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Optimal design of tong dies parameters for drill pipe clamping manipulator

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Abstract. The tong dies are one of the important components of the drill pipe clamping manipulator and they contact with the drill pipe directly, which are used to increase the friction force, improve the clamping effect and ensure the reliability of the drill pipe clamping. The parameters of the tong dies determine the performance of the clamp teeth, and in this paper, the objective function for parameter optimization of the tong dies is established, and the optimal solution is carried out, and the optimal parameters of the tong dies are determined.

1. Introduction

Automatic piping machine is one of the automation equipment for petroleum drilling, and the drill pipe clamping manipulator is the end-effector of automatic piping machine. The drill pipe clamping manipulator is used to clamp drill pipe string. Because the drill pipe string is long and heavy, and it needs to be completed lifting, transportation and other actions in space, so the reliability of the clamping manipulator is highly demanded. Tong dies are one of the important components of clamping manipulator, and their performance directly affects whether the clamping manipulator can work safely or not. This paper focuses on the study of tong dies parameters.

2. Structure of drill pipe clamping manipulator and layout of tong dies

Fig. 1 shows the structure of the drill pipe clamping manipulator. When working, the baffle is fixed, and the hydraulic cylinder drives two claws to shrink and clamp the drill pipe. Tong dies are installed on the inner side of the block and the two claws to increase the friction of the clamping drill pipe and ensure reliable clamping. The layout of the tong dies is shown in Figure 2.



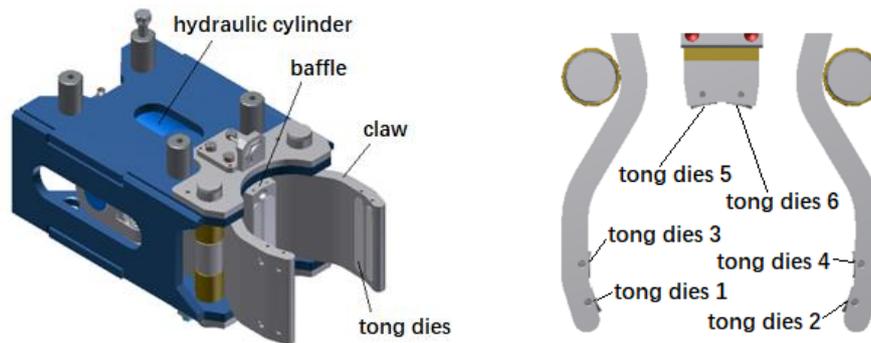


Figure 1. Structure of clamping manipulator. Figure 2. Layout of clamping manipulator's tong dies.

3. Objective function of parameter optimization of tong dies

During the working process of the clamping manipulator, the tong dies rely on the applied positive pressure to bite into the drill pipe surface, and produce friction, thus overcoming the gravity of the drill pipe string, clamping the drill pipe, and avoiding the drill pipe falling off. Therefore, the objective function of the parameter optimization of tong dies are as follows: biting depth and equivalent friction coefficient.

3.1. Tong dies biting depth

In the process of clamping the drill pipe with the tong dies, plastic deformation occurs when the stress on the drill pipe is greater than the yield limit [1]. With the increase of the biting depth of the tong dies, the contact area between the tong dies and the outer wall of the drill pipe will increase continuously.

Under the action of static friction, the clamping manipulator can hold the drill pipe tightly to move smoothly. However, the biting depth should not be too large, otherwise the drill pipe will be damaged. Figure 3 shows that a schematic diagram of the tong dies biting into the outer wall of the drill pipe, and figure 4 is that a schematic diagram of single tong dies biting into the outer wall of the drill pipe.

