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Multi-objective optimization of swash plate forging process parameters for the die wear/service life improvement

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Abstract. For the forging process of the swash plate, the author designed a kind of multi-index orthogonal experiment. Based on the Archard wear model, the influences of billet temperature, die temperature, forming speed, top die hardness and friction coefficient on forming load and die wear were numerically simulated by DEFORM software. Through the analysis of experimental results, the best forging process parameters were optimized and determined, which could effectively reduce the die wear and prolong the die service life. It is significant to increase the practical production of enterprise, especially to reduce the production cost and to promote enterprise profit.

1. Introduction

Auto air-condition compressor as an important part of a car has undergone several generations of development [1, 2]. Although the latest generation is the scroll compressor, swash plate compressor still accounts for 60% of the compressor market [3]. Swash plate as the core component of this type compressor directly affects the reliability and life of the compressor. However, the swash plate is characteristic of its small size and complex shape. It is worth noting because it has high requirement of precision and quality, which makes manufacture difficult and leads to a short life of the die. Therefore, precision forging process may be a good way to solve for the company [4, 5].

To improve the performance of swash plate, many researchers have made endeavors. Wan *et al* developed an indirect squeeze casting with pressurization and local pressurization method to reduce defects such as air bubble after heat treatment, slag etc. [6]. In order to solve the seizing problem of automotive air conditioning compressor, Wu carried out the experiments of improving the lubricating property on the swash plate surface by changing the coating and substrate material [7]. Furthermore, Chen *et al* reported that the total squeeze casting pressure of 100 MPa, the delayed time of 2.8 s, and the central thick area of swash plate was pressurized locally with 180 MPa for 6 s, which could eliminate shrinkage defects in swash plate [8, 9]. Of course, die life is also a crucial factor. Behrens [10] studied the hardness evolution due to thermal softening of the tool material, and performed an accurate estimation of die wear by the proposed model. The latter proved to be applicable to wear estimation of hot forging dies over a large number of operating cycles. Based on the abrasive wear model developed by Archard, the thermo-mechanical coupled FE model of the hot forging process was built by Shi *et al* to estimate the influence of initial die temperatures, forging rate and heat treatment method on the wear depth of die [11,12]. Zheng *et al* used the DEFORM wear analysis module to analyze the die wear of typical forward cold extrusion process. The wear profile of points of

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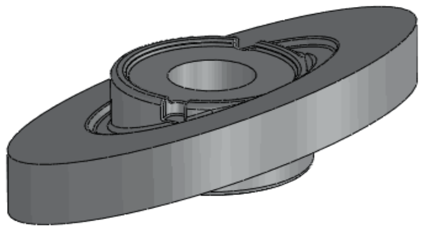
the die work surface was obtained, and the maximum die wear position was pointed out [13, 14].

In this paper, the wear failure of swash plate was analyzed, the forming numerical simulation was carried out and the orthogonal experiment was designed. Influences of the billet initial temperature, die temperature, die hardness, forming rate, and the friction coefficient between the work piece and dies on forming load and die wear were analyzed comprehensively based on the Archard wear model [15, 16]. As a result, relatively reliable optimal processing parameters were obtained, which has a certain guiding significance for the formulation of reasonable forging process and die life prediction.

