Quality prediction of polygonal helical curved tube by abrasive flow precision machining

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Received: 6 January 2021 / Accepted: 28 August 2021 / Published online: 9 November 2021
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Abstract
The polygonal helical curved tube is the main form of rifling barrel, which surface quality determines the shooting accuracy of the gun. Abrasive flow machining (AFM) technology can significantly improve its inner surface quality. In order to study the influence of AFM technical parameters on the inner surface quality of polygonal helical curved tube, orthogonal experimental design (OED) was used as the research method in this paper. Through the analysis of variance (ANOVA) of experimental data, the degree of influence of inlet pressure, abrasive concentration, abrasive particle size, and machining time on the inner surface quality of polygonal helical curved tube was determined, and the optimal combination of process parameters was obtained. Under the optimal process parameters, the surface roughness $Ra$ value in the inlet area of the polygonal helical curved tube was reduced to $0.080 \mu m$. The surface quality was significantly improved. Based on the regression analysis of experimental data, the quality prediction model of polygonal helical curved tube roughness by AFM was established to realize the effective prediction of surface quality after machining. The fitting value calculated by the model with optimal process parameters is close to the experimental value, which proves the accuracy and validity of the prediction model.

Keywords Abrasive flow machining · Polygonal helical curved tube · Surface quality · Prediction model

1 Introduction

With the rapid development of science and technology, free-form surfaces have been widely used in aerospace precision manufacturing, auto parts manufacturing, precision optical instruments, etc. The barrel is an important part of the gun. It has two forms: smooth hole and rifling hole. Compared with smooth holes, rifling holes can make the bullet rotate during firing, which can improve the stability of the bullet in the air [1]. The rifling in the barrel is a spiral curved surface, and its machining precision is very high. Poor surface quality will reduce the initial velocity and stability of the bullet and then affect the trajectory of the bullet, resulting in a decrease in the shooting accuracy of the gun [2]. Rifling is usually made with a broach [3], and the resulting rifling will have higher roughness and many edge burrs, which will affect the ballistic stability of the bullet. Abrasive flow machining (AFM) technology can effectively polish and deburr the inner wall of the parts [4, 5] and improve the finishing precision of the inner surface of the barrel and the shooting accuracy.

At present, scholars at home and abroad have developed a variety of AFM technologies from multiple directions. Zhao et al. proposed a new method of cavitation rotary AFM and studied the influence of the energy generated by cavitating bubble bursting on the kinetic energy of abrasive and the randomness of abrasive movement near the wall in low-pressure abrasive flow [6]. Shao and Cheng proposed a multiscale multiphysics field method combined with micro-cutting mechanics to study the surface texture and morphology generated by AFM [7]. Wei et al. proposed a guar gum gel-based medium with shear thickening property, which can be used to obtain a finely polished surface during AFM [8]. Tian et al. introduced the factors affecting the shear-thickening behavior, including volume fraction, particle size,
particle shape, carrier viscosity, temperature, and so on [9]. Cinefra studied the effect of the fluid on the hydrodynamic response of the nano-particle armed pipe and gave the critical velocity and system frequency of the fluid. The results show that the critical velocity and structure frequency of the fluid increase with the increase of the volume fraction of nanoparticles [10]. Venkatesh et al. applied high-frequency vibration orthogonal to the flow direction of the abrasive particle to the workpiece to study the influence of amplitude on the shear force of the abrasive particle on the workpiece wall [11]. Chawla et al. placed an electromagnet on the outer wall of the workpiece during AFM and studied the influence of magnetism on the effect of processing [12]. Ali et al. studied the influence of centrifugal force-assisted AFM, and the experimental results showed that this method had a great beneficial effect on material removal and surface quality of the workpiece [13].

