Die design and process optimization of plastic gear extrusion

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Abstract. The flow velocity of the melt in the extruder was simulated by using software Polyflow, and the size of the die channel with the best flow uniformity was obtained. The die profile shape is obtained by reverse design. The length of the shaping section is determined by Ansys transient thermal analysis. According to the simulation results, the design and manufacture of extrusion die of plastic gear and vacuum cooling setting were obtained. The influence of the five process parameters on the precision of the plastic gear were studied by the single factor analysis method, such as the die temperature T, the screw speed R, the die spacing S, the vacuum degree M and the hauling speed V. The optimal combination of process parameters was obtained by using the neural network particle swarm optimization algorithm (T = 197.05 °C, R = 9.04rpm, S = 67mm, M = -0.0194MPa). The tooth profile deviation of the extruded plastic gear can reach 9 level of accuracy.

1. Introduction

Gear is one of the most widely used transmission parts in mechanical equipment. Plastic gears are rapidly replacing metal gears in some applications with its low noise, light weight, oxidation resistance, corrosion resistance, and self-lubricating material properties [1]. For example, the power steering of a car is delivered through a set of plastic gears. Compared with metal materials, plastics has many advantages in cost, design, processing and performance. The freedom of plastic forming design ensures more efficient gear making. Because it can use plastic to form internal gear, gear sets, worm gears and other products, but it’s very difficult for the these products to use metal materials to form in a reasonable price. Plastic gears are generally made by injection molding. However, traditional injection molding technology has the disadvantages of difficult mold making, long molding cycle and low production efficiency. However, for the cylindrical plastic gears with cross-section, the products are in line with the features of extrusion molding process. Moreover, with the development of CAE technology and precision extrusion technology, the extrusion of plastic gear would be possible.

2. Design of extrusion die of plastic gear

As for the shape, plastic gears are similar to pipes and bars, so the design of die can refer to that of pipe and bar [2]. In the extrusion of plastic gears, the inner flow channel and the die is the most important factor affecting the plastics gears. Polymer melt flow in the die is very complex, so the design of the flow channel and die is often achieved by adjusting and correcting by experience to meet the requirements of molding [3-5]. Because the shape of the plastic gear die is complex and the precision is high, the empirical design method is difficult to meet the requirements. Therefore, this paper used finite software Polyflow to do numerical simulation and inverse extrusion research [6-9]. Firstly, the optimal flow channel structure was determined. Secondly, the cross-section shape of the
die was simulated when the inner rib stereotyping length was determined. Finally, the design of die is completed.

According to the comprehensive analysis of the characteristics of extrusion plastic gear, the straight-through die was selected. The parameters of inner flow channel of die are determined by the shape of the shunt cone. The structure of the inner flow channel is shown in Fig. 1, the main structural factors that affect the melt flow include the inner rib stereotyping length $L_1$, the compression length $L_2$, the shunting cone length $L_3$, the shunting segment length $L_4$, the total channel length $L_4$, the channel inlet diameter $D_0$, and the compression angle $\beta$ and the shunting angle $\alpha$ are the main structural factor affecting the melt flow.

In this paper, the plastic gear was researched, whose modulus $m$ was 0.5, the number of teeth $z$ was 12, the center hole diameter was 2mm, and the addendum circle diameter was 6.8mm. The optimal flow channel structure parameters were determined by orthogonal test of 16 sets of flow channel parameters by using the software Polyflow. $L_1 = 10\text{mm}$, $L_2 = 30\text{mm}$, $L_3 = 23\text{mm}$, $\alpha = 50^\circ$, $\beta = 50^\circ$, the reverse design of the cross-section of die is shown in Fig. 1. Using Ansys transient thermal analysis, the length of calibrator was 160 mm.

Straight-through die was used in the extrusion of plastic gear. The profile of die was manufactured by micro EDM technology. Vacuum calibrators are used in the extrusion of plastic gear. As shown in Fig. 2, the ends of the mold cavity are the cooling room, while the middle is the vacuum chamber.

