increase of $f$, while the undeformed chip volume changes little. Therefore, it can be considered that the axial force and torque in single-pass honing process will increase significantly with the increase of $f$.

When tool speed is 5000 rpm and feedrate per revolution $f$ is 0.01 mm/r, $A_c(t)$ under different initial bore diameter is shown in Fig. 8. Because of the taper structure of the tool cutting part, the length of the tool actual effective cutting part decreases with the increase of bore diameter, and the contact time between the tool and the workpiece is delayed. When the initial bore diameter is increased, $A_c(t)$ decreases significantly, which can decrease cutting force effectively.

### 3.3 Influence of tool contour on cutting force

The tool contour effects the axial distribution of $A_c(t)$ in honing process, and then effects cutting force. In order to study the influence of different tool contours on cutting force, the contour of different stages of tool dressing is taken. Under the conditions of tool speed $n = 5000$ rpm and feedrate per revolution $f = 0.01$ mm/r, $A_c(t)$ is calculated respectively, as shown in Fig. 9. With the dressing of the tool, the cutting load at the front end of the tool decreases significantly, the peak value of the cutting load at the tool end decreases and becomes more uniform, which lead to the difference between the peak and valley decreasing.

During the tool dressing, the radial wear of the tool makes the maximum height of tool contour decrease, which leads the actual cutting position to move backward and reduce the cutting load. Meanwhile, the radial wear of the tool makes the tool smooth, the cutting load fluctuation caused by the contour height fluctuation is reduced, and the tool cutting load is more uniform. Therefore, with the tool dressing, the cutting force at the front end gradually decreases, the peak value of the cutting force decreases, and the fluctuation of the cutting force is also smaller, which is conducive to improving the stability of the honing process.

### 4 Influence of cutting parameters on surface roughness

The surface roughness is one of the important factors that limit the improvement of machining efficiency. Therefore, the optimization basis of single-pass honing is to clarify the influence law of process parameters on surface roughness.

#### 4.1 Influence of spindle speed on surface roughness

When feedrate per revolution is 10 $\mu m$/r and retracting speed is 50 $\mu m$/r, surface roughness under different spindle speed is shown in Fig. 10. The surface roughness is between $R_a0.181$ $\mu m$ and $R_a0.189$ $\mu m$ at different tool speeds, which has little change. Only changing the spindle speed, the cutting paths of the effective grains and $A_c(t)$ do not change, thus the surface roughness formed by cutting is basically unchanged.
Therefore, it can be considered that the spindle speed has no effect on the surface roughness when the feedrate per revolution and tool retracting rate per revolution remain unchanged in the range of parameters used in the test. However, with the increase of spindle speed, the feedrate and retracting rate can be increased correspondingly on the premise that the surface roughness remains unchanged, so as to improve the machining efficiency. Therefore, the following tests will be carried out at the spindle speed of 5000 rpm.

### 4.2 Influence of feedrate on surface roughness

When the spindle speed is 5000 rpm and retracting speed is 200 mm/min, the influence of feedrate on surface roughness is shown in Fig. 11. Surface roughness gradually increases with feedrate increasing. When feedrate increases from 20 mm/min to 100 mm/min, surface roughness increases from 0.1468 \( \mu m \) to 0.2048 \( \mu m \). The machined surface morphology and contour height distribution obtained at different feedrates are shown in Fig. 12. According to Fig. 7, the slower the feedrate, the smaller the cutting force, the smaller the maximum \( A_c(t) \), the shallower the surface scratch of the workpiece. Furthermore, by comparing Figs. 12(a) and 12(b), when the feedrate is slow, the height difference between the wave peak and the wave valley is small, thus the lower surface roughness can be obtained. It can also be seen from Fig. 12(b) that a single grain continuously cuts the hole wall to produce equal interval cutting grooves. The interval of the deepest continuous groove is about 40 \( \mu m \), which is the same as the retracting rate per revolution. Therefore, it can be concluded that when the feedrate is 100 mm/min, the tool retracting not only removes the residual material on the workpiece surface, but also cuts the deeper material, resulting in new and deeper cutting grooves.