For these new AFM methods, scholars mainly study the single variable in the new methods, which is the most effective way to verify the degree of influence of the new method on the processing effect. For traditional AFM, many scholars have studied different processing variables, such as inlet pressure [14], inlet velocity [15], abrasive concentration [16], abrasive type [17], abrasive wear degree [18], and viscoelasticity of abrasive media [19]. Through the study of a single variable, the influence of the variable on the machining process can be effectively obtained to reach better surface quality. In fact, the combination of the best parameters derived from single variable studies will not achieve the best results. On the one hand, the quantitative values of various studies are not uniform. On the other hand, there are mutually exclusive factors among various research variables, which may achieve negative effects after combination. Therefore, it is necessary to experiment on multiple variable factors to determine the best scheme. Marzban et al. studied the material removal rate of the workpiece under multivariable factors [20], but there were few variable combination schemes, which could not comprehensively reflect the effect of the multi-factor combination.

Orthogonal experimental design (OED) is a common scheme to verify the influence of multivariable factors on the results. It is widely used in the fields of thermodynamics [21], mechanical engineering [22], and biology [23]. Previously, we used the OED to study the effect of different factors on the surface quality and the optimal combination scheme [24]. Compared with comprehensive experiments, OED can reduce the number of experiments and correctly reflect the influence of various factors on the results.

In order to explore the relationship between multiple parameters and surface roughness of polygonal helical curved tube, OED is carried out with four kinds of AFM parameters in this paper, which avoided the adverse reactions caused by single-variable research and complex comprehensive experiments. By analysis of variance (ANOVA) of experiment data, the influence of inlet pressure, abrasive concentration, abrasive particle size, and machining time on the surface roughness of polygonal helical curved tube is studied. The optimal parameter combination is determined, and an effective mathematical model of surface roughness of polygon helical curved tube is established, which can provide technical support for improving the surface quality of special-shaped curved workpiece processed by AFM.

2 Experimental scheme

2.1 Study workpiece selection

The helical surface is the key structure of the barrel. The accuracy and roughness of the inner surface of the barrel are very high, and the performance of the barrel directly determines the shooting accuracy. When the roughness of the inner surface of the barrel is high, the movement of the warhead in the bore will be unstable. Due to the particularity and complexity of the inner cavity structure of the polygonal helical curved tube workpiece, the traditional polishing method cannot meet the current processing requirements. Considering that the AFM technology can process parts with complex cavities, with good uniformity and repeatability, and high surface quality, the AFM method is adopted to process the workpiece in order to achieve the ideal processing effect. Fig. 1 shows the schematic diagram of the AFM process.

Because this experiment needs to compare the workpieces under several groups of experimental conditions, the polygonal helical curved tube on the same root is used to control the variables. The polygonal helical curved tube is cut into 10 segments by wire-cut electrical discharge machine (WEDM), and the length of each segment is the same, which is recorded as the sample 00#–09#. Any sample is shown in Fig. 2a. Due to the long internal flow channel of the sample workpiece, each sample workpiece is divided into three regions, namely the inlet region, the mid region, and the outlet region. The region division is shown in Fig. 2b.

2.2 Orthogonal experimental design

In the actual AFM process, the machining quality of the workpiece is affected by many factors. Inlet pressure, abrasive concentration, abrasive size, machining time, machining temperature, and the complex shape of the internal structure of the workpiece will have a significant impact on the machining quality of the workpiece. Because many factors are affecting the machining quality, OED is chosen to explore the influencing factors of each factor [25]. According to the previous research experience, inlet pressure, abrasive concentration, abrasive size, and machining time have a great
influence on the surface quality of the workpiece. Therefore, OED was carried out on these four factors, and the inner surface roughness before and after AFM was taken as the measurement standard.

According to the results of the previous study [26–28], the inlet pressure was selected to be 6MPa, 7MPa, and 8MPa. The abrasive size was selected to be 600 mesh, 800 mesh, and 1000 mesh. The abrasive concentration was selected to be 20%, 25%, and 30%. And the machining time was selected to be 20min, 30min, and 40min for the four-factor and three-level experiment. The orthogonal table is represented by $L_a(b^c)$, where $a$ is the total number of experiments, $b$ is the level number of each factors, and $c$ is the maximum number of factors. The orthogonal table uses $L_9(3^4)$ according to the number of factors selected and the number of levels. The orthogonal table is shown in Table 1.

