Numerical Simulation and Intelligent Optimization of Wax Injection in Investment Casting

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Abstract. Material property measurement was conducted in this study that can be used as input in Moldflow. The optimization scheme is simulated and actual experimented. The optimized process parameters is obtained by CAE and the response surface model. The packing time and packing pressure have the most significant effect on the average shrinkage of thin-walled wax pattern, followed by mold temperature and injection temperature. The deformation dimension of the wax pattern has been significantly improved.

1. Introduction
Because of the advantages of high dimensional precision and complex geometric in investment casting, it is especially suitable for casting expensive metal and hardworking metal components. Investment casting has the characteristics of long technological process and complex influencing factors. Mold manufacturing, wax pattern assembly, shell preparation and roasting, alloy casting, welding and heat treatment, involve thousands of process parameters. The process parameters contained in each process will affect the casting dimensional error. Wax injection is an important reason why the dimensional accuracy of large castings is difficult to control. Overall, the dimension fluctuation of wax pattern accounts for 10\%–70\% of casting dimension fluctuation. In order to reduce the cost of mold rework and reduce the size fluctuation of castings, Control wax pattern accuracy is very important. Therefore, to study the deformation law and mechanism of wax injection process, Control the dimensional accuracy of wax pattern, it is the theoretical basis of net near-shape casting technology [1].

The shrinkage of wax pattern is affected by many factors, such as geometric parameters, material performance parameters and process parameters, in which the injection process parameters directly affect the state of melt in the mold and the dimensional accuracy of the final wax pattern. Obtaining the optimized process parameters is the premise of high dimensional accuracy. Numerical simulation technology can assist process engineer to optimize process. Most investigators are concerned mainly with engineering properties, such as strength and volumetric expansion [2]. These data are excellent information on how well injected patterns will survive handling during the preparation, melting,
conditioning, and injection phases, but are of little use in determine wax flow behavior and wax pattern deformation. Gebelin has fully characterized the rheology of wax with Carreau model and Second-Order model for the purpose of modelling its injection process for the investment casting process [3]. Sadegh tried to get wax injection parameters by used CAE simulation software which used a similar wax data provided by Moldflow database [4]. Zhang et al. using Moldflow simulate a wax pattern with different gate configurations to optimize the injection modelling product design [5]. In recent years, researchers have used a variety of methods to study process optimization, such as traditional optimization techniques, genetic algorithms, and neural networks and so on. The nonlinear and multivariable characteristics of injection make it very difficult to set up the process. By using DOE technology, the influence of process parameters on the shrinkage of thin wall size of wax mold is studied and the process parameters are optimized.

2. Material properties
Wax for investment casting is a complex mixture of synthetic waxes, natural or synthetic resins, solid organic fillers and water, and additives such as plastics, oils and plasticizers [6]. Its components have their own uses, such as resin addition can increase the strength of wax, and the addition of filler can enhance the shrinkage of wax. Because of the existence of these additives, the wax for investment casting shows complex mechanical and thermal performance. As the basic properties of the polymer, the PVT (pressure-specific volume-temperature relationship of the polymer describes the change of the specific volume of the polymer with the change of temperature and pressure. It is the main basis for the flow analysis, injection molding process control and process analysis of the product injection molding. The equation PVT state of polymer is also used to describe the PVT relationship of polymer, which provides calculation formula and theoretical basis for injection molding simulation and control of polymer. The modified two-domain Tait equation of state is the most commonly used equation of state in the field of injection molding to describe the relationship PVT polymers, which plays a very important role in polymer correlation calculation. KC3898NRR is a filled wax, which was manufactured by Paramelt. The measured PVT data of the wax is shown in Figure 1.

![Figure1. PVT results for the wax KC3898NRR](image)

3. Numerical simulation and process optimization
The filling time of ring standard parts is shown in Figure 2, and the simulated warping results are shown in Figure 3. Figure 2 shows that the gate is arranged in the middle position of the outer ring of the ring standard part and the supporting plate. It is found that with the continuous pouring of wax, the joint between the support plate and the outer ring is first filled. According to Figure 3, the maximum deformation position of the ring wax mold is located at the edge of the outer ring and the inner ring, and the maximum deformation is 1.270mm.