In single-pass honing process, the micro formation process of the surface morphology of the workpiece is shown in Fig. 13. In the tool feeding stage, due to cutting force, the workpiece surface will have a slight elastic deformation, resulting in the actual maximum cutting height \( y_{wv} \) of the workpiece surface is less than the maximum height \( y_{max} \) of the tool. In the tool retracting stage, the cutting allowance of the workpiece surface is small, and the cutting force is also small. Meanwhile, the elastic deformation of the workpiece is less than that of the feeding stage. Therefore, the grains will produce new cutting grooves in the elastic deformation zone of the feeding stage. When the tool feedrate is increased, the cutting force in the feeding stage increases gradually. The thickness of the elastic deformation zone generated in the feeding process gradually increases, which makes the cutting scratch generated on the workpiece surface in the tool retracting stage more obvious, as shown in Fig. 12(b).

### 4.3 Influence of retracting speed on surface roughness

From the foregoing analysis, the residual material on the workpiece surface in the feed stage is removed, which can improve surface roughness. However, the new cutting grooves are created in the elastic deformation area, which can deteriorate surface roughness. In order to study the influence of tool retracting speed on surface roughness, the tests were carried out under the conditions of tool speed 5000 rpm and feedrate 100 mm/min. The measured surface roughness is shown in Fig. 14. Reducing the tool retracting speed can effectively improve the machined surface roughness. When the retracting speed is reduced from 500 mm/min to 10 mm/min, the surface roughness decreases from 0.24 \( \mu m \) to 0.08 \( \mu m \). According to Fig. 14, with the decrease of tool retracting speed, the effect of improving surface roughness becomes more and more prominent, which accelerates the reduction speed of surface roughness. When the retracting speed is 10 mm/min, the machined surface morphology and profile height distribution are shown in Fig. 15, where the machined surface has no obvious scratches and leads to better surface quality.
5 Influence of cutting parameter on geometric accuracy

Bore diameter and shape accuracy are two important indexes to evaluate the geometric accuracy of a hole. The bore diameter of the inlet and outlet is taken as the evaluation index of bore diameter, and the absolute value of the difference between the inlet and outlet bore diameters is used as the evaluation index of shape accuracy.

5.1 Influence of spindle speed on geometric accuracy

Keeping the feedrate per revolution 110 μm/r and tool retraction rate per revolution 50 μm/r unchanged, the bore diameter and shape accuracy obtained at different spindle...
speeds are shown in Fig. 16. With spindle speed increasing, the inlet diameter remains unchanged, while the outlet diameter increases gradually. When the spindle speed increases from 2000 rpm to 5000 rpm, the outlet diameter increases from 0.7785 mm to 0.7806 mm, resulting in the increase of shape error from 0.6 μm to 1.9 μm.

In honing, the residual material and the elastic deformation under the action of cutting force lead to the bore diameter slightly smaller than the maximum diameter of the tool. When the tool remains unchanged, the cutting force and residual height in the machining process affects the bore diameter. When the feedrate per revolution is the same, the cutting force is similar, and the elastic deformation caused by the cutting force is also similar. In addition, with the same feedrate per revolution, the roughness machined surface remains unchanged and the height of residual material remains unchanged only with the increase of spindle speed. Therefore, when the feedrate per revolution is the same, only increasing the spindle speed, the bore diameter obtained should remain unchanged, which is consistent with the inlet diameter.

However, with the tool feeding, the length extending out of the workpiece gradually increases. Under the influence of the uneven mass of the tool and the clamping position error of the initial hole, there is a certain eccentric mass between the tool and the rotary axis. When the tool rotates at high speed, the part of the tool extending out of the workpiece will deform elastically. When the centrifugal force and the deformation resistance of the tool reach balance, it will reach a stable state, as shown in Fig. 17. The tool deformation will lead the bore diameter to increase at the outlet and form a trumpet hole. With the spindle speed increasing, the deformation of the tool increases due to centrifugal force, and the outlet diameter and shape error also increase.

5.2 Influence of feedrate and retracting speed on geometric accuracy

When the spindle speed is 5000 rpm and the retracting speed is 200 mm/min, the influence of feedrate on the bore diameter and shape accuracy is shown in Fig. 18. When the spindle speed is 5000 rpm and the feedrate is 100 mm/min, the influence of retracting speed on the bore diameter and shape accuracy is shown in Fig. 19. Under the aforementioned
processing parameters, the outlet diameter is always larger than the inlet diameter. With the increase of feedrate or retracting speed, the outlet diameter decreases significantly, while the inlet diameter only slightly decreases, and the shape accuracy of the hole is also improved. When the retracting speed is further increased, the bore diameter and shape error are basically unchanged. Compared with Figs. 18 and 19, increasing the tool retracting speed can reduce the outlet diameter and improve the shape error significantly.