According to Table 1, the AFM experiment is carried out. The polishing equipment used in the experiment can be processed in one way and two way by adjusting the inlet pressure, processing time, and processing times. As shown in Fig. 3a, it is the AFM experimental equipment. In order to observe the machining effect of the inner wall surface of the sample workpiece, the workpiece is cut by a wire cutting machine. Fig. 3b shows the actual figure of WEDM, and Fig. 3c shows the sample workpieces after cutting and the amplifying view of the polished region of the unpolished sample 00# and the polished sample 09#. After the workpieces are subjected to wire cutting operation, ultrasonic

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**Fig. 1** Schematic diagram of abrasive flow machining.

**Fig. 2** a Any sample figure obtained by cutting; b any sample region division figure.
### Table 1 Orthogonal table of AFM experiment.

| Sample no. | Inlet pressure (MPa) | Abrasive concentration (%) | Abrasive size (mesh) | Machining time (min) |
|------------|----------------------|----------------------------|----------------------|---------------------|
| 01#        | 6                    | 20                         | 600                  | 20                  |
| 02#        | 6                    | 25                         | 800                  | 30                  |
| 03#        | 6                    | 30                         | 1000                 | 40                  |
| 04#        | 7                    | 20                         | 800                  | 40                  |
| 05#        | 7                    | 25                         | 1000                 | 20                  |
| 06#        | 7                    | 30                         | 600                  | 30                  |
| 07#        | 8                    | 20                         | 1000                 | 30                  |
| 08#        | 8                    | 25                         | 600                  | 40                  |
| 09#        | 8                    | 30                         | 800                  | 20                  |

**Fig. 3**  
a) Self-developed abrasive flow precision machining machine; b) wire-cut electrical discharge machine; c) sample workpieces after cutting
cleaning is used to remove residual dirt in the workpieces, and then cleaned and dried with absolute ethanol and acetone, and finally related detections are carried out.

3 Results and discussion

3.1 Detection and analysis of surface morphology and roughness of polygonal helical curved tube

3.1.1 Comparison and analysis of morphology of sample surface

In order to obtain the surface roughness and surface morphology of the inner surface of the polygonal helical curved tube before and after precision machining of AFM, Wyko NT1100 grating roughness measuring instrument was used to detect the surface roughness of the sample workpieces. Divide the sample workpiece area into three equal regions, select the intersection point of the axial midpoint position and the longitudinal position of each region as the measurement point, fix the sample workpiece in the same position in turn, and measure the measurement point by adjusting the microscope lens. The selection of the measurement position is shown in Fig. 4, and the Wyko NT1100 grating roughness measuring instrument is shown in Fig. 5.

The histogram of the surface roughness values of the inner surface of samples 00#-09# is shown in Fig. 6. It can be seen that the surface roughness of the sample after AFM is greatly reduced, and the surface roughness of the inlet region is the lowest, followed by the middle region, and the export region has the highest surface roughness. It shows that the polishing effect weakens with the increase of channel distance, but it can be found that the roughness values of the three zones are significantly decreased by observing the numerical bar, and the polishing effect of the whole workpiece is very significant. At the same time, the surface morphology of sample 00 # and sample 02 # can be observed in Fig. 7. It is found that the inner surface of sample 00# is uneven, and the inner surface finish and smoothness of sample 02# are significantly improved, which further proves that abrasive flow polishing technology has a good polishing effect on polygonal spiral elbow workpiece.

Since the inner surface of the workpiece is a spiral surface, the scanning surface is not a plane, and the surface roughness error is relatively large. In order to obtain accurate surface roughness values, Mahr MarSurf LD 120 stylus measuring instrument is used for surface roughness detection to obtain more accurate surface roughness values. The measurement effect weakens with the increase of channel distance, but it can be found that the roughness values of the three zones are significantly decreased by observing the numerical bar, and the polishing effect of the whole workpiece is very significant. At the same time, the surface morphology of sample 00 # and sample 02 # can be observed in Fig. 7. It is found that the inner surface of sample 00# is uneven, and the inner surface finish and smoothness of sample 02# are significantly improved, which further proves that abrasive flow polishing technology has a good polishing effect on polygonal spiral elbow workpiece.

