A Computer Simulation Method for Mold Optimization of Rotational Molded Objects

Wai-On NG, Ching-Yuen CHAN, Kai-Leung YUNG, Hui-ying CHEN, and Chi-wo LAM

Abstract**—**Rotational molding is a popular process for producing seamless hollow plastic parts. The process has a number of distinctive advantages, including the low pressure requirement, simple tooling, and uniform thickness capacity. For process improvement, temperature data of the process cycle is vital to most of the manufacturing processes and this applies to rotational molding as well. However, the nature of a rotational molding machine makes the measurement of temperature data during the heating stage difficult.

This paper describes the method of using computer simulation to understand the temperature profile and heat distribution of a rotational molded doll head during the heating stage for mold design optimization. This includes the method used to determine the film coefficient between the furnace hot gas and mold surface. In addition, the performance gain, in terms of heating time reduction and lowered oven temperature, by redesigning the mold.

Keywords**—**computer simulation, PVC plastisol, rotational molding

I. INTRODUCTION

ROTATIONL molding has been embraced by the industry over the time due to its ability to produce seamless, stress-free, hollow parts of extremely complex shapes. The process can be divided into 4 steps: i) Loading of material, ii) Heating, iii) Cooling, and iv) Unloading of finished part. The process is well known for its simplicity, thus low equipment cost. However, the low pressure characteristic makes it a slow molding process[1].

For years, rotational molding operators have relied on their experience to optimize the processes by using trial-and-error method and the growing demand was fulfilled primarily by increasing the number of production lines. A more systematic and economic way of processes optimization is required to meet the growing demand in the future.

Being the first step of the complete redesign process, understanding the existing processes systematically could serve three important purposes in the process of the re-innovation, i.e. i) solid understanding of the process for the generation of new ideas, ii) provision of production data for reference, and iii) definition of a baseline for benchmarking alternative technologies and the technologies to be developed. An in-depth understanding of an existing process also has the potential to improve the existing process itself. This paper illustrates how computer simulation was used to obtain the heat transfer information of the current rotational molding process of a doll head; and it also demonstrates the achievements of shortened process time and reduced oven temperature, using computer simulation, by mold optimization.

Temperature acquisition of the parts in rotational molding is inherently difficult due to the design of the mechanism [1]. With regard to these factors, computer simulation is a cost efficient and a flexible alternative to obtain detailed heat distribution information during the rotational molding process, with satisfactory accuracy for the further development of the re-innovation process.

II. LITERATURE REVIEW

A. Rotational molding, PVC plastisol, and related computer simulation methods

In the process of rotational molding, the mold with the raw material is rotated along two perpendicular axes simultaneously while the whole rotation mechanism is being heated and then cooled to let the material form. Conventionally, the heating process incorporated a fuel combustion furnace as the heating device during the heating process. The rotation mechanism and the use of a fuel burning furnace make the measurement of temperature difficult for both contact type and non-contact type thermometers. Alternative temperature measurement methods include sampling the in mold air temperature to obtain an indirect temperature data of the part; however the method requires high investment [1],[2].

The doll head in our study is made of PVC plastisol. PVC plastisol is prepared by mixing a dedicated formula of PVC particles and other addictive with plasticizer. Due to the presence of a plasticizer, the PVC plastisol appears as liquid before processing. The PVC plastisol then experience the gelation and fusion process when the material is being heated to specified temperature. The PVC particles absorb the surrounding plasticizer during the gelation process and grow in size, with the rise of the temperature the growing particles eventually touch and fuse with their surrounding particles in

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The work described in this paper was fully supported by a grant from the Innovation and Technology Commission, The Government of the Hong Kong Special Administrative Region and Department of Industrial and Systems Engineering of The Hong Kong Polytechnic University (project code: UIT/112 and RTB0)

http://dx.doi.org/10.15242/IIE.E0114075

the process of fusion. The PVC part is cooled and de-molded after the completion of the fusion process [1], [3], [4].

Several publications in the last decade investigated the sintering process of powder type material used in rotation molding and some of these publications further studied the computer simulation methods for this kind of powder type material [5] – [8]. In contrast, there is no publications we are aware of regarding the computer simulation of plastisol. The comparative lack of studies of plastisol might be the result of two factors. First, the complex rheological behavior while being processed. Second, the fact that plastisol plays a relatively small part in the rotational molding industry when compared to that of powder type material [1].

