DESIGN OF THERMAL ENVIRONMENT IN PLASTIC INJECTION MOLD BASED ON EVALUATION OF RESIN COOLING UNIFORMITY

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Abstract

Thermal state in plastic injection molds greatly influences the molding quality of products. This paper discusses the optimum design of thermal environment in the molds by observing and estimating the cooling uniformity of resin. Numerical analysis based on unsteady heat transfer is conducted to confirm the utility of the proposed evaluation method, and case studies show the comparison results of resin deformations under different cooling systems conditions and the improved designs.

Introduction

In current molding technology, many methods have been used for describing the heat state in an injection mold. These methods include measuring the deformation of the product, watching the physical appearance, or testing the temperature of assigned positions inside a mold through a sensor system. These methods, however, takes into account factors like resin properties and molding conditions but cannot completely describe the mold heat state, finally results in the problems of heat related design failures to affect formability. In this paper, first, an integrated concept, the thermal environment is defined to describe the heat state and its variations in plastic injection mold. Next, by observing the resin cooling uniformity, an evaluation function is given for evaluating the cooling system and realizing the automatic design. By arranging cooling system, a design procedure of thermal environment is provided. Finally, by using the proposed procedure, a numerical analysis example, which has a Cu-Be alloy constructed cooling system, is given to show the process of how to realize the automatic design of cooling system and build an ideal thermal environment in a mold.

Thermal Environment in Plastic Injection Mold

Heating and cooling is the basic means which is used to change the state of resin in injection molding, how to recognize, evaluate and arrange the heat in a mold, will be the most important issue for improving the performance during molding process. In this section, thermal environment is defined to describe the heat state and the variations in plastic injection mold, also, the relationship of thermal environment to products, molding process, and cooling systems is discussed.

Concept of Thermal Environment

In injection mold, the molten resin in cavity finishes its solidification under a thermal condition provided by the surrounding mold material. This structured a space, in which the heat exchange is achieved in a certain form and velocity that determined by the spatial temperature potential and material thermal conductivity. To describe this, a new concept, thermal environment, is installed in this research. The definition is given as: in the entire

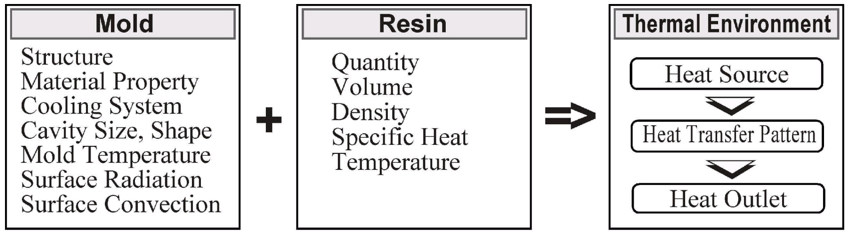

Figure 1: Concept of thermal environment in an injection mold

space of injection mold, the heat quantity distribution and its transfer behaviors, which are determined by the thermal properties and spatial components of the resin and mold, is called thermal environment of injection mold.

Thermal environment of an injection mold includes three basic elements, heat source, heat outlet and heat transfer pattern. Heat source is the resin material, which is injected into the mold cavity with a plenty of heat by the injection machine. Sometimes, heaters are used in mold, they can be a part of heat source. Heat outlet includes all components that can take the heat out form the mold, usually, it refers to the cooling system of the mold. Both heat source and heat outlet have their thermal properties and spatial properties, such as material thermal conductivity, layout and etc. Heat transfer pattern includes heat flow direction, transfer velocity, and all transfer rules between the heat source and outlet. Figure 1 shows the concept of the thermal environment in an injection mold.

The concept of thermal environment provided a new method of handling the heat in an injection mold. It is integrated expression of the thermal results of influencing factors in injection mold, it takes the advantages as: a) it is a unified concept that can directly describe the thermal property in an injection mold, which can instead of some vague way such as mold temperature, b) it separates the heat performance design of an injection mold form concrete cooling means, make the evaluation and management become clearly and easy. c) it improved the versatility of design rules to apply in different design cases.