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results of inner wall roughness of the samples from 00# to 09# are drawn in the histogram of Fig. 8; it can be seen that the surface roughness of the workpiece after AFM is significantly reduced, which proves that the AFM method can make the inner wall of polygonal helical curved tube surface reach a smaller roughness value. However, by comparing the differences of surface roughness Ra values among three regions of the samples, the trend is still that the inlet region is smaller than the mid-region smaller than the outlet region, which is the same as the trend of the roughness detection results of the optical profiling system. That is, the overall surface quality performance deteriorates from the inlet region to the outlet region, indicating that the surface material removal amount of the workpiece is also affected by the machining distance of the runner.

Fig. 9 shows the roughness detection curves of three typical samples in the inlet region. Fig. 9a is the roughness detection result of the inlet area of the sample 00# without machining. Fig. 9b is the roughness detection result of the inlet area of the sample 02#, and the roughness value of this sample is the maximum value of all the samples in the inlet region. Fig. 9c is the roughness detection result of sample 08# inlet area, and the roughness value of this sample is the minimum value of all samples in the inlet region. As can be seen from Fig. 9, after the sample 02# and sample 08# were processed by AFM, most of the peaks of the inner surface contour were cut, and the surface morphology became smoother. However, the deeper defects, it cannot be eliminated by AFM. Looked from the overall, AFM can significantly reduce the roughness of the inner surface of the polygonal helical curved tube.

3.1.2 Comparison and analysis of the surface morphology of the samples by SEM

In order to better observe and analyze the surface morphology of polygonal helical curved tube before and after AFM, German ZEISS EVO MA25 scanning electron microscope (SEM) was used to detect the inner surface of the samples.
The obtained surface morphology of polygon helical curved tube before and after AFM is shown in Fig. 10.

It can be seen from Fig. 10 that there are many rust impurities and burrs on the surface of sample 00# before AFM, and there are pits of different sizes, gullies of different shapes, and strip protrusions. After AFM, most of the rust impurities and burrs of the sample 08# were removed, and the surface morphology became smooth. Most of the bad morphology of pits, ravines, and protrusions disappeared, and there were clear scratches and lines on the inner surface. Under the action of plowing and sliding, the surface peak disappeared, and the surface became smooth and formed scratches parallel to the flow direction of the abrasive particles. It can be seen from Fig. 10 d, e, and f that the number of surface scratches gradually increases with the increase of distance from the entrance. This phenomenon conforms to the conclusion that the farther the workpiece is from the inlet, the greater the roughness. It indicates that the surface material removal amount of the workpiece is also affected by the machining distance of the runner.
3.2 Analysis of variance of OED data

The degree of influence of factors, optimal combination, and optimal combination confidence can be obtained by using analysis of variance (ANOVA) for OED experiment data. The effect of AFM is the best on the inlet region of the polygonal helical curved tube, so the surface roughness of the inlet region was selected as the index for analysis, and the ANOVA table of experiments data was obtained as shown in Table 2.

In the process of ANOVA, the deviation square sum value of factor C (abrasive size) is $SS_C=0.003$, indicating that this factor has little influence on the roughness, so it is classified as the error term. It can be found from Table 2 that $F$ value of inlet pressure is $F=11.43$, $F_{0.10}<11.43<F_{0.05}$, so the inlet pressure is significant at the level of $\alpha=0.10$. That is, the influence of this factor is significant. The $F$ values of abrasive concentration and machining time are $F=6.13$ and $F=7.52$, $F_{0.25}<6.13<7.52<F_{0.10}$, so the abrasive concentration and machining time were significant at the level of $\alpha=0.25$, and the machining time was more significant than the abrasive concentration.