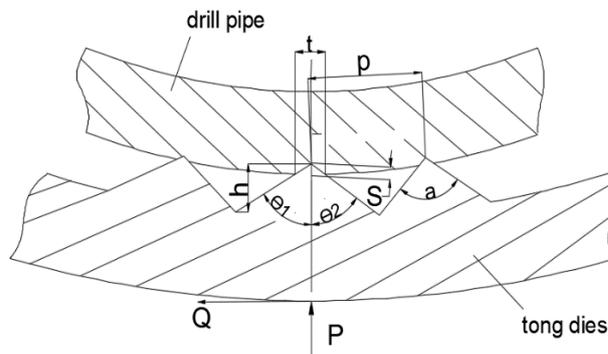


Figure 3. Diagram of tong dies biting into the outer wall of drill pipe.

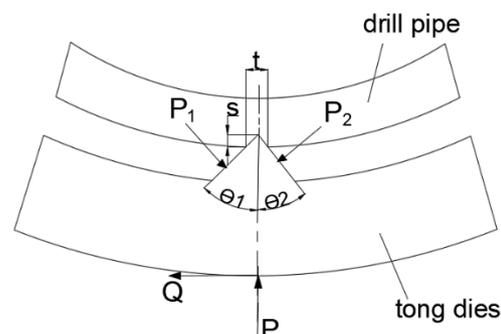


Figure 4. Diagram of single tong dies biting into the outer wall of drill pipe.

According to the geometric relationship in Figure 3, the depth of the tong dies biting into the drill pipe s can be obtained.

$$s = \frac{t}{2 \tan \theta_1} \tag{1}$$

Where, t is the contact width of the tong dies biting into the drill pipe; θ_1 and θ_2 are the rake angle and the relief angle of the tooth respectively, $\theta_1 + \theta_2 = \alpha$, and α is the thread angle.

According to Figure 3, stress of tong dies is as follow:

$$\sigma_s = \frac{P}{kmnlt} \tag{2}$$

Where, p is normal pressure, and k is safety factor, and m is the number of vertical tong dies, and n is the number of transverse tong dies, and l is the length of each tong dies.

Take:

$$\sigma_s = [\sigma_j] \quad (3)$$

Where, $[\sigma_j]$ is the yield strength of the tong dies.

The space width p is obtained from Figure 3:

$$p = h \tan \theta_1 + h \tan(\alpha - \theta_1) \quad (4)$$

Where, h is the depth of tooth.

Combined (1) to (4), the biting depth of the tong dies can be obtained as follows:

$$s = \frac{p}{[\sigma_j]klmn} \cdot \frac{1}{\frac{p}{h} + 2 \sqrt{\frac{p^2}{4h^2} + \left(\frac{p}{h} - 1\right) \cdot \frac{1}{\tan \alpha}}} \quad (5)$$

From the formula, it can be seen that the biting depth s is related to external force p , depth of tooth h , space width p and thread angle α .

3.2. Equivalent friction coefficient

The main function of the clamping manipulator tong dies is to increase friction coefficient to achieve smooth clamping and migration drill pipes, and to reduce damage to the outer wall of drill pipes.

In the clamping state, the equivalent friction coefficient f_v is:

$$f_v = \frac{Q}{P} \quad (6)$$

Where, Q is the tangential load.

Fig. 4 is a schematic diagram of a single tong dies biting into the drill pipe, the individual tong dies bear the combined action of the average distributed radial load p and tangential load Q . According to the geometric relation, it can be obtained:

$$\begin{cases} P = -f \cdot P_1 \cos \theta_1 + P_1 \sin \theta_1 - f \cdot P_2 \cos \theta_2 + P_2 \sin \theta_2 \\ Q = f \cdot P_2 \sin \theta_2 + P_2 \cos \theta_2 - f \cdot P_1 \sin \theta_1 - P_1 \cos \theta_1 \end{cases} \quad (7)$$

where, f is the friction coefficient; P_1 is the pressure on the rake angle; P_2 is the pressure on the relief angle.