The elastic deformation of the tool under the action of centrifugal force increases the outlet diameter, resulting in the outlet diameter larger than the inlet diameter. However, the cutting effect of tool end deformation on the hole outlet is similar to constant force cutting, and material removal volume is determined by both pressure and cutting time [28]. When the speed of the tool remains unchanged, it can be approximately considered that the pressure of the deformed tool on the outlet hole wall remains unchanged. With the increase of feedrate or retracting speed, the total cutting time is shortened, which leads to the decrease of the outlet diameter and shape error. In the feeding stage, most of the machining allowance is removed, and the bore diameter increases rapidly. The shape error in the feeding stage can be corrected by the subsequent material removal. However, the residual material is removed by tool retracting sightly, and the shape error is completely retained in the final part. Therefore, compared with the feedrate, the retracting speed has a greater impact on the final bore diameter and shape error.

### 6 Optimization of honing parameters

When single-pass honing tool is applied to fuel nozzle machining, honing parameters should be optimized according to the foregoing discussion, to achieve the highest process efficiency under the premise of meeting machining accuracy. Therefore, the shape accuracy and surface roughness are taken as the technical indexes to optimize the single-pass honing parameters.

Under the condition that the feedrate per revolution and tool retracting speed per revolution remain unchanged, increasing the spindle speed will increase the feedrate and retracting speed, thus improving the honing efficiency. At the same time, surface roughness remains basically unchanged, but the deformation of the tool end will reduce the shape accuracy of the hole, and even cause tool damage. Considering the machining efficiency, shape accuracy, and machining stability, it is safe to set 5000 rpm as the spindle speed.

According to the aforementioned analysis, the feedrate and retracting speed will affect the shape accuracy. Fig. 20 shows the shape error obtained when the feedrate and retracting speed change together at the tool speed of 5000 rpm. When the feedrate and retracting speed are both not less than 20 mm/min, the shape error is less than 3 μm. Therefore, the feedrate and retracting speed used in single-pass honing are not smaller than 20 mm/min, which can meet the design requirements of shape error of 4 μm. Finally, taking the surface roughness as the index, the feedrate and tool retracting speed will be further optimized within parameter range.
The machined surface morphology obtained by single-pass honing is formed by the combined action of feeding and retracting, and the elastic deformation thickness and residual material produced in the feeding process will affect the micro cutting state of the retracting process. In order to study the interaction between feedrate and retracting speed and the influence on surface roughness, the full factor test of feedrate and retracting speed was carried out with spindle speed of 5000 rpm. Finally, surface roughness is shown in Fig. 21. The higher the retracting speed, the greater the influence of feedrate on surface roughness. When smaller retracting speed is taken, most of the surface topography formed in the feeding process will be cut off in the retracting process, so the influence of the feedrate on the final surface roughness is small. When larger retracting speed is taken, the tool retracting process has little effect on the surface topography of the workpiece, and the surface topography is mainly formed during the feeding process, which shows that the feedrate has a greater impact on the surface roughness. When the tool feedrate and retracting speed are small, the surface roughness obtained by single-pass honing is also small. Therefore, when the required surface roughness is 0.1 μm, the tool feedrate can be appropriately increased and the lower retracting speed can be used to obtain higher machining efficiency. When the required surface roughness is 0.2 μm, the tool retracting speed can be appropriately increased to improve the machining efficiency.

In order to realize the precision optimization of process parameters, it is necessary to establish the mathematical model on the influence of feedrate and retracting speed on surface roughness. The empirical formula of roughness can be expressed as [17]

$$R_a = C_0 F_1^{C_1} F_2^{C_2}$$  \hspace{1cm} (13)

Where $R_a$ is surface roughness, $F_1$, $F_2$ are feedrate and retracting speed respectively, $C_1$, $C_2$ are the influence indexes of feedrate and retracting speed, respectively, and $C_0$ is a coefficient related to conditions other than feedrate and retracting speed. The logarithm of Eq. (13) is obtained

$$\ln R_a = \ln C_0 + C_1 \ln F_1 + C_2 \ln F_2$$  \hspace{1cm} (14)

The linear least square method is used to fit the parameters of Eq. (14), and the parameters, namely, $C_0 = 0.01852$, $C_1 = 0.1466$ and $C_2 = 0.3247$, can be obtained. Contour map of roughness with respect to feedrate and retracting speed is shown in Fig. 22.