Thermal Environment and Molding Molding Process

Figure2 shows the relationship and position of thermal environment in all molding process items. These molding process items can be roughly divided into three categories: resin properties, molding conditions, and mold design and process scheduling, thermal environment is an integration of these items. Each item keeps the action and reaction relationship with the thermal environment, and most items are affected each other through the thermal environment, those affections will finally result in the reflection of product molding quality.

Injection molding is a very complicated process, is difficult to find a simple corresponding relationship for a certain factor to formability of the products. The concept of thermal environment can be an integrated description of those factors form the viewpoint of heat, it is relative easy to find how a certain factor to affect the thermal environment, then to observe the affection of thermal environment to the molding quality. On the other hand, when try to improve the product formality, can realize it by first improving the thermal environment, not directly access a certain design factor. In Figure2, the path circled by bold lines shows the conception of how a cooling system in an injection mold affects the thermal environment, and then change the resin shrinkage, and finally affect the molding product quality.

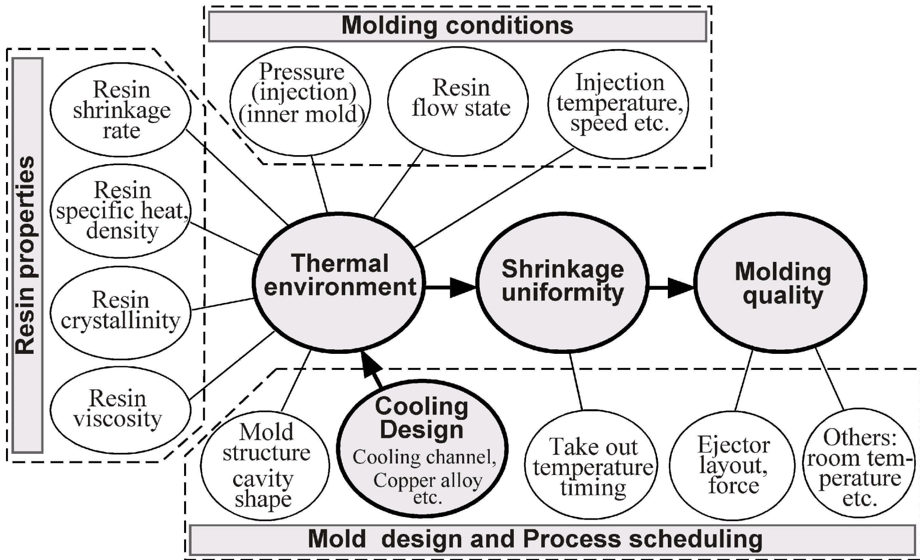

Figure 2: Thermal environment and molding process

Resin Cooling Uniformity based Thermal Environment Design

Among the three basic elements of the thermal environment, the heat outlet is the most accessible one by arranging cooling system in mold. In this research, thermal environment design is realized by properly arranging the cooling system layout based on resin cooling uniformity.

