

Numerical Analysis and Optimization of Hole Roundness in Gun Drilling Deep Hole Machining

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Abstract. According to the actual situation of gun drill processing and the fact that the guide pad has effect on improving processing quality, optimized structure with three guide pads is designed. Finite element analysis method and characteristic matrix of mechanical model is used to deduce the formula of the rifling mark when the calculation accuracy is guaranteed. The results of two kinds of gun drill worked in the same situation are compared and analysed by simulation. From the result, gun drill with three guide pads is good at inhibiting the errors and improving the machining quality.

1. Introduction

Gun drill is used in military, aviation, aerospace, engines, automobiles, models and other fields widely, which plays an important role in the equipment manufacturing industry. Because of the disparity of the aspect ratio and hollow structure, gun drill owns special weak stiffness. And gun drill worked in the closed condition with the interference of high-pressure cutting fluid and chips, so deep hole machining is hard especially in micro hole. Many scholars at home and abroad have made more researches on the processing quality of deep hole. Lingfei Kong used the semi-analytical method of kinetics and Newton-Raphson iterative method got the formula of roundness morphology in the process of traditional BTA drill ^[1]. Bayly discussed the theory of torsional chatter and analyzed the approach to find the chatter and stable boundary condition in the frequency domain ^[2]. From these researches, nonlinear dynamic lead to the errors of roundness morphology and many countermeasures are found. Roundness is a kind of indicator of deep hole processing quality ^[3]. Because of the chatter and whirl of drill pipe, rifling marks ^[4, 5] (as shown in figure 1) appear on the workpiece, which reduce the accuracy and life of deep hole parts. So additional process is used to improve machining quality, that more costs and energy is wasted. However it's much less researches on the roundness than other kinds of qualities.



Figure 1. Rifling mark



The guide pad is an essential part in the structure of gun drill, which play an important role in the self-directed [6]. In the processing, the pressure between guide pads and workpieces make the machining quality better. Meanwhile, guide pads also can reduce the influence of chatter and whirl. Owing to the requests for deep hole parts are increasingly strict, traditional gun drill with two pads can't satisfy the requests. As such, an optimized drill with three pads is designed and their machining quality is compared to verify the superiority of the three guide pads structure.

2. Gun drill machining processing system model

Gun drill system is hollow cylinders with cutting edges and guide pads. The guide pads that support the tool are located at angular positions and from the cutting edge. The system is shown as figure 2. The tool is rotated and fed to cutting the workpiece. Cutting oil is not only cooling and lubricating tool but also being used to discharge the chips, which is injected into the work area by the drill pipe. Due to the weak stiffness of gun drill, additional support is used to improve the stiffness.

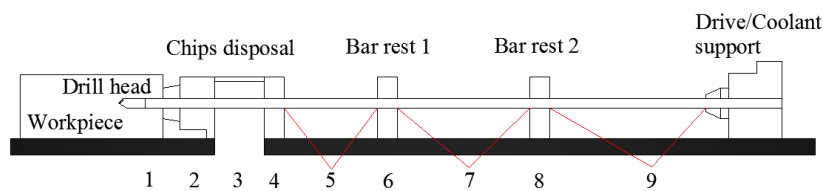


Figure 2. Gun drill machining processing system model

Drilling system is dispersed into nine independent beam elements with uniform structure features. Dynamics formula of the system is as followed by Euler-Bernoulli Beam theory.

$$\rho A \frac{\partial^2 U}{\partial t^2} + c \frac{\partial U}{\partial t} + kU + EI \frac{\partial^4 U}{\partial z^2} = 0 \quad (1)$$

Where E , I , ρ and A represent the modulus, inertia, density and the sectional area respectively. In the machining process, vibration amplitude of drill pipe reaches the maximum when the vibration frequency is close to its rotation frequency, which is the main reason for the roundness error.

