Optimization of process parameters of GMP for 3D ultrathin glass based on cuckoo search algorithm

Wuyi Ming¹, Haojie Jia¹, Xing Liu¹, Xin Liu², Wenbin He¹, *, Aiyun Wei¹, ², Zhijun Chen¹, ²
¹Henan Key Laboratory of Intelligent Manufacturing of Mechanical Equipment, Zhengzhou University of light Industry, Zhengzhou, China
²Guangdong Huazhong University of Science and Technology Industrial Technology Research Institute, Guangdong Provincial Key Laboratory of Manufacturing Equipment Digitization, Dongguan, China

*Corresponding author e-mail: hwb@zzuli.edu.cn

Abstract: From the current development trend of mobile phone industry, 3D curved glass screen is undoubtedly the hot spot of the industry, and glass molding processing (GMP) is the main method of 3D curved glass manufacturing at present. 3D curved glass is a kind of curved glass which is formed by heating, softening, and annealing process in the mold. In GMP, process parameters not only determine the efficiency and quality of curved glass processing, but also affect the emission of CO2. Moreover, there is no definite mathematical model for the influence of these involved process parameters on the effect of hot bending. In this paper, the GMP experiment of the finished glass is carried out, and the relationship between the processing parameters and the processing quality of the finished glass is summarized. Furthermore, the experimental data is analyzed to investigate the influence of process parameters on performances of GMP. By cuckoo search algorithm method, the parameters of GMP are optimized.

1. Introduction

In recent years, with the rapid development of automobile, communication, electronic technology products and other industries, the demand for 3D glass applications is growing. Curved glass is treated with arc surface in the middle or edge part. After forming process, the arc surface can fit the palm more closely and conform to the human retinal arc, so as to bring better visual experience for users. 3D curved glass has the advantages of clean and transparent, light and thin, antiglare, anti-fingerprint, scratch resistance and good weather resistance, etc. It can not only bring new appearance and excellent touch feeling to electronic products, but also solve the problem of insufficient wire layout space and enhance the signal receiving function. Therefore, the development of 3D curved glass may become the research focus in the future optical field.

However, the traditional optical glass lens processing is formed by grinding and polishing, which is time-consuming and labor-consuming, and cannot meet the growing market demand at present. And the new glass molding process (GMP) technology has been widely used for its high forming accuracy, short material flow distance and low equipment cost [1]. The surface quality and micro size accuracy of curved glass processed by GMP will be affected by the process parameters, among which the temperature has a great influence on performances. At present, the most commonly used heating
method is to use electric heating tube. In order to obtain good surface quality, surface dimensional
accuracy and optical properties, high requirements are needed for the GMP technology.

Cuckoo search (CS), is inspired by cuckoo's egg laying behavior and flying characteristics of birds
in nature. This algorithm has the advantages of strong optimization ability, easy implementation, easy
operation and few parameters, so it is widely used in optimization problems in engineering. Yang [2]
and others [3] proposed a multi-objective cuckoo search algorithm, and used a set of multi-objective
test functions to verify it. Moreover, CS was applied to structural design optimization problems, and it
was found that compared with other algorithms, CS performed well in almost all these test problems.
The advantage can be attributed to the combination of vectorization variation, displacement crossover,
Levy flight and selective elitism. In the practical engineering problems, the problem of multi-objective
optimization was often encountered.

2. Basic principle of CS

CS algorithm was originally designed to deal with single-objective optimization problems. In order
to solve multi-objective problems and provide a good Pareto leading edge approximation, it can be
applied to a more general framework. Yang [4] assumes that the cuckoo search algorithm has three
steps as follows:

(1) Each cuckoo lays one egg at a time and randomly places the egg in the nest;
(2) Nest with the best eggs (solution) will go to the next iteration;
(3) The number of hosts is pre-determined. The probability of host bird finding the intruder's egg is pa \in [0,1]. If host bird finds a strange egg, it will leave its nest and rebuild in a new place. The
calculation for the location and path of cuckoo's nest is as follows [5]:

\[ x_i(t+1) = x_i(t) + \alpha \otimes L(S, \lambda) \]  
\[ L(s, \lambda) = \frac{\lambda}{\pi} \sin \left( \frac{\pi s}{2(1 + s\lambda)} \right) \]

where, \(X_i(t)\) denote the position of the i-th nest at the time of iteration t, the step factor \(\alpha > 0\) is used to
control the step, and its value follows the normal distribution. After position update by Equation (1),
random number \(r (r \in [0,1])\) is generated. If \(r > Pa\), the nest position will be updated at  randomly,
otherwise the nest position will not change.

3. Experiment and the influence of process parameters.

3.1 Experimental equipment

The machine of GMP, used in this experiment, is a multi-workstations machine, and the mold is
made of graphite. The physical equipment is shown in Figure 1.