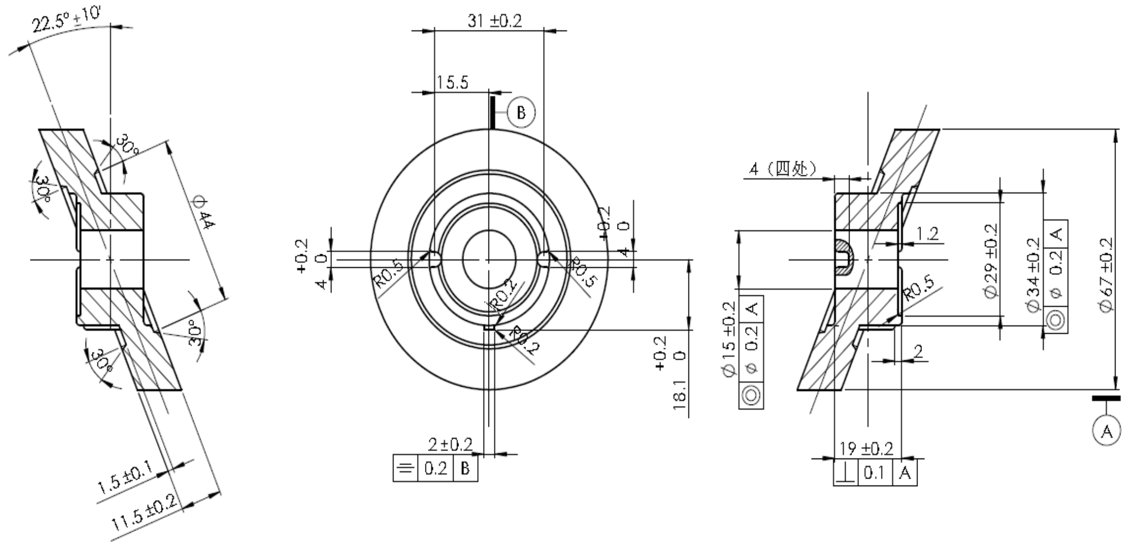
2. Forging process numerical simulation

2.1. Experimental model

Taking a type of swash plate as our experiment object, processing die and billet size were designed according to the actual requirements. The swash plate and die are shown in figure 1. It is made of A390 alloy, which has good wear resistance, corrosion resistance, low coefficient of linear expansion, good thermal conductivity, especially good mechanical properties and good dimensional stability at high temperature. Meanwhile, after modification, the grain size of silicon will be refined, so that the tensile strength, yield strength and plastic properties of the metal will be greatly improved. Therefore, it is suitable for forging process and the part can obtain good mechanical properties [17]. Through the analysis of the characteristics and technical requirements of forging, closed die forging can be used. The Die forging process consisted of the following steps: blanking – heating – forging - grinding burr - T6 heat treatment - surface cleaning.



(a)



(b)

Figure 1. Forging and the geometries of the swash plate. (a) Forging of the swash plate and (b) The geometry of the swash plate.

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2.2. Simulation mechanism

The Archard wear model was adopted to calculate the wear of die cavity in the deformation, and the computational formula of wear was defined as follows:

$$W = \int K \frac{p^a v^b}{H^c} dt \quad (1)$$

where W is wear depth (mm), p is positive pressure inside the mold cavity interface (N), v is relative sliding speed between die and modified material contact point (mm s-1), H is hardness of mold material (HRC), dt is unit time of deformation, while K, a, b, c are mold material constants.

3. Design of multi-objective orthogonal experiment

In the actual production and scientific experiment, the result of experiment cannot be comprehensively evaluated by any single index, so it is particularly meaningful to design the multi-objective experiment [18]. There are two common analysis methods to analyze multi-objective orthogonal experiment, and they are comprehensive balance method and comprehensive evaluation method. In this paper, the comprehensive evaluation method was adopted to solve the problem of the multi-objective orthogonal experiment. This method analyzes the test results and gives each test a score as the total index of it. According to the total index (score), the experimental results of the single index are analyzed and the best test plan is determined. In other words, multiple indexes can be reduced to a single index so as to get the result of multi-index experiment.

3.1. Selection of the experiment factor levels and indicators

In hot forming, the basic forms of die failure are wear, deformation, fracture, fatigue, etc. Deformation and wear are the most common failure forms of the hot forging die. When deformation resistance of the billet exceeds the strength of the die material, plastic deformation will occur. When the wear of die reaches a certain degree, it leads to the die failure [19].

The selections of experiment factors and levels are very important, so main influence factors in the forging should be chosen and the selected level should be in accordance with the actual forming conditions. Combined with practical production experience and practical operability, reasonable processing parameters were selected and listed in table 1. In addition, the billet initial temperature, die temperature, forming rate, die hardness and friction coefficient in the current production process are about 430 ℃, 110 ℃, 11 mm s^{-1}, 52 HRC and 0.4, respectively.

Table 1. Processing parameters/factors

Level number	Factors				
	A Billet initial temperature, ℃	*B* Die temperature, ℃	*C* Forming rate, mm s^{-1}	*D* Die hardness, HRC	*E* Friction coefficient
1	390	80	7	45	0.3
2	420	100	10	50	0.4
3	450	120	13	55	0.6
4	480	140	15	60	0.7

3.2. Results of the orthogonal experiment

Regardless of the interaction among different affecting factors, the L_{16} (4^5) orthogonal table was selected to conduct the experiment for five factors and four levels. DEFORM software was used in the simulation analysis and the forming load and upper die wear can be obtained from it in table 2 [20,21].