1-shaping tube, 2- plexiglass visual tube, 3- rubber ring, 4- bracket side plate, 5- bracket plate, 6- fastening screw

**Figure 1.** (a) The structure of inner flow channel[11] (b) the result of reverse extrusion

**Figure 2.** The Vacuum calibrator of plastic gear extrusion
3. Extrusion experiments

The experimental platform mainly consists of the extruder, extrusion die, calibrator, vacuum machine and traction device, as shown in Fig.5. The experimental material is produced by DuPont in America. The model is POM-500P NC010. The material was heated and plasticized by the extruder, the basic shape was completed through the extrusion of die, the plastic gear profile was cooled and shaped by the calibrator, the vacuum machine was to ensure that the calibrator was in a negative pressure state, and finally the formed of plastic gear was pulled out of the calibrator device by the traction device. The characteristic of the experimental platform was that it used the calibrator with cooling function to direct cool, but didn’t use the cooling water tank. Therefore it avoided the long distance between the calibrator and traction device, which made the extrusion process unstable and difficult to adjust.

![Figure 3](image)

Figure 3. The experiment platform for plastic gear extrusion

4. Results and discussion

4.1 The analysis of experimental process Parameters

This paper uses the single-factor analysis method to study the effect of five parameters on the forming accuracy of plastic gear, which includes the screw speed, the die temperature, the distance between the die inlet and the die outlet (“die spacing”), the vacuum degree of calibrator, and the hauling speed. As the measurement of the accuracy of the extrusion gear was taken by visual parallel detection technology, the four experimental values of the center hole radius, the radius of the tooth circle, the deviation of tooth pitch and the total deviation of tooth profile are taken as the evaluation index of the forming accuracy. The accuracy is different from the general profile of the size requirements of the pipe, the evaluation of more indexes, according to the above four evaluation indexes which are of different importance to accuracy of plastic gears, the four different weight of indexes are to describe the final evaluation of gear forming accuracy $F_\omega$. The weight of each evaluation index is shown in Tab.1, and the final evaluation accuracy $F_\omega$ is calculated as:

$$F_\omega = 0.1f_\varphi + 0.2f_\varphi + 0.3f_{pt} + 0.4f_{pt}$$

| Table 1. Four corresponding weights of different evaluation indexes |
|---------------------------------------------------------------|
| Radius deviation of Center hole $f_\varphi$ | Radius deviation of addendum circle $f_\varphi$ | Deviation of tooth pitch $f_{pt}$ | Total deviation of tooth profile $F_\omega$ | 0.1 | 0.2 | 0.3 | 0.4 |

The value of the five extrusion process parameters is shown in Tab.2. As shown in Fig.4-7, the influence of each process parameter on the accuracy of forming for plastic gear. The conclusions are as follows: (1) the higher the die temperature is, the higher the accuracy of tooth profile will be. (2) Too small screw speed will affect the fit of the gear profile and calibrator, making the vacuum chamber can’t work; the tooth profile accuracy is high when screw speed is between 7 and 9rpm. (3) When the die spacing is too large, the time of gravity action increases, the mobility decreases, and the tooth profile accuracy will be reduced; when the die spacing is too small, it is easy to be sticky. When the die spacing is about 70mm, the tooth shape accuracy is best. (4) The higher the degree of vacuum
is, the higher the accuracy of the tooth will be, but high degree of vacuum makes the products and mold friction increase significantly, resulting in hauling difficulties. (5) The higher the hauling speed is, the more the tooth profile accuracy will reduce; high hauling speed will affect the fit of the gear profile and calibrator, making the vacuum chamber can’t work properly. (6) The ability of the system to adjust the degree of vacuum would be best when ratio of the screw speed and hauling speed was 4.28.