The schematic diagram of feeding stroke and retracting stroke is shown in Fig. 23. When the minimum initial bore diameter is 0.75mm, the tool will not contact the workpiece until it is fed to point $W$, thus rapid feeding should be used before point $W$. Because the feedrate in fast feeding stage is far greater than the feedrate in cutting stage, the fast feeding time can be ignored. When the tool is fed to point $W'$, the finishing part of the tool has passed through the workpiece completely and the tool starts retracting. Since the residual height of the workpiece surface is very small, the tool has been completely separated from the workpiece when the tool is retracted to the point $W''$. After that, the tool continues retracting with fast retracting speed, and the surface roughness will not be affected. Because the retracting speed in fast retracting stage is far greater than the retracting speed in cutting stage, the fast retracting time can be ignored.


\[ T_m = \frac{50}{F_1} + \frac{30}{F_2}, \quad 20 \leq F_1 \leq 100, \quad F_2 \geq 20 \]  

(15)

In order to avoid excessive cutting force in the feeding process, which may cause machining instability or even damage the tool, the maximum value of feedrate \( F_1 \) is set as 100 mm/min. The process parameters of single-pass honing meet

\[
\begin{align*}
20 & \leq F_1 \leq 100 \\
F_2 & \geq 20 \\
C_0 F_1^{C_1} F_2^{C_2} & \leq R_{aD}
\end{align*}
\]  

(16)

Where \( R_{aD} \) is the design value of nozzle surface roughness. Matlab is used to solve the nonlinear programming problem to obtain the optimal feedrate and retracting speed.

When the design requirement of fuel nozzle surface roughness is 0.1 \( \mu \)m, the optimal process parameters are the spindle speed of 5000 rpm, the feedrate of 100 mm/min, the retracting speed of 190 mm/min, and the required processing time of 0.66 min. When the design requirement of fuel nozzle surface roughness is 0.2 \( \mu \)m, the optimal process parameters are the spindle speed of 5000 rpm, the feedrate of 100 mm/min, the retracting speed of 190 mm/min, and the required processing time of 0.66 min.

7 Conclusion

Single-pass honing test was carried out by a flexible honing tool. The process characteristics are explored, which are cutting force, surface quality, and geometric accuracy, and the process parameters are optimized according to the design requirements. The main conclusions are as follows:

1. The relationship model between cutting force and undeformed chip cross-sectional area \( A_c(t) \) is established. The cutting force can be reduced by reducing the feedrate per revolution or the removal allowance.

2. The surface roughness obtained under different process parameters shows that the spindle speed has no effect on the surface roughness when the feedrate per revolution remains unchanged. The surface roughness will increase with the increase of feedrate or tool retracting speed. When the tool will deform due to centrifugal force, which will increase the outlet bore diameter and shape error. When the feedrate per revolution remains unchanged, the outlet bore diameter and shape error will increase with spindle speed increasing. The outlet bore diameter and shape error will be decreasing with feedrate and retracting speed increasing. When the feedrate and retracting speed are not less than 20 mm/min, the shape error is less than 3 \( \mu \)m.

(4). According to the requirements of nozzle honing, the process parameters are optimized within the allowable parameters range. When the design requirement of fuel nozzle surface roughness is 0.1 \( \mu \)m, the optimal process parameters are the spindle speed of 5000 rpm, the feedrate of 100 mm/min, the retracting speed of 23.85 mm/min, and the required processing time of 1.76 min. When the design requirement of fuel nozzle surface roughness is 0.2 \( \mu \)m, the optimal process parameters are the spindle speed of 5000 rpm, the feedrate of 100 mm/min, the retracting speed of 190 mm/min, and the required processing time of 0.66 min.

Author’s contribution Changyong Yang conceived the analysis and wrote the manuscript. Hao Su and Shaowu Gao performed the experiment and collected the data. Yucan Fu provided supervision on experiment. Wenfeng Ding and Jiuhua Xu revised the manuscript.

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Data availability All data generated or analyzed during this study are included in the present article.

Declarations

Ethics approval and consent to participate The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

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