(a) Overview of GMP           (b) The hot furnace

Figure 1. Experiment equipment of GMP

3.2 Parameter settings and experimental results

In this experiment, L-BAL42 glass was used as the experimental sample, and the orthogonal
experimental method was adopted [6]. Heating temperature (\(T_0\)), pressure of first bending step (\(P_1\)),
temperature of first bending step (\(T_1\)), pressure of second bending step (\(P_2\)), temperature of second
bending step (\(T_2\)), pressure of final bending step (\(P_3\)) and lasting time of final bending step (\(t\)) were
selected as experimental parameters, and cycle time (\(CT\)) and the emission of CO2 (EOC) were used
as the experimental performance indexes to evaluate the influence of the experimental parameters.
The influence of each parameter on the molding process effect is analyzed. The setting values and
experimental results of the experimental parameters are shown in Table 1.

| Numble | $T_0$ (°C) | $P_1$ (MPa) | $T_1$ (°C) | $P_2$ (MPa) | $T_2$ (°C) | $P_3$ (MPa) | t (s) | CT (s/pcs) | EOC (g/pcs) |
|--------|------------|-------------|------------|------------|------------|------------|-------|-----------|-------------|
| 1      | 800        | 0.35        | 789        | 0.35       | 769        | 0.45       | 55    | 91.7      | 1850.6      |
| 2      | 800        | 0.35        | 792        | 0.4        | 772        | 0.5        | 58    | 89.2      | 1797.5      |
| 3      | 800        | 0.35        | 795        | 0.45       | 775        | 0.55       | 61    | 87.1      | 1752.2      |
| 4      | 800        | 0.35        | 798        | 0.5        | 778        | 0.6        | 64    | 256.0     | 5139.3      |
| 5      | 800        | 0.4         | 789        | 0.35       | 772        | 0.5        | 61    | 122.0     | 2454.0      |
| 6      | 800        | 0.4         | 792        | 0.4        | 769        | 0.45       | 64    | 85.3      | 1704.4      |
| 7      | 800        | 0.4         | 795        | 0.45       | 778        | 0.6        | 55    | 110.0     | 2231.8      |
| 8      | 800        | 0.4         | 798        | 0.5        | 775        | 0.55       | 58    | 116.0     | 2335.7      |
| 9      | 800        | 0.45        | 789        | 0.4        | 775        | 0.6        | 55    | 110.0     | 2232.7      |
| 10     | 800        | 0.45        | 792        | 0.35       | 778        | 0.55       | 58    | 92.1      | 1864.6      |
| 11     | 800        | 0.45        | 795        | 0.5        | 769        | 0.5        | 61    | 122.0     | 2439.7      |
| 12     | 800        | 0.45        | 798        | 0.45       | 772        | 0.45       | 64    | 85.3      | 1703.8      |
| 13     | 800        | 0.5         | 789        | 0.4        | 778        | 0.55       | 61    | 244.0     | 4934.8      |
| 14     | 800        | 0.5         | 792        | 0.35       | 775        | 0.6        | 64    | 101.6     | 2040.2      |
| 15     | 800        | 0.5         | 795        | 0.5        | 772        | 0.45       | 55    | 144.7     | 2920.7      |
| 16     | 800        | 0.5         | 798        | 0.45       | 769        | 0.5        | 58    | 92.1      | 1843.7      |
| 17     | 810        | 0.35        | 789        | 0.5        | 769        | 0.6        | 58    | 116.0     | 2354.4      |
| 18     | 810        | 0.35        | 792        | 0.45       | 772        | 0.55       | 55    | 110.0     | 2242.6      |
| 19     | 810        | 0.35        | 795        | 0.4        | 775        | 0.5        | 64    | 168.4     | 3406.7      |
| 20     | 810        | 0.35        | 798        | 0.35       | 778        | 0.45       | 61    | 244.0     | 4954.6      |
| 21     | 810        | 0.4         | 789        | 0.5        | 772        | 0.55       | 64    | 168.4     | 3408.2      |
| 22     | 810        | 0.4         | 792        | 0.45       | 769        | 0.6        | 61    | 244.0     | 4929.9      |
| 23     | 810        | 0.4         | 795        | 0.4        | 778        | 0.45       | 58    | 232.0     | 4732.2      |
| 24     | 810        | 0.4         | 798        | 0.35       | 775        | 0.5        | 55    | 144.7     | 2949.5      |
| 25     | 810        | 0.45        | 789        | 0.45       | 775        | 0.45       | 58    | 116.0     | 2367.0      |
| 26     | 810        | 0.45        | 792        | 0.5        | 778        | 0.5        | 55    | 220.0     | 4509.2      |
| 27     | 810        | 0.45        | 795        | 0.35       | 769        | 0.55       | 64    | 168.4     | 3388.2      |
| 28     | 810        | 0.45        | 798        | 0.4        | 772        | 0.6        | 61    | 160.5     | 3242.0      |
| 29     | 810        | 0.5         | 789        | 0.45       | 778        | 0.5        | 64    | 128.0     | 2604.2      |
| 30     | 810        | 0.5         | 792        | 0.5        | 775        | 0.45       | 61    | 160.5     | 3260.9      |
| 31     | 810        | 0.5         | 795        | 0.35       | 772        | 0.6        | 58    | 152.6     | 3096.6      |
| 32     | 810        | 0.5         | 798        | 0.4        | 769        | 0.55       | 55    | 550.0     | 11148.0     |