B. Heat transfer coefficient of convection

One of the dominating parameters of convection is the Heat Transfer Coefficient, *h*, or Film Coefficient. The Film coefficient frequently appears as a boundary condition in the solution of heat conduction through solids. The higher the value the higher rate of energy that can be transferred from the fluid to the solid and vice versa. In the analysis of thermal systems, one can assume an appropriate *h* if not available. The film coefficients for some typical materials in different types of flow can be found from the literature, e.g. Table I [9], [10].

TABLE I
TYPICAL VALUES OF HEAT TRANSFER COEFFICIENT IN W/M^{2}K [9]

Type of Fluid Flow	Values
Gases (stagnant)	15
Gases (flowing)	15-200
Liquids (stagnant)	100
Liquids (flowing)	100-2000
Boiling liquids	2000-35,000
Condensing vapours	2000-25,000

Although radiation could be another heat transfer mode, it is negligible in this case because convection dominates the total heat transfer when the hot body is below 600°C [11], while the highest process temperature in our study is only slightly over 400°C.

C. Improvement of molded product quality by extended surface

One of the potential benefits of studying the heat distribution of a part is the provision of evidences for improving the part quality by redesigning the mold. Modifying the surface of the mold exterior is one of the most common ways to improve the convection efficiency in a combustion furnace. A number of studies have investigated how the surface texture could improve the heating and cooling efficiency of the mold and reduce the cycle time [12], [13]. For instance, Shih and Kwang [12] published a detailed report in 2007 showing how extended surfaces, or fins, on the mold with different geometries could enhance the heating and cooling efficiency of the rotation molding process and improve the molded product quality.

III. METHODOLOGY

In this study, we took a common rotational molded doll head model as our example. The aims of this paper are i) to acquire the temperature profile and heat distribution of the doll head part using computer simulation and ii) to optimize the process and/or the mold design by studying the information obtained from the simulation result. As the highest process temperature in our study will not over 600^{o}C, the scope of the computer simulation covered in this paper was bounded to the heat transfer via convection and conduction, i.e. from the measurable hot gas in the combustion furnace to the part. Since we are interested in the final temperature profile and heat distribution in the mold, in our simulation model, the motion of the mold in the furnace is ignored and the doll head part was assumed to be a single phase material which was a layer of solid PVC. A heat transfer sequence was then setup with the conditions i) Ambient temperature was 400°C, ii) the mold was heated by the ambient via convection, iii) the solid hollow part was heated by the mold via conduction, as shown in Fig.1.

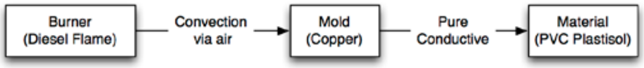

Fig.1 Heat Transfer diagram in the combustion furnace

Fig.2 CAD Model of the rotational molded part

Fig.2 illustrates the original CAD model of the rotational molded part. The part is an irregular shape that is composed of many free-form surfaces. The maximum dimension of the model is from the top of the head to the lower jaw, which is about 40mm.

A. Determine the film coefficient

To setup a transient thermal analysis for convection heat transfer, the value of the film coefficient is essential. However, the film coefficient can be difficult to obtain since the film coefficient depends on the fluid velocity and density, and the coefficient on all geometries might not be known [10]. In such cases, the value has to be estimated by using a film coefficient table, e.g. Table I. The film coefficient table lists the range of coefficient value of the corresponding type of fluid flow. Nonetheless, the range stretches broadly in some cases thus the result could be dramatically varied by the estimated value. In our case, the film coefficient between the furnace hot gas and the mold which was considered to be in the type of Gases(flowing), was estimated to be ranged from 15W/m^{2}K to 250 W/m^{2}K according to Table I.

To obtain a better estimation of the film coefficient, a control simulation experiments was done. Six sets of transient thermal analysis were conducted using six selected values in the range of the typical film coefficients of the flowing gases provided in Table.1, i.e. 15W/m^{2}K to 250 W/m^{2}K. A simulation using a simplified mold model with the same material and similar size of the actual mold was setup. The ambient fluid was assigned as air at 400°C to emulate the actual working furnace. The terminating condition was set to be the mold temperature of 250^{o}C The results of the control simulation experiments are shown in Fig.3.