Parameter optimization based on Taguchi experiments is to find points with optimal values in these discrete points, the best combination of factors can’t be guaranteed to be the combination point of process parameters in the whole mapping space. To solve this problem, an approximate mathematical model can be used to replace CAE simulation into the optimization process, such as the response
response surface method (RSM) is to select an appropriate, expressive function to approximately replace the relation or function that can’t be clearly expressed. That is, fitting a response surface to replace the unknown, true limit state surface by a series of numerical calculations, further combining the optimization algorithm, find more accurate optimal solutions. Therefore, this paper chooses the response surface method, using a simple numerical model to replace the complex wax injection process, to reduce the computational cost of the optimization algorithm, increase the speed of calculation, so that it can meet the requirements of dimensional accuracy control. Box-Behnken experimental design is another experimental design method that can evaluate the nonlinear relationship between indicators and factors.

According to the design principle of the central combination test of the Box-Behnken and the results of the single factor, five factors, such as melt temperature, mold temperature, injection rate, pressure holding pressure and pressure holding time, were selected. On the basis of the single factor test, the five factors and three horizontal response surface analysis method was adopted. This experiment takes the above parameters as the main investigation factors (independent variables), expressed as A, B, C, D and E, respectively. Analysis factors and horizontal design are shown in Table 1.

Table. 1 Factors and levels of response surface analysis

| Level | Factor | Level | Factor |
|-------|--------|-------|--------|
|       | A      | Injection temperature (°C) | B      | Injection temperature (°C) |
|       | C      | Injection velocity (cm³/s) | D      | Packing pressure (bar) |
|       | E      | Packing time (s) |
| -1    | 68     | 25    | 100    | 8       | 5       |
| 0     | 70     | 30    | 150    | 12      | 10      |
| 1     | 72     | 35    | 200    | 16      | 15      |

The P values in the ANOVA are usually used to analyze whether the factors have a significant effect on the output and whether the fitting degree of the model is good. If the fitting degree of a model or the P value of a factor is less than 0.05, it can be considered that the model fits well, or this factor is the key factor that has an important influence on the final output. And the smaller the P value, the better the model fitting or the more critical the influence of this factor. The closer the correlation coefficient is to 1, the better the correlation between the predicted value of the model and the experimental value. R² of this study is 0.9550, indicating that the model can describe the experimental results well. The significance test of regression coefficient shows that the BD, CD, DE of the interaction term in E², square term is a significant factor. Among the influencing factors, the pressure holding time and pressure holding pressure are the largest, followed by die temperature and melt temperature. Among the total factors, the influence of primary term and square term is greater, but the influence of interaction term is relatively small. Among them, mold temperature and pressure holding pressure, injection rate and pressure holding pressure, pressure holding pressure and pressure holding time have interaction. According to the results of regression analysis, the corresponding surface
diagram is calculated, as shown in Figure 4. The best parameters and the interaction between the parameters can be found from the response surface analysis diagram. The interaction diagram intuitively reflects the influence of two factors with interaction on the response value. Compared with the four groups of interaction diagrams, the effect of pressure holding time and pressure holding pressure on the average shrinkage rate is the most significant, which is characterized by steep curve, followed by die temperature and injection temperature. The injection rate and melt temperature showed that the curve was smooth, and the response value changed little with the increase or decrease of the value.

![Figure 4. (a) Interaction of mold temperature and injection temperature; (b) Interaction of packing pressure and packing time.](image)

The optimized average shrinkage target value is 0.1%, showing that the number of optimized tests is 41, the optimized process parameters are melt temperature 69.92 °C, die temperature 26.08 °C, injection rate 101.01 cm³/s, holding pressure 16 bar, holding time 5.06 and shrinkage 0.062. It can be seen that the optimized response surface model finds the optimal process parameters well, and the dimension shrinkage of the wax mold is reduced by an order of magnitude.

4. Conclusions

The characteristics of melt compressible PVT of wax were obtained. The shrinkage and deformation trend of wax mold is predicted by using numerical simulation, and the shrinkage law and mechanism of wax mold are revealed. From the RSM agent model of process parameters and wall thickness shrinkage, it can be seen that the pressure holding time and pressure holding pressure have the most significant effect on the average shrinkage of thin-walled wax mold, followed by die temperature and injection temperature. The injection rate and melt temperature show smooth curve. The effective numerical method provides a reliable and scientific guidance for the casting production process.

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