First of all, it is necessary to compare and score the experiment index of every experiment number. On the basis that forming and wear indicator are as small as possible, Y_{jmin} represents 100 points, while Y_{jmax} represents 0 points. The formula for calculating Y_{ij} is as follows:

$$Y_{ij} = 100\left(Y_{jmax} - Y_j\right)/(Y_{jmax} - Y_{jmin}) \quad (2)$$

Table 2. Orthogonal experiment results.

Test number	Factors					Target		Compre-hensive weighted
	A	*B*	*C*	*D*	*E*	Forming load *F*, N*10^6	Upper die wear W, mm*10^-5	Y^*
1	1	1	1	1	1	2.01	0.36	43.74
2	1	2	2	2	2	2.01	0.33	48.30
3	1	3	3	3	3	2.02	0.36	42.86
4	1	4	4	4	4	1.93	0.29	61.58
5	2	1	2	3	4	2.03	0.49	16.51
6	2	2	1	4	3	2.26	0.38	22.43
7	2	3	4	1	2	1.62	0.37	67.79
8	2	4	3	2	1	1.61	0.37	68.67
9	3	1	3	4	2	1.73	0.27	78.51
10	3	2	4	3	1	1.53	0.29	89.92
11	3	3	1	2	4	1.81	0.45	39.57
12	3	4	2	1	3	1.68	0.50	39.73
13	4	1	4	2	3	1.70	0.33	68.96
14	4	2	3	1	4	1.69	0.47	44.55
15	4	3	2	4	1	1.61	0.23	95.21
16	4	4	1	3	2	1.72	0.34	65.88
K1	196.48	207.72	171.62	195.81	297.53	The sum of quality targets in each relative level of various factors		
K2	175.40	205.21	199.75	225.50	260.48			
K3	247.72	245.43	234.59	215.19	173.99			
K4	274.61	235.85	288.25	257.72	162.21			
k1	49.12	51.93	42.91	48.95	74.38	The average of quality targets in each relative level of various factors		
k2	43.85	51.30	49.94	56.37	65.12			
k3	61.93	61.36	58.65	53.80	43.50			
k4	68.65	58.96	72.06	64.43	40.55			
R	24.80	10.05	29.16	15.48	33.83	Extreme value		

Thus, the score Y_1 and Y_2 of forming load and die wear can be calculated shown in table 3. Weighted composite score values Y^* can be obtained by the formula:

$$Y_i^* = \alpha_1 Y_{i1} + \alpha_2 Y_{i2} + \cdots + \alpha_j Y_{ij} \quad (3)$$

From this formula, the weight factor coefficient of the test index is expressed by α_j, which represents the weight that each index should take in the comprehensive weighted score. The sum of all index weight factor coefficients is equal to 1, and their determination should be based on analysis of the quality of the part, production efficiency and manufacturing cost, the weight factor coefficient of important test indices should be increased. Based on the actual requirements, the forming load factor coefficient α_1 is 0.5 and the wear weight factor coefficient α_2 is 0.5. At this point, the dual indices have been transformed into a single target index and then Y_i^* can be calculated. In addition, In order to get the influence law of each factor at different levels, we also calculate the sum of quality targets in each relative level of various factors (K_{ij}) and the average of quality targets in each relative level of various factors (k_{ij}) from Y_i^*. Meanwhile, the extreme value (R_i) also can be obtained from k_{ij}.

Table 3. Scores of forming load and wear values.

Test number	Y_1	Y_2
1	34.25	53.23
2	34.25	62.36
3	32.88	52.85
4	45.21	77.95
5	31.51	1.52
6	0	44.87
7	87.67	47.91
8	89.04	48.29
9	72.60	84.41
10	100	79.85
11	61.64	17.49
12	79.45	0
13	76.71	61.22
14	78.08	11.03
15	90.41	100.00
16	73.97	57.79

The performed analysis of tables 2 and 3 provided no obvious evidence of any correlation between the forming load and die wear parameters. Besides, the combinations of five factors at different levels have different influences on load and die wear. However, simply from the experimental results, we cannot directly obtain the curve of the influences of the five factors at different levels of load and die wear. Thus, the experimental results should be further analyzed in more detail.