Fig.3 Control simulation results using different film coefficient

These results of the simulation models with different film coefficients were then compared with the actual mold temperature measured on-site. Since the heating profile of the model with film coefficient 15W/m^{2}K had the best match to the actual measurement. We believe 15W/m^{2}K is the best film coefficient estimation of the system in our study. , Thus, 15W/m^{2}K was used in the succeeding simulations as the film coefficient between the hot furnace gas and the mold.

B. Thermal Analysis using the reconstructed CAD models and CAD models with optimized mold design

A new case was then created with the meshes representing the bodies of the copper mold and the PVC part, with the mesh size set to normal. The type of the thermal analysis was transient thermal analysis, initial temperature of all bodies was set to 60°C, and the simulation time was 250s. Temperature and thermal error were captured during the transient thermal analysis. In addition, two more identical cases with finer and coarser size of body meshes were created to verify the result of normal size meshes.

The heating profile and heat distribution result of the PVC part model with normal sized meshes was the basis for mold optimization. An attempt of redesigning the mold with added fins was done and the result is shown in the chapter.

IV. RESULTS

The temperature profile and heat distribution of the PVC part in the current process as well as the improved heating performance by the optimized mold with fins were the information in interest. Fig.4 shows the simulated heating profile of the part during the 250s simulated heating process. The temperature of the part rose gradually from the initial temperature 60°C to about 140°C. The final temperature deviation of the part was about 4.6°C.

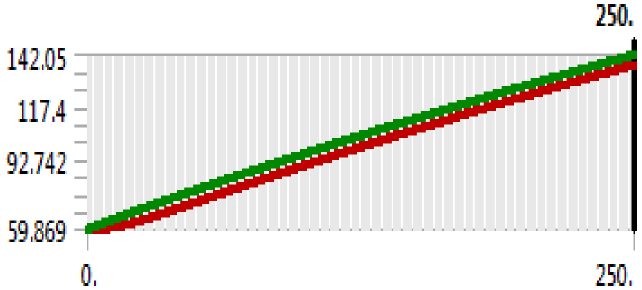

Fig.4 Temperature profile showing the maximum and minimum temperature of the part body

Fig.5 illustrates the heat distribution of the part at *t*=250s. The heat distribution maps show that the current process achieved a generally uniform heat distribution of the part. The locations of the hotspots of the part were similar to that of the mold, i.e. nose and tips of the lips.

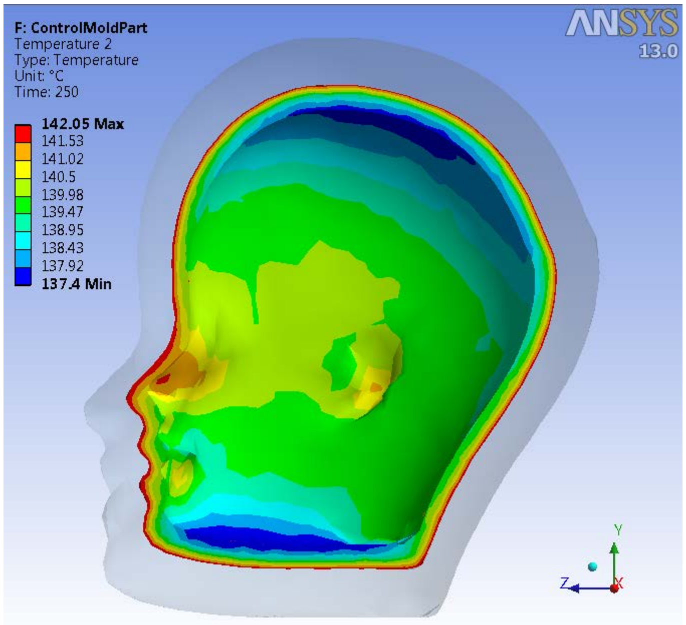

Fig.5 Section view of the part heat distribution

As mentioned in the literature review, fins on the mold exterior have the potential to enhance the heating and cooling performance of the mold according to Shih and Kwang [12]. Inspired by their idea, a redesigned doll head mold model with 96 triangular fins was created to investigate the performance gain in this case. The redesigned doll head mold is shown in Fig.6.