Through the analysis of $F$ value, it can be concluded that the order of influence of AFM factors to reduce surface roughness is that inlet pressure > machining time > abrasive concentration > abrasive size. And $k_{A3}>k_{A2}>k_{A1}$, $k_{B3}>k_{B2}>k_{B1}$, $k_{C3}>k_{C2}>k_{C1}$, $k_{D3}>k_{D2}>k_{D1}$. Therefore, it can be judged that the optimal horizontal combination of A, B, C, and D factors is $A_3B_1C_3D_3$. That is, the optimal machining parameters of the workpiece in AFM are inlet pressure of 8MPa, abrasive concentration of 20%, abrasive particle size of 1000 mesh, and machining time of 40min. Under the condition of these parameters, the precision machining of the polygonal helical curved tube by AFM can reach the optimal quality.

In order to clearly observe the interaction between various factors on surface roughness, the two-dimensional isoline maps between surface roughness and inlet pressure, machining time, and abrasive concentration were drawn, as shown in Fig. 11.

It can be seen from Fig. 11a that the surface roughness of the samples decreases gradually with the increase of inlet pressure and the decrease of abrasive concentration. The reason is that the greater the inlet pressure, the more intense the fluid motion. The smaller the concentration of abrasive, the more disorderly and active the particle movement. The combined action of the two reasons makes the collision

| Sample no. | A  | B  | C  | D  | Roughness Ra (μm) |
|------------|----|----|----|----|-------------------|
|            | Inlet pressure (MPa) | Abrasive concentration (%) | Abrasive size (mesh) | Machining time (min) |                  |
| 01#        | (1) 6 | (1) 20 | (1) 600 | (1) 20 | 0.352             |
| 02#        | (1) 6 | (2) 25 | (2) 800 | (2) 30 | 0.395             |
| 03#        | (1) 6 | (3) 30 | (3) 1000 | (3) 40 | 0.319             |
| 04#        | (2) 7 | (1) 20 | (2) 800 | (3) 40 | 0.134             |
| 05#        | (2) 7 | (2) 25 | (3) 1000 | (1) 20 | 0.246             |
| 06#        | (2) 7 | (3) 30 | (1) 600 | (2) 30 | 0.338             |
| 07#        | (3) 8 | (1) 20 | (3) 1000 | (2) 30 | 0.153             |
| 08#        | (3) 8 | (2) 25 | (1) 600 | (3) 40 | 0.116             |
| 09#        | (3) 8 | (3) 30 | (2) 800 | (1) 20 | 0.331             |
| $k_{j1}$   | 1.066 | 0.639 | 0.806 | 0.929 |
| $k_{j2}$   | 0.718 | 0.757 | 0.860 | 0.886 |
| $k_{j3}$   | 0.600 | 0.988 | 0.718 | 0.569 |
| $\Delta_j$ | 0.466 | 0.349 | 0.142 | 0.360 |
| $SS_j$     | 0.039 | 0.021 | 0.003 | 0.026 |
| $F_j$      | 11.43 | 6.13 | - | 7.52 |
| $P_j$      | 0.080 | 0.140 | - | 0.117 |
| Order      | A>D>B>C |
| Optimal level | $A_3$ | $B_1$ | $C_3$ | $D_3$ |
| Optimal combination | $A_3B_1C_3D_3$ |
between the abrasive particles and the inner wall more intense, which improves the cutting efficiency and reduces the surface roughness. It can be seen from Fig. 11b that the surface roughness of the samples tends to decrease with the increase of inlet pressure and machining time. The reason is that the greater the inlet pressure is, the greater the energy of the fluid and the abrasive particles. It makes the impact cutting effect on the wall enhanced. With the increase of machining time, the total impact cutting time of abrasive particles increases. The combined action of the two reasons resulted in a significant decrease in surface roughness. It can be seen from Fig. 11c that the surface roughness of the workpiece decreases gradually with the increase of machining time and the decrease of abrasive concentration. This is because the concentration of abrasive is small, and the turbulence degree of fluid is more intense. So the number of times that abrasive particles hit the inner wall increases. As a result, the peaks on the surface are cut off, and the surface roughness is reduced.