3.3. Analysis of the orthogonal experiment results

To further analyze the above data, the influence of experimental comprehensive index on the forming load and die wear was drawn as a trend chart [22] (shown in figure 2) on the basis of data of each factor levels in table 2. In table 2, extreme values of each factor were ordered as follows: $R_E > R_C > R_A > R_D > R_B$, which determined the importance of the influence of the various factors on swash plate forming load and die wear [23,24]. The impact degree is ranked as follows in the decreasing order: the coefficient of friction between the work piece and its dies, forming speed, billet initial temperature, die hardness, and die temperature.

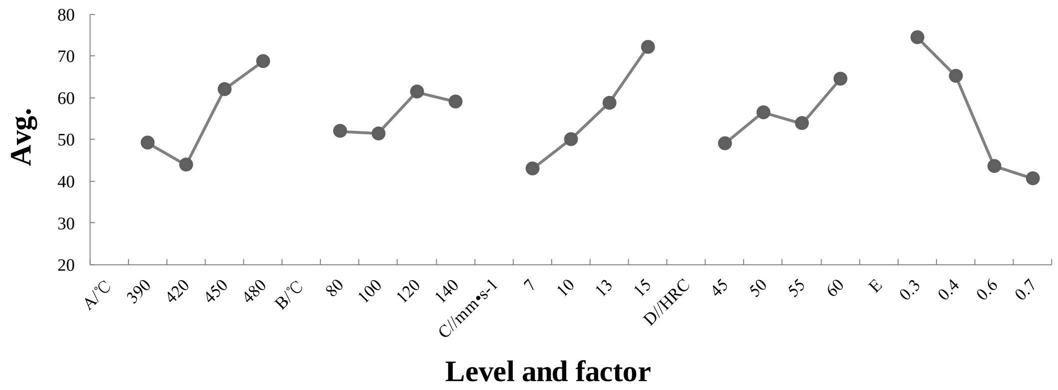
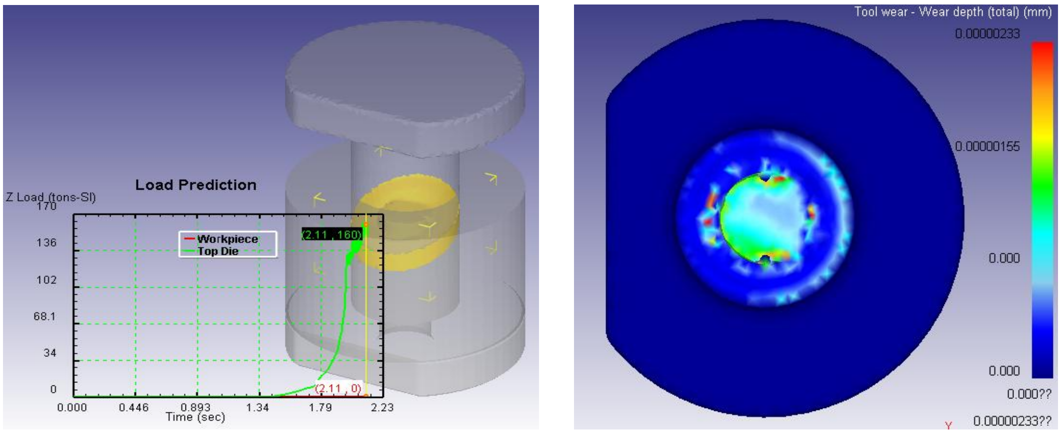


Figure 2. Influence of experiment comprehensive index on the forming load and die wear.

Through the analysis of the results on test No.16 in table 2, the forming load *F* and the die wear *W* in test No. 15 were the smallest, the parameter combination of which was A4B3C2D4E1. Comparing the average of comprehensive indices in each relative level of various factors in table 2, the highest were k14, k23, k34, k44, k51, while the corresponding parameters' combination was A4B3C4D4E1. Thus, DEFORM was used again, yielding the forming load of $1.60*10^6$ N and upper die wear of $2.33*10^4$ mm, as compared to $1.61*10^6$ N and $2.34*10^4$ mm, respectively. It is clear that A4B3C4D4E1 is the best combination of parameters. Therefore. the processing parameters combination was finally selected as billet initial temperature 480 ℃, die temperature 120 ℃, forming speed 15 mm s-1, die hardness 60 HRC and friction coefficient between the work piece and its dies 0.3. The curve of forming load and upper die wear obtained by DEFORM can be seen in figure 3, we can see from that wear easily occurs in the middle circular region. The area of φ29-φ34 can be seen in figure 1 [25-27].