3. Analysis of optimized structure of gun drill

Structure and stress diagrams of traditional gun drill and optimized gun drill is shown as figure 3(a) and (b). In the pictures, i ($i=1,2,3$) is used to mark guide pads. The angles between guide pads and cutting edge are represented by α_i . Tool receives the force from workpiece through the guide pads. Cutting edge receives cutting force. And cutting edge and guide pads are pressed against the workpiece. Cutting force and radial force are represented by T_c and Q_c . Normal force and friction worked on the cutting edge is represented by N_c and F_c respectively. In addition, normal force and friction worked on the guide pads are represented by N_i and F_i . The third guide pad in optimized gun drill is located at angular position 210° from cutting edge.

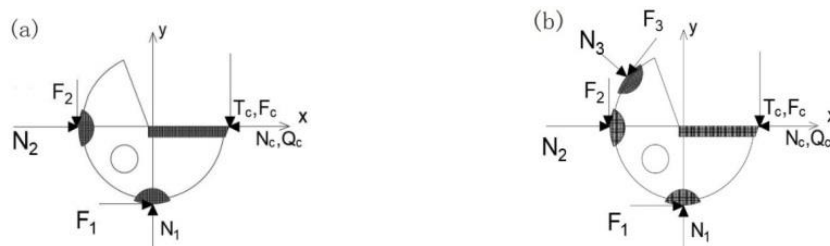


Figure 3. (a) The forces acting on gun drill; (b) The forces acting on optimized gun drill

According to the figures, the mechanics equation of gun drill during the machining is as follows [7]:

$$\begin{cases} F_x = -Q_c - N_c - \sum_{i=1}^n (N_i \cos \alpha_i + F_i \sin \alpha_i) \\ F_y = T_c + F_c + \sum_{i=1}^n (N_i \sin \alpha_i - F_i \cos \alpha_i) \end{cases}, \begin{cases} n=2, \text{ two guide pads} \\ n=3, \text{ three guide pads} \end{cases} \quad (2)$$

Cutting edge is attached to the n_c area on the workpiece, so the axial contact length is $n_c \xi$. The time spent on this area is $t-2\pi l/\omega$, where $l=1, \dots, n_c$. Letting the constant and damping coefficient be k_c and c_c , and the coefficient of kinetic be μ_c . The formulas of normal force and friction between cutting edge and workpiece are as follows.

$$\begin{cases} N_c = \sum_{l=1}^{n_c} \left\{ k_c \xi [x_E(t) - x_E(t - \frac{2\pi l}{\omega})] + c_c \xi [\dot{x}(t) - \dot{x}_E(t - \frac{2\pi l}{\omega})] \right\} \\ = \xi \left\{ n_c [k_c x_E(t) + c_c \dot{x}(t)] - \sum_{l=1}^{n_c} [k_c x_E(t - \frac{2\pi l}{\omega}) + c_c \dot{x}_E(t - \frac{2\pi l}{\omega})] \right\} \\ F_c = \mu_c N_c \end{cases} \quad (3)$$

Similarly, guide pads are contact with the n_g area, the axial contact length is $n_g \xi$. The drilling time is $t-(\alpha_i+2\pi l)/\omega$, where $l=0, \dots, n_g-1$. Letting the constant and damping coefficient be k_g and c_g , and the coefficient of kinetic be μ_g . The formulas of normal force and friction between guide pads and workpiece are as follows.

$$\begin{cases} N_i = \sum_{l=0}^{n_g-1} \left\{ k_g \xi \left[r_i(t) - x_E \left(t - \frac{\alpha_i + 2\pi l}{\omega} \right) \right] + c_g \xi \left[\dot{r}_i(t) - \dot{x}_E \left(t - \frac{\alpha_i + 2\pi l}{\omega} \right) \right] \right\} \\ = \xi \left\{ n_g \left[k_g r_i(t) + c_g \dot{r}_i(t) \right] - \sum_{l=0}^{n_g-1} \left[k_g x_E \left(t - \frac{\alpha_i + 2\pi l}{\omega} \right) + c_g \dot{x}_E \left(t - \frac{\alpha_i + 2\pi l}{\omega} \right) \right] \right\} \\ F_i = \mu_g N_i \end{cases} \quad (4)$$