Resin Deformation and Cooling Uniformity

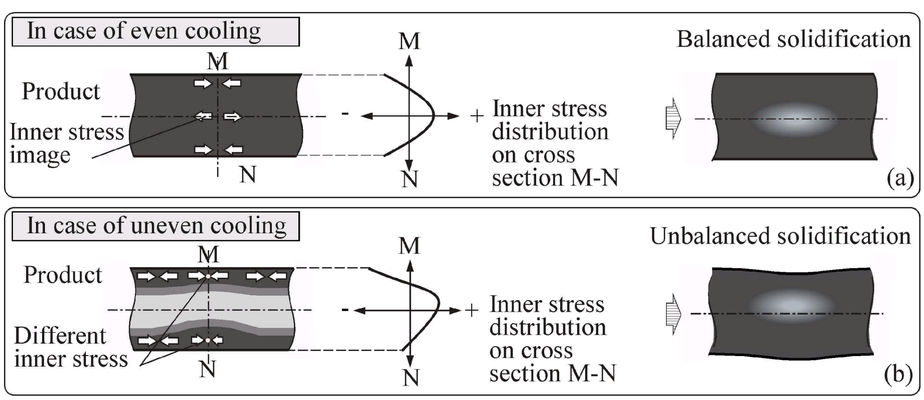

Figure 3: Residual stree and deformation

Heat transfer velocity is an essential factor to the resin solidification. In general, plastic molding parts are shell shape structure with a relative thin wall thickness, in this case, if the heat transfer conditions of the both side of resin wall are the same, inner stress distribution will be symmetrical to the center line of the resin wall (Figure 3, (a)). However, this state is not always can be realized, thermal environment determines the heat transfer patterns in every location near the mold cavity. if there is a difference exists between the two sides of the resin wall, unbalance inner stress distribution will occur, this will cause a bending moment in the thickness direction, and result in a deformation if the bending moment is bigger enough (Figure 3, (b)).

In current mold design, Interpretations and judgments of resin cooling uniformity are quite different by cases. some technicians used the nearby areas temperatures of mold cavity to evaluate, some directly observing the appearance or deformation degree of products. Despite of those differences, actually, resin cooling uniformity is an evaluation of the thermal environment, because it is a description of the result of the thermal environment.

However a clear definition and evaluation standard for the cooling uniformity is necessary. when the resin holding heat transfers to mold, the surface where the resin contacts the mold cavity is very important. The temperature distribution and variations on this surface will determine the solidification and shrinkage behaviors of the molten resin form surface to inner part. During resin cooling process, if the temperature on every part of resin surface can drop keeping the same level, that is, keep a uniform temperature distribution, the resin is regard as on an even cooing state. However, this is an ideal situation, in most cases, temperature on resin surface varies with the cooling time, the degree of an even cooling is called the cooling uniformity in this research.

Evaluation of Resin Cooling Uniformity

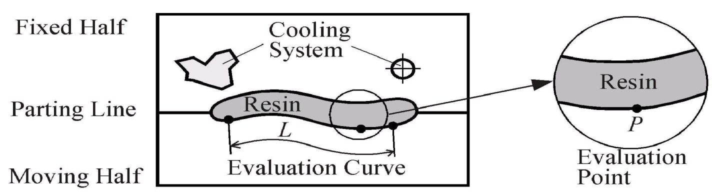

Figure 4: Evaluation model for cooling uniformity

Figure 4 shows a two-dimension evaluation model used in this research. There is a cavity space for an equal wall thickness molding parts in the mold area, molten resin is filled into this space. Surrounding the resin area, cooling system is arranged, which may in different forms such as cooling channels or high thermal conductivity materials. In this model, choosing an arbitrary point as an evaluation point P in the surface. Then, including all the evaluation points, choose a curve in a certain range, which is called evaluation curve L. based on the temperature value of every evaluation points on evaluation curve. the dispersion can be calculated to evaluate the resin cooling uniformity. The length of evaluation curve can be chosen according to the mold design specifications,

Based on two-dimension unsteady state heat transfer, the evaluation function of resin cooling uniformity is defined as follow:

At first, calculating the temperature error. for a certain evaluation point P, which is located on evaluation curve L at a moment τ during the cooling process. the temperature error is give by equation 1.

$$e_P = T_P - \frac{1}{L}\int_0^L T(l)dl \tag{1}$$

where, T_p is the temperature of evaluation point P, L is the length of evaluation curve, $T(l)$ is the temperature function of variable l on the curve of L at the moment τ, dl is a small distance on l. Actually, the second part of equation 1 is the average temperature on the evaluation curve at the cooling moment τ. Next, calculating the dispersion of temperature distribution on the evaluation curve at a certain moment τ during the resin cooling. The dispersion defined as the value of E, which is a integration of the squares of temperature errors $e_p(l)$ to all evaluation points along the evaluation curve, this is shown in equation 2.