3.3 Experimental optimization analysis

Based on the theory of the data analysis method, the mathematical model of surface roughness of experimental index is established, and then the surface roughness value is analyzed and predicted. According to ANOVA data in Section 3.2, the abrasive size (factor C) has little influence on the surface roughness. Therefore, the inlet pressure (factor A), abrasive concentration (factor B), and machining time (factor D) are respectively taken as independent variables \( x_1, x_2, \) and \( x_3 \), and the surface roughness \( Ra \) value is taken as the dependent variable. The regression equation established is shown in Eq. (1):

\[
Ra = a + bx_1 + cx_2 + dx_3
\]

where \( Ra \) is the surface roughness, \( x_1 \) is the inlet pressure (factor A), \( x_2 \) is the abrasive concentration (factor B), and \( x_3 \) is the machining time (factor D).

Through regression analysis, the regression model is shown in Eq. (2).

\[
Ra = 0.693 - 0.0777x_1 + 0.01163x_2 - 0.006x_3
\]

The model’s goodness of fit is \( R^2 = 0.8741 \), and the adjusted goodness of fit is \( R^2_{adj} = 0.7986 \). Both values are greater than 0.75, and the difference is small, indicating that the regression model has a good fitting. The values \( F \) and \( P \) of this regression model are \( F=11.58 \) and \( P=0.011 \), that is \( F_{0.05}<11.58<F_{0.01} \), which proves that the regression model is significant at the \( \alpha=0.05 \) level. To further verify the validity of the regression model, the residual values of the regression model were analyzed, as shown in Fig. 12.

It can be seen from Fig. 12a that the normal probability graph of the residual is roughly a straight line, indicating that the residuals follow the normal distribution. In Fig. 12c, the residual frequency histogram also shows a normal distribution. In Fig. 12d, residuals in observation order vs residual line plot are randomly distributed around the centerline, which is a reasonable result. However, Fig. 12b shows a poor performance between the residual and the fitting value. The reason is that the response parameter surface roughness \( Ra \) values are concentrated around 0.15 and 0.35. Therefore, Fig. 12b shows a phenomenon that the residuals of the fitting values are concentrated on both sides. This phenomenon is caused by the uneven distribution of response parameters and is not a problem of the regression model, so it is a reasonable phenomenon.

Multicollinearity refers to the linear relationship among multiple factors, which is an important factor affecting the accuracy of the regression model. If collinearity exists between the variables of the regression model, the coefficients of the model will be affected and become unreliable [29]. The collinear diagnosis table of the regression model is shown in Table 3.

It can be seen from Table 3 that the eigenvalue of the regression model is close to 0 only in 4D. That is, there may be multicollinearity between variables in the regression model.
Eq. (2). However, in 4D, the condition index is 26.974, less than 30, so it can be considered that there is no collinearity among variables. In the variance proportions value, there is at most one term of any dimension greater than 0.5 (apart from the constant). Based on the above judgment methods, the regression model has no multicollinearity.

In order to further analyze and illustrate the validity of the regression model, standardized residual values of regression model fitting values are tested, and the diagnostic table of regression model fitting values is shown in Table 4.

According to Table 4, it can be analyzed that the fitting values and the detection values are within reasonable variation and relatively close to each other. The standardized residual is within the range of (−2,2), indicating that the regression model is reliable and has strong anti-interference. So, the regression model can be used to analyze the surface roughness. The optimal combination was obtained in Section 3.2 by ANOVA, that is inlet pressure of 8MPa, abrasive concentration of 20%, and machining time of 40min. The optimal combination is applied to regression model Eq. (2) to obtain the minimum surface roughness of 0.069μm.

### 3.4 Optimal combination experimental analysis

Based on the analysis of the above OED data, the optimal combination is the inlet pressure of 8MPa, the abrasive concentration of 20%, the abrasive size of 1000 mesh, and the machining time of 40min. Under this condition, the surface quality of the inlet region of the polygonal helical curved tube processed by AFM can reach the best.