As described in last section. Gun drilling system is dispersed into nine independent beam elements. Characteristic equation of the system is calculated by the transition matrix which is obtained by the transposed matrix of every units. Take one unit whose length is L for example, the cutting force on this unit is expressed as matrix:

$$F_i = \begin{bmatrix} f_1(L) & \frac{f_2(L)}{\beta} & \frac{f_3(L)}{EI\beta^2} & \frac{-f_4(L)}{EI\beta^3} \\ \beta f_4(L) & f_1(L) & \frac{f_2(L)}{EI\beta} & \frac{-f_3(L)}{EI\beta^2} \\ EI\beta^2 f_3(L) & EI\beta f_4(L) & f_1(L) & \frac{-f_2(L)}{\beta} \\ -EI\beta^3 f_2(L) & -EI\beta^2 f_3(L) & -\beta f_4(L) & f_1(L) \end{bmatrix}, i=1 \dots 9 \quad (5)$$

The transfer matrix between the base and the end of the boring bar is represented as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = F_9 F_8 F_7 \dots F_2 F_1 \quad (6)$$

According to Equations (2), (3), (4) and displacement of the tool, the follow equation can be obtained:

$$\begin{cases} \tilde{F}_x = -\gamma_{11} \tilde{X}_E - \gamma_{12} \tilde{Y}_E \\ \tilde{F}_y = -\gamma_{21} \tilde{X}_E - \gamma_{22} \tilde{Y}_E \end{cases} \quad (7)$$

Where,

$$\begin{aligned} \gamma_{11} &= \xi [\mathbf{b} \mathbf{K}_c + k_c n_c - k_c D_c + C_c \omega s n_c - C_c \omega s D_c + \sum_{i=1}^n (k_g + c_g \omega s) (n_g \cos \alpha_i - D_i) (\cos \alpha_i + \mu_g \sin \alpha_i)] \\ \gamma_{12} &= -\xi \sum_{i=1}^n (n_g k_g + c_g n_g \omega s) (\sin \alpha_i \cos \alpha_i + \mu_g \sin^2 \alpha_i) \\ \gamma_{21} &= -\xi \sum_{i=1}^n (k_g n_g + c_g n_g \omega s) (\sin \alpha_i \cos \alpha_i + \mu_g \sin^2 \alpha_i) \\ \gamma_{22} &= \xi \sum_{i=1}^n (k_g n_g + c_g n_g \omega s) (\sin^2 \alpha_i - \mu_g \sin \alpha_i \cos \alpha_i) \\ D_c &= \sum_{l=1}^{n_c} e^{-2\pi l s} = \frac{1 - e^{-2\pi n_c s}}{(1 - e^{-2\pi s}) e^{2\pi s}} \\ D_i &= \sum_{l=1}^{n_g-1} e^{-(\alpha_i + 2\pi l)s} = \frac{1 - e^{-2\pi n_g s}}{(1 - e^{-2\pi s}) e^{2\pi s}} \\ n &= 2, \text{two guide pads} \\ n &= 3, \text{three guide pads} \end{aligned} \quad (8)$$

The boundary condition of the base of the boring bar is considered as a fixed end. Therefore, the moments and cutting force on the fixed end can be obtained, and then the characteristic equation of the drilling system is derived.

The characteristic roots of last matrix are got by calculating. The real part of the root represents the stability of the rifling mark generating phenomenon [8]. If there is one root whose real part is positive, the roundness error occurs. On the contrary, if all the real parts are negative, the rifling mark doesn't occur. The imaginary part of the root corresponds to the polygonal number of the pattern because the nondimensional time ωt is used.