$$E = \frac{1}{L} \int_0^L e_P^2(l) dl \tag{2}$$

E is the dispersion of temperature errors at a certain cooling moment τ. for the whole cooling process, take a integration as $E(\tau)$ from the beginning of cooling to the mold open, the evaluation function F can be defined as equation 3, which is including the cooling time factor.

$$F = \frac{1}{\tau_c} \int_{\tau_0}^{\tau_c} E^2(\tau) d\tau \tag{3}$$

Where, τ_0 is the start time of resin cooling, τ_c is the ending of resin cooling. $d\tau$ is a short time period. Equation 3 gives a total description of mold cooling state, which considers both the spatial factors and the temporal factors in the whole cooling process. From a given cooling system in mold, a small the evaluation value means an even cooling state of the resin.

Design of Thermal Environment

By properly arranging cooling system, thermal environment can be designed to realize the high formability of resin products. Based on evaluation function defined in equation 3, it is possible to choose an improving cooing system design or doing the cooling system automatic arrangement.

In practical molding design, evaluating and choosing a better design form possible cooling system types or arranging layouts is often occurred problem. Considering the resin cooling uniformity, the system can be decided by following equation:

$$F_{select} = min(F(Sys_1), F(Sys_2), \ldots, F(Sys_n)) \tag{4}$$

Where, $F(Sys_1), F(Sys_2), \ldots,$ and $F(Sys_n)$ are the evaluation values that gained from equation 3 correspond the possible cooling systems $Sys_1, Sys_2, \ldots,$ and Sys_n. F_{select} is the minimum among those values, the cooling system which correspond $F_(select)$ is selected as the best one the can create a thermal environment for resin even cooling.

Also, by using evaluation function defined in equation 3, it is possible to realize the automatic design of cooling system. The principle is to minimize the value of F by gradually change the layout of cooling system in the mold until the F convergences. The arrangement of cooling system when F get to the minimum is regarded as the minimum design. Figure 5 shows the automatic arrangement procedure.

a) Setting the arrangement restrictions. this may caused by some reasons such as, mold sturcture, machining conditions or design requests, which need to restrict the cooling system layout or shape.

b) Setting of the initial layout of cooling system. In the allowed arrangement area, the initial layout of cooling system is assigned arbitrarily, it can be discribed as L_0.

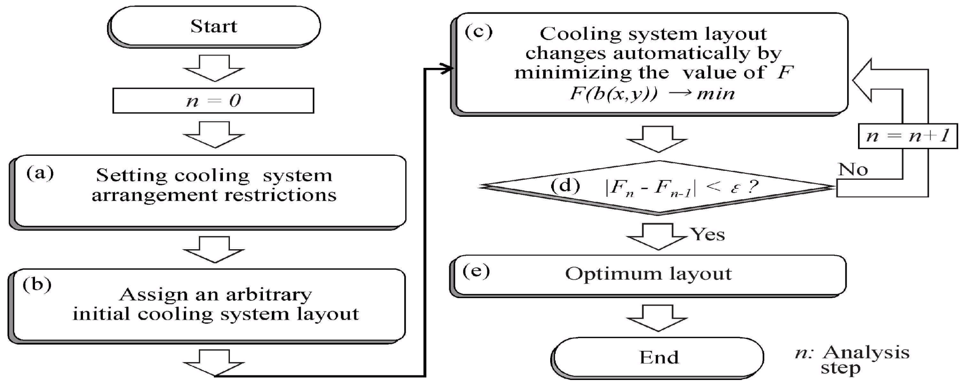

Figure 5: Automatic arrangement procedure

c) Automatic searching of optimum layout. For the initial layout, the cooling uniformity of the current cooling system layout is evaluated, by arranging the small shift to the direction which can reduce the value of evaluation function F, a new layout L_1 can be earned. The process repeats untill the F converges by changing the L_m continuously. equation 5 is the driven function.