(a) (b)

Figure 3. Simulation results of optimum parameters by DEFORM. (a) The curve of forming load and (b) Upper die wear.

4. Practical application of the optimized parameters

In order to check the optimizing effect of the simulated parameters on the die life, we put the five optimal parameters into practical production and compare the die life of the optimized die with the non-optimized one.

4.1. One test of die wear

Figure 4. A hydraulic press with a die.

Referring to previous die swash plate forgings average life of 8500 pieces, for the first test, we made two same dies in operation in the same machine to produce swash plate forgings which used optimized processing parameters and un-optimized parameters separately. Then the surface states of the two dies were observed when they both finished producing 8000 pieces of forgings. The machine used in this test is hydraulic press, the type of which is LYF-500SA. In the test, the upper and bottom die were put into the hydraulic press simultaneously, as shown in figure 4.

Figure 5 shows the surface states of the two dies after the production of 8000 pieces of forgings. Figure 5(a) is the upper die with un-optimized parameters while figure 5(b) depicts the upper die with the optimized parameters. It is obvious that both dies were worn after the production. By comparison, the die wear of the former is more serious than the latter, indicating that the optimized process can significantly decrease the die wear and prolong the die service lifetime.

(a) (b)

Figure 5. The surface state of the die working for non-optimized processing parameters (a) and optimized ones (b).

4.2. Comparison of die service life

Table 4. The number of actual forgings before the die failure.

Test number	Hydraulic machine	Die label	Number of forgings before die failure
1	LYF-500SA	03001	10523
2	LYF-500SA	03001	9536
3	LYF-500SA	03001	11324
4	LYF-500SA	03001	11230
5	LYF-500SA	03001	9876

However, results of a single test are not reliable enough to draw the conclusions since the two dies do not fail. On the basis of the experience of production and previous die failures, the verticality of the plane based on the datum plane A is 0.1 mm, which is perpendicular to another plane with the length of 19$\pm$0.2 mm (see figure 1). The verticality is very critical because it may affect the stability and assembly of the swash plate. When the wear reaches 0.05 mm, the surface of the die has obvious pits and deformation, it may cause further damage if it continues to use. So just to be on the safe side, the failure of the die is defined when the die wear amount reaches 0.05 mm [28]. Thus, we used the optimal parameters to produce the swash plate forgings for 5 times. Five same dies labeled of 03001 were used in this experiment and detected the dimension of the part online, it is treated as a failure when the round area (φ29-φ34) exceeds 0.05mm from the original ones. Then the number of actual forgings until the dies failed was recorded and tabulated in table 4. By calculation, the average forgings number with a set of the die can produce when the die wear reaches 0.05 mm is 10498, which increased by 23.5%, as compared to the non-optimized average die life of 8500. The above experiments and analysis demonstrate the benefit of the optimized processing parameters and provide a good reference for the real production of swash plates forgings.

5. Conclusions

- Based on the Archard wear model, the curve relationship between the billet initial temperature, die temperature, die hardness, forming rate, friction coefficient and forming load, die wear were obtained through simulation. In addition, the influence of various processing parameters on forming load and wear of die was also investigated, providing certain guidance for the design of die process parameters.
- Through orthogonal experiment, the influence of multi-targets on the swash plate forming force and die wear was comprehensively considered and the optimal processing parameters were obtained as follows: billet initial temperature 480 ℃, die temperature 120 ℃, die hardness 60 HRC and the workpiece/die friction coefficient of 0.3.
- Applying the optimized parameters into practical production, the die wear of the non-optimized one is more serious than the optimized one when the two same dies produce 8000 pieces of swash plates forgings using the same operation machine. Besides, taking five same dies as an experimental object and calculating their die life under the optimized processing parameters, the average die life is 10498 pieces, increased by 23.5%, compared with the un-optimized average die life of 8500 pieces. These results demonstrate that through the multi-objective optimization of the orthogonal test, the die wear can be reduce, greatly improving the die service life.

6. Acknowledgments

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