4. Simulation of roundness morphology

In this section, machining quality is compared between traditional gun drill and optimized gun drill while only changing the depth of processing. The related processing parameters are shown in the following table:

Table 1. The related processing parameters

$\rho(\text{kg}/\text{m}^3)$	$E(\text{N}/\text{m}^2)$	$A(\text{m}^2)$	$I(\text{m}^4)$	$m(\text{kg})$	$K_c(\text{N}/\text{m}^2)$	b	$k_c(\text{N}/\text{m}^2)$	μ_c
7.8×10^3	2×10^{11}	2.01×10^{-4}	4.45×10^{-8}	0.164	1.0×10^3	0.1	5.0×10^7	0.1
$C_s(\text{Ns}/\text{m}^2)$	n_c	$\xi(\text{m})$	α_1	α_2	$kg(\text{N}/\text{m}^2)$	μ_g	$C_g(\text{Ns}/\text{m}^2)$	n_g
2.5×10^3	20	0.075×10^{-3}	90°	180°	5.0×10^7	0.1	2.5×10^5	40

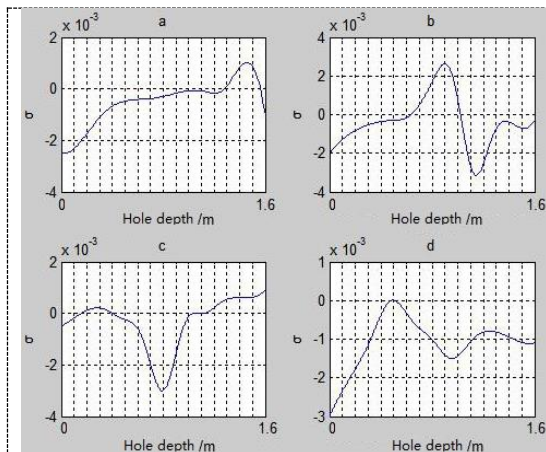


Figure 4. Variation of characteristic root with respect to hole depth of traditional gun drill. (a) $N_0=3$ (b) $N_0=5$ (c) $N_0=7$ (d) $N_0=9$

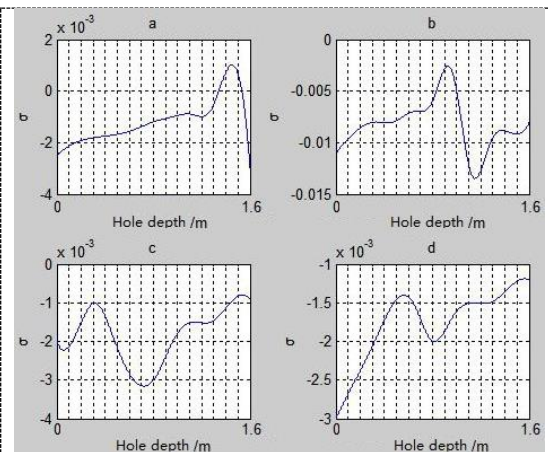


Figure 5. Variation of characteristic root with respect to hole depth of optimized gun drill. (a) $N_0=3$ (b) $N_0=5$ (c) $N_0=7$ (d) $N_0=9$

The roundness morphology of gun drill with two guide pads is shown in figure 4. According to the result, the polygonal deformation phenomenon occurs in 3, 5 and 7 sided polygonal deformation. According to figure 5 which express the roundness morphology of gun drill with three guide pads, roundness errors are suppressed effectively except for a small range of hole depths in three-sided polygonal deformation.

5. Conclusion

Optimized gun drill is designed according to the actual processing condition. Because of the complex structure, the tool system is dispersed into several beam units with uniform structure features and dynamic model is established. The formula of roundness errors of gun drill with three guide pads is obtained from the research method of traditional gun drill.

Letting the characteristic root of drilling system to represent the stability of roundness morphology and researching the differences between the two kinds of gun drill to obtain the result that 5 and 7 polygonal deformation are suppressed by the third guide pad. The superiority of the optimized gun drill is verified.

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