$$F(L_m) \rightarrow min \tag{5}$$

d) Judgement of the convergence. To judge whether a new generated cooling system is at the convergence state or not, equation 6 is used.

$$\mid F_n - F_{n-1} \mid < \varepsilon \tag{6}$$

where, the F_n and F_{n-1} are the values from evaluation function F in step n and $n-1$, ε is the calculation accuracy level for the convergence numerical analysis. If the absolute value of the difference of F_n and F_{n-1}, is smaller than ε, the F is regard as that has been reached the convergence state, and the process go ahead to step (e). if not, the process is back to (c), the repeat form (c) to (d) continues until equation 6 is satisfied. and every repeat of (c) and (d) is regard as one analysis step.

e) Decision of the final arrangement of cooling system layout. The layout at the last step is regard as the optimum layout L_n of the cooling system.

Numerical Analysis

Analysis Model

This research chosen Cu-Be alloy insert, whose even cooling effect has been confirmed[1][2], and cooling channel constructed cooling system as analysis objective. Cooling channel is fixed, Cu-Be alloy is to be arranged to its optimum shape. Figure 6 shows the product and mold model for numerical analysis. (a) of Figure 6 is the box-shape product and the mold which is used for forming the product. In order to simplify the simulation, surface ABCD is chosen as the analysis section which is shown in (b) of Figure 6.

Since section AD is the symmetrical center, it is regard as a heat insulation section. Because the resin product has a sharp corner N, in the inner side of the product, especially

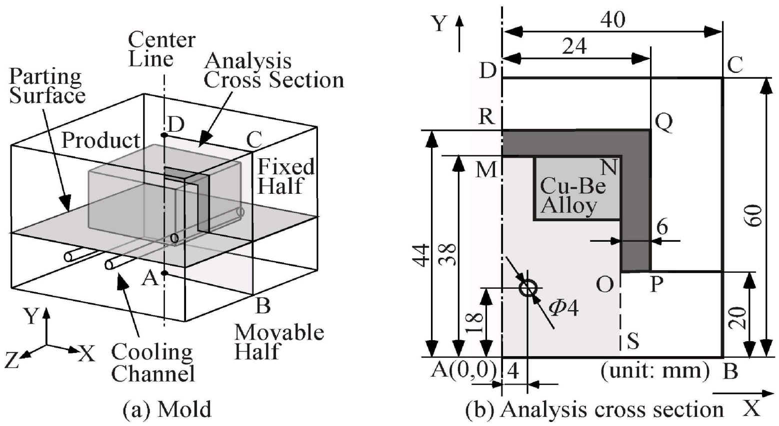

Figure 6: Analysis model

around this corner, the condition of heat diffusing is poor. So, the area MNSA is assigned as allowed arranging area for the Cu-Be alloy.

Results and Discussion

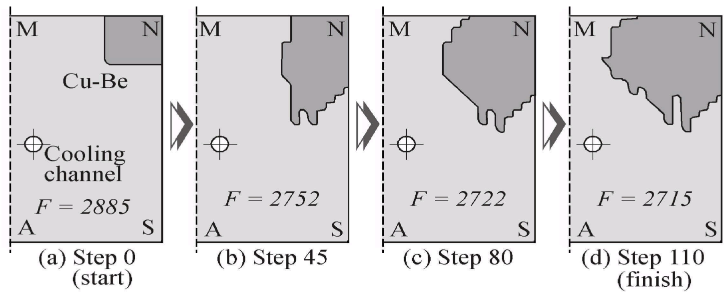

Figure 7: Automatic arrangement from a rectangle initial shape

Followed the procedure of automatic arrangement of cooling system proposed in before section, a initial layout L_0 of Cu-Be alloy insert, which has a square shape, is put on the corner near point N. Figure 7 show the shape changing during the automatic arrangement. Accompanying with the growth of Cu-Be alloy insert, the evaluation value F is becoming small. When the calculation continues to step 110, the value of F reaches the minimum, and the shape of Cu-Be alloy insert changes no more. The shape at this moment is regard the optimum arrangement of the insert.