3.3 Analysis of experimental results

In this section, Minitab 17 software is used to analyze the experimental data of each group, and the main effect diagrams (as shown in Figure 2) of the influence of seven hot bending process parameters on the results of glass molding process (CT and EOC) are obtained.
Figure 2 (a) shows the main effect of process parameters on CT. When $T_0$ is 810 $^\circ$C, the correlation between $T_0$ and the mean peak value of CT is desired. Furthermore, when $P_1$, $P_2$, $P_3$, $T_1$, $T_2$, and $t$ have stronger correlation with the peak average value of CT, their values are 0.5MPa, 0.4MPa, 0.55MPa, 798 $^\circ$C, 778 $^\circ$C, and 55s, respectively. That is to say, the cycle time of GMP is the lowest at this time.

Figure 2 (b) shows the main effect of process parameters on EOC. It can be seen from Fig.2 that when the value of $T_0$ is 800 $^\circ$C, the correlation between $T_0$ and the trough average value of EOC is desired. That is to say, the CO$_2$ emitted by the hot bending test is at the lowest value. Moreover, when $P_1$, $P_2$, $P_3$, $T_1$, $T_2$, and $t$ have stronger correlation with the trough average value of EOC, their values are 0.45MPa, 0.45MPa, 0.5MPa, 789 $^\circ$C, 775 $^\circ$C, and 58s, respectively.

4. Optimization of process parameters

4.1 Prepare for optimization of process parameters

The process parameters in Table 1 should be transformed to [-5, 5] by using the transformation function [7]. Then, a response surface method based on Minitab17 software is used to regress and fit the regression models between process parameters and response performances. The regression models of CT and EOC are obtained by Equations (3) and (4).

$$Y_1= 157.28 + 7.09X_1 + 16.23X_2 + 0.41X_3 + 20.41X_4 + 1.89X_5 -13.85X_6 + 0.32X_7 + 0.587X_1X_2 + 3.63X_1X_3 + 0.907X_1X_4 -2.81X_1X_5 + 0.339X_1X_6 -1.69X_2X_4 + 3.25X_2X_5 + 2.1X_3X_6 + 4.06X_4X_6$$

(3)

$$Y_2= 2907 + 145.9X_1 + 251X_2 + 54.1X_3 -1.9X_4 + 13.1X_5 + 54.0X_6 - 46.9X_7 - 18.9X_1X_7 - 33.2X_2X_7 + 56.1X_3X_7 - 17.1X_4X_7 - 8.40X_1X_2X_7 + 14.86X_2X_3X_7 + 6.2X_4X_6X_7$$

(4)

Where, $Y_1$ and $Y_2$ represent CT and EOC; $X_1, X_2, X_3, X_4, X_5, X_6$ and $X_7$ represent the above seven process parameters respectively.

According to Equation 3 and 4, the average error between CT fitting value and actual value is 19.86%, and that between EOC fitting value and actual value is 24.49%. It can be seen that the error of CT is relatively small, while that of EOC is relatively large, but the average error is still within the acceptable range, except for the maximum error, the other errors are within the acceptable range and the average error is not more than 25%.

4.2 Using cuckoo search algorithm to optimize the process parameters

In GMP, there is an inevitable conflict between the quality characteristics and energy consumption of products. High quality products need to be obtained at the cost of high energy consumption. CS algorithm has excellent ability in finding Pareto optimal solution because of its few parameters and high speed. In this subsection, CS algorithm is used to optimize process parameters. Considering that the optimization range of cuckoo search is limited, the parameters are transformed before fitting the function relationship, so it is necessary to reverse the parameters, and the results are shown in Table 2.
Table 2. Optimized parameters for single-objective optimization

| Experimental index | T0 (℃) | P1 (MPa) | T1 (℃) | P2 (MPa) | T2 (℃) | P3 (MPa) | t (s) |
|-------------------|--------|----------|--------|----------|--------|----------|-------|
| CT                | 805.293 | 0.489054 | 796.14 | 0.371979 | 776.573 | 0.59495  | 60.766 |
| EOC               | 801.220 | 0.361347 | 789.54 | 0.418781 | 772.872 | 0.59342  | 60.418 |

Finally, the results of CS algorithm optimization method are compared with the original scheme. It can be found that the optimization values of EOC and CT are 931.76 g/pcs and 55 s/pcs, respectively. In general, the EOC is in line with the trend of process parameters optimization of experimental results, while the experimental results of CT and the optimized values may have deviation due to the artificial restriction of the optimization range of cuckoo search, but they are also within the predicted range.