Table 2. Extrusion process parameter

| Serial number | Die temperature (°C) | Screw speed (rpm) | Die spacing (cm) | Vacuum degree (MPa) | Hauling speed (mm/s) |
|---------------|----------------------|-------------------|------------------|---------------------|----------------------|
| 1             | 190                  | 6                 | 60               | 0                   | 1                    |
| 2             | 195                  | 7                 | 70               | 0.005               | 1.5                  |
| 3             | 200                  | 8                 | 80               | 0.01                | 2                    |
| 4             | 205                  | 9                 | 90               | 0.015               | 2.5                  |
| 5             | 210                  | 10                | 100              | 0.02                | 3                    |

Figure 4. The curves between gear cross-section and screwing speed

Figure 5. The curves between gear cross-section and die spacing
4.2 Optimization of process parameters for extrusion of plastic gear

Optimization process parameters of extrusion of plastic gear included die temperature T, screw speed R, die spacing S, vacuum degree M, hauling speed V, but it was found that when ratio of the screw speed and the hauling speed was 4.28, the adsorption capacity of the vacuum room would be the best, so we change the process parameters into four, taking the die temperature T, screw speed R, die spacing S and vacuum degree M as the optimization target parameters. For the multi-objective optimization problem, orthogonal test method was generally used in tradition, while extrusion of the plastic gear has higher requirements on the accuracy of the size, and it could only obtain fine combination of process parameters rather than the optimum parameters in the orthogonal test. In this paper, we will firstly select 25 groups parameters to experiment in the way that orthogonal test table select combination of parameters, then conclude the experimental results as BP neural network training learning samples and establish BP network prediction model, finally obtain the sim () function. Then the population was established by IPSO, and the sim () function was used as the fitness function to figure out the optimal combination of process parameters.

The results of orthogonal test were analyzed by extreme difference analysis, and the degree rank of tooth shape accuracy that all process parameters affected were: S> M> T> R. The optimum process parameters were as follows: T = 200 ℃, R = 9rpm, S = 70mm, M = -0.02MPa. The process parameters of plastic gear extrusion optimized by BP-IPSO were: T = 197.05 ℃, R = 9.04rpm, S = 67mm, M = -0.0194MPa.

The optimum combination from two optimization models was post-rounding experimented according to the actual condition, the corresponding tooth profile accuracy of the indicators are shown in Tab.3. The results show that after using neural network and improved particle swarm optimization algorithm, the optimum accuracy of the extrusion of plastic gear which was 0.0415 in the orthogonal table increased by 27.07%. And the deviation of tooth profile $F_a$ which was 0.014 reached 9th level of gear accuracy. It was verified that the BP-IPSO method was effective and reliable in improving the accuracy of gear extrusion. The corresponding extrusion gear samples under the optimum process parameters are shown in Fig.8.

| Table3. The accuracy of gear extrusion of two optimization models |
|-----------------|-----------|------|------|--------|------|------|------|------|
|                 | T °C      | R rpm | S cm | M MPa  | $f_\varphi$ | $f_\phi$ | $f_{pt}$ | $F_a$ | $F_\omega$ |
| Orthogonal Optimum | 200      | 9    | 70   | 0.02   | 0.05     | 0.11     | 0.027   | 0.016 | 0.0415     |
| BP-IPSO Optimum    | 197.05   | 9.04 | 67   | 0.0194 | 0.025    | 0.12     | 0.003   | 0.014 | 0.0326     |
5. Conclusion
In this paper, the finite element software was used to simulate the design of extrusion die and vacuum calibrators of plastic gears. The optimum size of the die was determined, which provided the basis for the design and processing. The process parameters that influenced the accuracy of tooth profile were performed by univariate analysis and rules were obtained. The higher the degree of vacuum and die temperature is, the higher the accuracy of the tooth will be, when screw speed is between 7 and 9rpm and the die spacing is about 70mm, the tooth shape accuracy is high. The ability of the system to adjust the degree of vacuum would be best when ratio of the screw speed and hauling speed was 4.28. The parameters of extrusion process were optimized by using the comparison between the orthogonal test and the neural network particle swarm algorithm. T = 197.05 °C, R = 9.04rpm, S = 67mm and M = -0.0194MPa. And the tooth profile deviation of extrusion plastic gear reached 9th level of accuracy which reaches general level. The production efficiency was 10 times higher than that of injection molding. The research in this paper can guide the actual extrusion of plastic gears.

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