When it enters the clamping state, the rake angle is the main force surface. In order to simplify the mathematical model, taking $P_2=0$, considering the geometric relation in figure 4, the equivalent friction coefficient can be obtained as follow:

$$f_v = \frac{Q}{P} = \frac{f \left[\sqrt{\frac{p^2}{4h^2} + \left(\frac{p}{h} - 1\right) \frac{1}{\tan \alpha}} \right] + 1}{f - \frac{p}{2h} \sqrt{\frac{p^2}{4h^2} + \left(\frac{p}{h} - 1\right) \frac{1}{\tan \alpha}}} \quad (8)$$

It can be seen that the equivalent friction coefficient is related to the depth of tooth h , the space width p and thread angle α of the tong dies.

3.3. Parameter optimization standard

The optimal index of the tong dies is biting depth s and equivalent friction coefficient f_v . Two optimization standards are set according to the work requirements: Biting depth $s \leq 1\text{mm}$, equivalent friction coefficient $f_v > f = 0.15$.

4. Theoretical optimization of tong dies parameters

4.1. Parameter optimization method and initial conditions

The main parameters of tong dies design are depth of tooth h , space width p and thread angle α . Changing any one of the three parameters will produce different combinations, which can generate different biting depth and equivalent friction coefficient. The problem of optimizing the three factors is a multi-factor preference problem, and the change of each group of factors has a great influence on the results. It is suitable to use orthogonal optimization method to deal with this problem^[2], which is a

very effective means to solve the multi-factor problem, and it is a reliable and efficient test method^[3]. The designed tong dies' material is 20CrMnTi, and the yield limit $[\sigma_j]$ can reach 8356MPa, with good intensity, ductility and other physical characteristics^[4-5]. According to the design parameters of the tong dies, the number of the teeth in the vertical direction is $m=22$, the number of the teeth in the lateral direction is $n=6$, the distance of each tooth is $l=20\text{mm}$, and the maximum value of radial load is $p=72.5\text{kN}$.

4.2. Optimization processing and results

According to the selected optimization parameters of the tong dies, the level table of optimization factors is drawn up, as shown in table 1. Then the optimization numerical calculation is carried out according to the objective function of formula (5) and formula (8), and the optimization data are obtained, as shown in table 2.

Table 1. Optimization factor level table

Level factor	A thread angle α	B space width p	C depth of tooth h
1	60	$2\sqrt{2}$	$\sqrt{2}$
2	80	6	3
3	110	4	2

Table 2. Theory orthogonal optimization table of the tong dies parameter

Column number	Factor	A thread angle α	B space width p	C depth of tooth h	optimization scheme	biting depth (mm)	equivalent friction coefficient
		1	2	3			
	1	1	1	1	$A_1B_1C_1$	0.4368	0.6420
	2	1	2	3	$A_1B_2C_3$	0.3008	0.4776
	3	1	3	2	$A_1B_3C_2$	0.8092	0.9838
	4	2	1	3	$A_2B_1C_3$	0.6730	1.0944
	5	2	2	1	$A_2B_2C_1$	0.2253	0.3945
	6	2	3	2	$A_2B_3C_2$	0.7161	0.6420
	7	3	1	2	$A_3B_1C_2$	1.0217	0.6438
	8	3	2	3	$A_3B_2C_3$	0.3750	0.7963
	9	3	3	1	$A_3B_3C_1$	0.4945	0.5212
Biting depth	K_1	1.5468	2.1315	1.1566			
	K_2	1.6144	1.9955	2.5470			
	K_3	1.8912	2.0198	1.3488			
	k_1	0.5156	0.7105	0.3855			
	k_2	0.5381	0.6651	0.8490			
	k_3	0.6304	0.6733	0.4496			
	Range	0.3444	0.1117	1.3904			

	Primary and secondary of the factors	C A B			
	Optimal scheme	A1 B2 C1			
Equivalent friction coefficient	K_1	2.1034	2.3802	1.5577	
	K_2	2.1309	1.6684	2.2696	
	K_3	1.9613	2.14701	2.3693	
	k_1	0.7011	0.7934	0.5192	
	k_2	0.7103	0.5561	0.7565	
	k_3	0.6538	0.7157	0.7894	
	Range	0.1696	0.7118	0.8116	
	Primary and secondary of the factors	C B A			
	Optimal scheme	A2 B1 C3			

In the table, K_i is the sum of the biting depth or equivalent friction coefficient of the combination of factors i ; k_i is the arithmetic average of the biting depth or equivalent friction coefficient of the corresponding combination when the factor is i ; Range is $R = \max\{K_1, K_2, K_3\} - \min\{K_1, K_2, K_3\}$ on any column.