### Table 4 Diagnostic table of regression model fitting values

| No. | Detection value | Fitting value | Residual | Standardized residual |
|-----|----------------|---------------|----------|-----------------------|
| 01  | 0.352          | 0.344389      | 0.0076111| 0.16050               |
| 02  | 0.395          | 0.342556      | 0.0524444| 1.10592               |
| 03  | 0.319          | 0.340722      | -0.0217222| -0.45807             |
| 04  | 0.134          | 0.146722      | -0.0127222| -0.26828             |
| 05  | 0.246          | 0.324889      | -0.0788889| -1.66356             |
| 06  | 0.338          | 0.323056      | 0.0149444| 0.31514               |
| 07  | 0.153          | 0.129056      | 0.0239444| 0.50493               |
| 08  | 0.116          | 0.127222      | -0.0112222| -0.23665             |
| 09  | 0.331          | 0.305389      | 0.0256111| 0.54007               |
Therefore, the AFM experiment was carried out under the optimal machining parameter combination, and the workpiece is marked as sample 10#. The surface quality detection results of sample 10# are shown in Fig. 13.

It can be seen from Fig. 13 that the surface roughness obtained by using the optimal parameter combination is significantly better than the processing parameter combination in OED, and the detected surface roughness value is 0.080μm. Compared with the maximum roughness of 0.395μm (sample 02#) in OED, the surface roughness decreased by 79.7%, which confirmed the necessity of the existence of a regression model. Under the optimal parameter combination condition, the minimum surface roughness fitting value obtained by regression model calculation is 0.069μm, which is close to 0.080μm of the surface roughness value of sample 10#. The correctness of the mathematical model between the surface roughness Ra value and the machining parameters is verified. It is shown that the inner surface quality of the polygonal helical curved tube can reach the optimal level after processing with the optimal parameter combination.

4 Conclusions

(1) Through experimental research, it is found that AFM can effectively improve the surface quality of polygonal helical curved tube, which is conducive to obtain better performance. However, the quality of the inner surface is uneven, and the surface quality of the workpiece inlet region is better than the mid region, and the surface quality of the mid region is better than the outlet region.

(2) Under the experimental conditions in this paper, the optimal process parameter combination for precision machining of the polygonal helical curved tube by AFM was obtained through ANOVA. That is, the inlet pressure is 8MPa, the abrasive concentration is 20%, the abrasive size is 1000 mesh, and the machining time is 40min. Determine the order of the influence degree of process parameters on surface roughness of AFM. Inlet pressure>Machining>Abrasive concentration>Abrasive size. Compared with other parameter combination conditions, the surface roughness of polygon helical curved tube can be reduced by 79.7% at most under the optimal parameter combination condition.

(3) Through the regression analysis of OED data, the quality prediction model for the precision machining of the polygonal helical surface by AFM is established. Through comprehensive analysis, it is found that the quality prediction model can accurately reflect the functional relationship between surface roughness Ra and inlet pressure, abrasive concentration, and machining time. Under the optimal parameter combination, the predicted result of the model is 0.069μm, which is close to the experimental value of 0.080μm, indicating that the model can effectively predict the surface quality of the precision-machined polygonal helical curved tube.

![Fig. 13](image_url) Sample 10# surface quality detection results. a Surface contour curve and roughness value of the inlet region. b 3D scanning image of the inlet region. c SEM detection surface morphology map of the inlet region.
Acknowledgements The authors would like to thank the National Natural Science Foundation of China (No. NSFC 5120601), Jilin Province Science and Technology Development Program of Jilin Province (No. 20200301040RQ), and Changchun Science and Technology Program of Changchun City (No. 18DY017).

Author contribution Junye Li designed and performed the manuscript, analyzed the data, and drafted the manuscript. Shangwu Zhu and Jinbao Zhu analyzed the data and supervised this study. Chengyu Xu, Hengfu Zhang, and Guangfeng Shi conceived the project; WeiHong Zhao and Jianhe Liu organized the paper and edited the manuscript. All authors read and approved the manuscript.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication All presentations of case reports have consent for publication.

Conflict of interest The authors declare no competing interests.

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