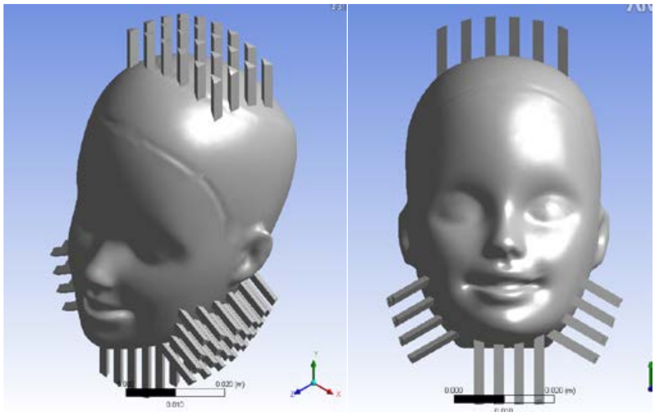

Fig.6 Redesigned doll head mold with 96 fins

The performance improvement was evaluated in terms of i) heating time reduction and ii) oven temperature reduction. The target temperature of both of the evaluations were set to 140°C, which was the result of the original mold.

For the heating time simulation, the part reached 140°C at *t*=170s. In contrast, the part required 250s to reach 140°C using the original mold. The 80s heating time reduction equals to 32% heating time saving by using the redesigned mold while holding all conditions unchanged. Fig.7 shows the temperature profile using the redesigned finned mold.

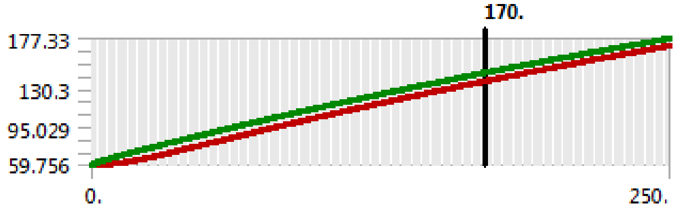

Fig.7 Temperature profile of the part body using the redesigned finned mold

For the oven temperature simulation, different values of oven temperature were applied to obtain a set of temperature profiles of the part. The result of 350°C oven temperature matched closely to that of the original mold which was originally achieved by using a 400°C oven. The result is shown in Fig.8.

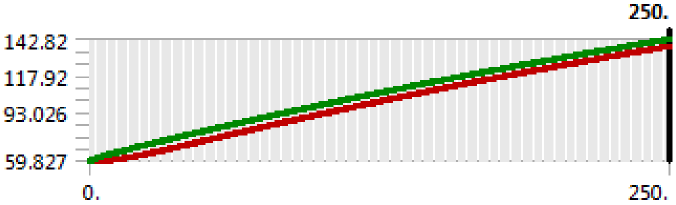

Fig.8 Temperature profile of the part body using the redesigned finned mold in a 350°C oven

V. CONCLUSION

This paper presented a computer simulation method for mold optimization of rotational molded objects. Due to the physical constraints of rotational molding process in obtaining actual temperature profile and heat distribution measurement, computer simulation can be a cost effective alternative to acquire the thermal data for the mold and process optimization. Film coefficient, which is a necessary parameter in the thermal analysis with convection heat transfer, cannot be obtained easily by simple measurement. This study demonstrated a method to obtain an estimate by comparing the actual heating profile and the simulated heating profile of samples molds. Using computer simulation, the part temperature profile and heat distribution diagrams of the mold and the PVC parts were ontained. By studying the profile and distribution, possibility of improving the mold and process design were identified and verified by simulation. According to the heat distribution obtained, the mold design could be improved by adding fins to cooler area to avoid hot-spot in the molded parts. Using the information provided by temperature profile result, the process could be improved without compromising the product quality by shortening the heating time and lowering the oven temperature, thus increasing productivity and decreasing energy consumption.

ACKNOWLEDGMENT

The authors wish to acknowledge the Innovation and Technology Commission, The Government of the Hong Kong Special Administrative Region and Department of Industrial and Systems Engineering of The Hong Kong Polytechnic University for the financial support of the research (project code: UIT/112 and RTB0).

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