According to the application requirements, it is necessary to ensure that the biting depth is small at the same time to ensure that the equivalent friction coefficient is large, which involves the problem of taking the optimal value. The larger the value is, the greater the influence on the optimal parameters is when the parameters change in the optimization process. Therefore, the parameters corresponding to the maximum range in the calculation results are a more important factor than other parameters^[6-7].

According to the design requirements, the extent of the index is determined: the requirement of biting depth K_i is as little as possible, and the requirement of equivalent friction coefficient is as large as possible. The theoretical optimization scheme is obtained based on the comparison and selection of the above optimization schemes. The tong dies parameters of the scheme are as follows: the thread angle α is 110° , the depth of tooth h is 2 mm, and the space width p is 6 mm.

5. Preferred Test

In order to verify the feasibility of the optimization results of the theoretical parameters, the simulation optimization experiments are carried out. Since the equivalent friction coefficient cannot be reflected in the simulation model, the simulation experiments are mainly carried out on the biting depth of the tong dies. Fig. 5 is the simulation model of the drill pipe and the tong dies. Using the same factors and levels as shown in table 1, the simulation bite depth corresponding to the scheme numbers in table 2 is obtained. For comparison, the theoretical bite depth data and the simulation bite depth data are drawn in the same coordinate system, as shown in figure 6.

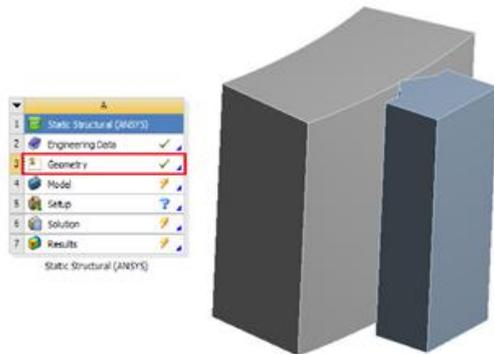


Fig. 5. Simulation model of the drill pipe and the tong dies

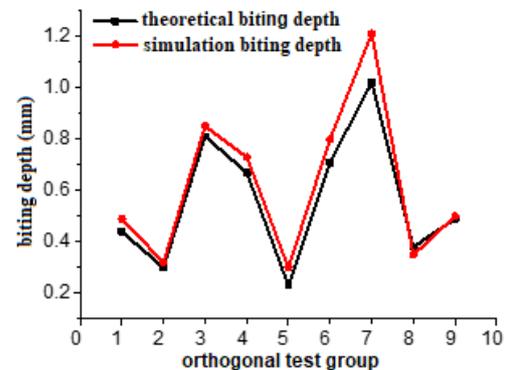


Fig. 6. Comparison of simulation biting depth and theoretical biting depth

From figure 6, it can be seen that the theoretical biting depth keeps good consistency with the simulation depth, and there is only a small error. Therefore, the theoretical calculation is reasonable, and $A_3B_2C_3$ is the optimal parameter selection. The optimum experimental parameters obtained by theoretical calculation are of high value in application.

6. Conclusion

In this paper, the objective function of optimizing the tong dies of the drill pipe clamping manipulator, namely biting depth and equivalent friction coefficient, is established. It can be seen that the two functions are related to depth of tooth h , space width p and thread angle α . According to the application requirements: the biting depth $s \leq 1\text{mm}$, and as small as possible to reduce the damage to the drill pipe; the equivalent friction coefficient $f_v > 0.15$, and as large as possible to increase the friction force. Orthogonal optimization method is used to solve the problem, and the parameters of the optimal scheme are determined as follows: the thread angle α is 110° , the depth of tooth h is 2 mm, and the space width p is 6 mm.

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