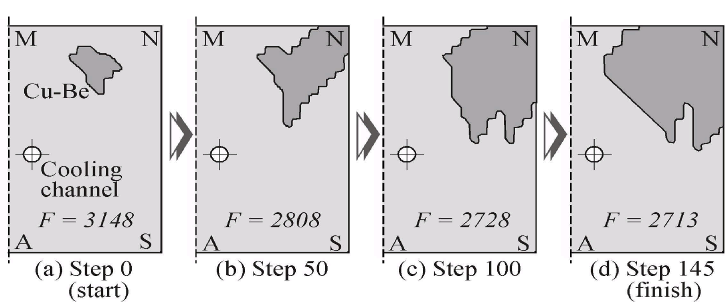

Figure 8: Automatic arrangement from an arbitrary initial shape

In order to confirm the convergence performance of the automatic arrangement, another case study is conducted by assigning a different initial shape of Cu-Be alloy insert, which has a arbitrary shape and located out from the cavity surface. The automatic arrangement process is shown in Figure 8. Almost the same finish shape and evaluation value of the insert was confirmed. The tiny difference can be considered as the computing error.

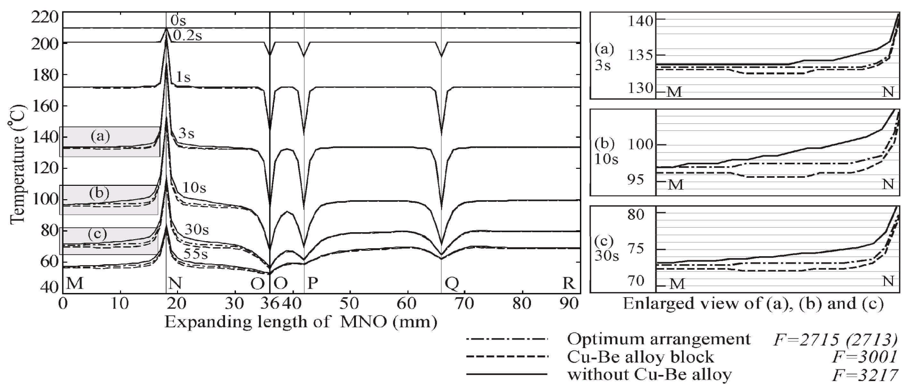

Figure 9: Tempearture distribution on product surface

Figure 9 shows the the temperature distributions and its variations with time on evaluation curve during the cooling process, also the values of evaluation function F are shown in the figure. The vertical ordinate in the graph is the temperature, the horizontal ordinate is the distance that the expending length surrounding the evaluation curve MNOPQR. The solid curve stands for the temperature distributions when no Cu-Be alloy is applied to the mold. The doted curve stands for the case of using the a 16mm $\times$ 16mm Cu-Be alloy insert, The dashed interval curve stand for the case of using an optimum shape of Cu-Be alloy insert. This graph indicate, that the application of Cu-Be alloy insert reduced the heat concentration near the inner surface of the product, and the optimum arrangement gained the most improved result. Simultaneously, deformation numerical analysis is conducted for the three cases, the optimum case shows the minimum deformation amount of the right angles at point N. The results are show in Table 1.

Table 1: Values of right angel at point N

Cooling system	without Cu-Be	16mm square Cu-Be	Optimum Cu-Be
Angle value	87 ° 17'	88 ° 10'	88 ° 29'

Conclusion

This research defines the concept of thermal environment, provides a new way to handling the heat in an injection mold. Based on observing resin cooling uniformity, automatic arrangement procedure of cooling system in an injection mold is given. By properly arranging the cooling system, the design method of thermal environment is proposed. At the same time, through the analysis example, the utility of the thermal environment design method is confirmed.

Reference

1. Engelmann, P.,et.al.: *Journal of Injection Molding Technology*, **1**, 1,18(1997)
2. Gao, F.,et.al.: *Proc. of ICAMT'99*, 1196(1999)