Moreover, the two experimental parameters CT and EOC are optimized by the method of weights, and the weight of two objectives are 0.5. The new optimization function is obtained by multiplying the two single objective functions by the weight coefficient of 0.5 and summing them up. The multi-objective optimization effect can be achieved by incorporating the function into the cuckoo search program for optimization. The new optimization function obtained by the combination is Equation (5), where the expressions of \( Y_1 \) and \( Y_2 \) are Equation (3) and (4).

\[
Y = 0.5Y_1 + 0.5Y_2
\]  

In the multi-objective optimization, considering the accuracy of the fitting equation and the negative direction without practical significance, referring to the range of experimental results and the above single-objective optimization value, the range of comprehensive optimization is limited. Finally, each independent variable value of the multi-objective optimization result is calculated, and the result of the multi-objective optimization is shown in Table 3.

Table 3. Optimized parameters for multi-objective optimization

| T0 (℃) | P1 (MPa) | T1 (℃) | P2 (MPa) | T2 (℃) | P3 (MPa) | t (s) | CT (s/pcs) | EOC (g/pcs) |
|--------|----------|--------|----------|--------|----------|-------|------------|-------------|
| 800.04 | 0.3968   | 794    | 0.4565   | 769    | 0.4718   | 58    | 55         | 932.01      |

It can be seen from Table 3 that when T0 is 800.04 ℃, T1 is 794 ℃, T2 is 769 ℃, P1 is 0.3968MPa, P2 is 0.4565MPa, P3 is 0.4718MPa, and t is 58s, the CT and EOC can reach the optimal value at the same time (CT: 54s/pcs, EOC: 938.01g/pcs). Compared with the above two single-objective optimization values, it is not difficult to find that by properly adjusting the combination of process parameters, the optimization values of multi-objective optimization evaluation indexes can be close to the single-objective optimization values.

5. Conclusion

This study presents that experimental investigation of sustainable performance on precision 3D ultra-thin glass molding process, and orthogonal test and CS multi-objective process optimization are used for data analysis. The main conclusions are as follows:

1) In this experiment, seven process parameters in the forming process are taken as the variable factors, selects CT and EOC are taken as the evaluation indexes of the experimental results. It is found that the process parameters, such as molding temperatures and pressures, have an important influence on the cycle time and carbon emission.

2) The mapping relationship between experimental factors and response targets is molded, and the main effect diagram of experimental results is drawn. It is found that the relative error of CT is 19.86%, while that of EOC is 24.49%.

3) According to the single-optimization results of CS algorithm, the optimization values of EOC and CT are 931.76 g/pcs and 55s/pcs respectively. Moreover, the multi-optimization results of EOC and CT are 938.01 g/pcs and 54 s/pcs, and it close to the single-objective optimization values.
6. Acknowledgements

This research is supported by the Local Innovative and Research Teams Project of Guangdong Pearl River Talents Program (2017BT01G167), the Natural Science Foundation of Guangdong Province (2018A030313679) and the 2018 Henan Provincial Natural Science Foundation of China (182300410170, 182300410215).

References

[1] J H Hong. Finite Element Analysis of (Micro) Hot Press Forming of Optical Glass(II)[J]. 2005.
[2] X S Yang, S Deb. Multi-objective cuckoo search for design optimization[M]. Elsevier Science Ltd, 2013.
[3] H Jiang, Q Ruan. Based on variable scale method and adaptive step size cuckoo search algorithm[J]. Computer Technology and Development, 10(2015)38-43.
[4] X S Yang, S Deb. Cuckoo search via levy flight[C]//Proceedings of World Congress on Nature & Biologically Inspired Computing. India, Washington: IEEE Publications, 2009: 210-214.
[5] X F Zhang, X Y Wang. A review of cuckoo search algorithms[J]. Computer Engineering and Applications, 2018, 54(18).
[6] X J Wang. Application and analysis of orthogonal experiment design[J]. Journal of Lanzhou University of Arts and Science, 30(2016)17-22.
[7] Z Zhou, Y J Zhu. Multi-objective tolerance design based on cuckoo search algorithm[J]. Aeronautical Science & Technology, 30(2019)29-35.