热成形工艺热管理技术

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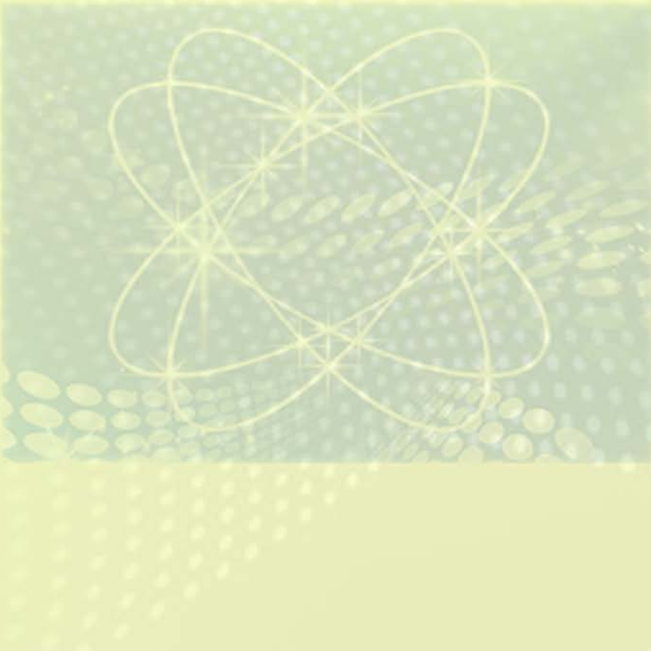

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Thermal Management Technology for Thermoforming Processes

热成形工艺热管理技术

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Introduction of the research team

We belong to the Institute of Renewable Energy & Energy Conservation and Emission Reduction of Wenzhou University in China. The objective of our research team is developing basic theorem and technology for renewable energy & energy conservation and emission reduction. Recently, we have carried out more than 20 research projects including the projects funded by National Natural Science Foundation of China, Planned Science and Technology Project of Zhejiang Province in China, Natural Science Foundation of Zhejiang Province in China, Planned Science and Technology Project of Wenzhou City in China and etc. Also, we have published more than 100 papers including over 20 SCI journal papers published in the *International Journal of Precision Engineering and Manufacturing*, *Journal of Thermal Science and Technolocy*, *Journal of Mechanical Science and Technology*, etc. Simultaneously, we have more than 20 patents including 6 international patents.

The results of the research for thermoforming achieved by our research team are as follows:

[1] Li Zhenzhe, Heo Kwangsu, Seol Seoungyun, Time-dependent optimal heater control in thermoforming preheating using dual optimization steps, *International Journal of Precision Engineering and Manufacturing*, 2008, 9(4): 51-56. SCI.

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[5] Li Zhenzhe, Shen Guiying, Li Meiqin, Wang Xiaoqian, Shen Yunde, Optimal heater control in thermoforming preheating using approximate function, *Advanced Materials Research*, 2011, 314-316: 576-580. EI.

[6] Li Zhenzhe, Shen Guiying, Wang Xiaoqian, Li Meiqin, Shen Yunde, A study on storing process of thermoforming using finite difference method, *Advanced Materials Research*, 2011, 314-316: 571-575. EI.

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[13] Li Zhenzhe, Seol Seoungyun, Shen Yunde, A study on the stage of storing for quality of the final products, *The 2nd Asian Conference on Industrial Engineering and Management*, Jun. 12-14, 2009, Wenzhou, China.

[14] Li Zhenzhe, Heo Kwangsu, Seol Seoungyun, A study of time-dependant optimal heater control for thermoforming using response surface method, *Proceeding of KSME Annual Spring Conference*, 2007, Pusan, Korea.

[15] Li Zhenzhe, Heo Kwangsu, Seol Seoungyun, Prediction of characteristics of water spray cooling used to thermoforming, *Proceeding of KSME Annual Fall Conference*, 2007, Pyoungchang, Korea.

[16] Li Zhenzhe, Heo Kwangsu, Seol Seoungyun, Optimal heater control of thermoforming using analytic solution, *Proceeding of KSME Annual Spring Conference: Thermal Engineering Part*, 2008, Jeongseon, Korea.

[17] Li Zhenzhe, Heo Kwangsu, Choi Junhoo, Seol Seoungyun, Development of approximate analytic method for uniform temperature, *Proceeding of KSME Annual Spring Conference: Thermal Engineering Part*, 2008, Jeongseon, Korea.

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Contents

Preface

Thermoforming is one of the most versatile and economical processes available for shaping polymer products, but obtaining a uniform thickness of final products using this method is difficult. Thermal management of thermoforming processes is very important because the thickness distribution strongly depends on the distribution of the sheet temperature.

The detailed contents of this book are as follows:

Chapter 1: The research background was described, and the related researches were reviewed.

Chapter 2: In this chapter, the time-dependent temperature distribution of total sheets in the storing stage was studied because the temperature after the storing stage is the initial temperature of the preheating process. An analytic solution for simulating the storing stage was derived. Using the solved analytic solution, the time-dependent temperature distribution of total sheets was found out under the condition of assuming that the temperature-dependent specific heat of ABS sheet was a certain constant value.

1st part of Chapter 3: The analysis model of thermoforming preheating was summarized, and the used assumptions were also described.

2nd part of Chapter 3: An analysis code suitable for the preheating system of thermoforming was developed for simulating the time-dependent temperature distribution of ABS sheet.

3rd part of Chapter 3: The steady-state optimum distribution of heater power is ascertained by a numerical optimization to obtain a uniform sheet temperature. The optimal results show that the optimum heater power distribution gives an acceptable uniform surface temperature in the forming temperature range. Then, the control methods for a successful thermoforming using the heater power or the heating time was researched in order to improve the quality of final products. The results show that the satisfied temperature distribution can be obtained by adjusting the heater power or the heating time.

4^{th} part of Chapter 3: At first, the effect of the time-dependent variation of heat to the temperature difference between the surface and the center of the sheet was checked. In the following step, the time-dependent optimal heater input is then determined to decrease the temperature difference through the direction of the thickness using response surface method and D-optimal design. Then, Duhamel's theorem was used in order to solve a one-dimensional heat conduction with a time-dependent boundary condition when neglecting the effect of the natural convection, but the analytic solution was difficult to be applied when the boundary condition is complicate or noncontinuous. Using the developed analytic solution, an optimal heating profile expressed by an exponential function was recommended from 9 simple optimal cases using Duhamel's theorem. Next, in order to compensate the drawback of the simple model based on Duhamel's theorem, the integral method which is one of the approximate analytic method was used to define the coefficients of the exponential function. Optimization was carried out using the developed approximate analytic solution under the condition of satisfying the requirements of thermoforming. Finally, in order to upgrade the accuracy, finite difference method was used. The results show that the temperature difference between the surface and the center of ABS sheet can be remarkably minimized using the developed methods in this chapter.

Chapter 4: In this chapter, water spray cooling was simulated to apply to a cooling system instead of compressed air cooling in order to shorten the cycle time and reduce the cost of compressed air used in the cooling process. At first, the cooling time using compressed air was predicted in order to check the state of mass production. In the following step, the ratio of removed energy by air cooling or water spray cooling among the total removed energy was found by using 1-d analysis code of the cooling system under the condition of checking the possibility of conversion from 2-d to 1-d problem. The analysis results using water spray cooling show that the cycle time can be reduced because of the high cooling efficiency of water spray, and the cost of production caused by using compressed air can be reduced by decreasing the amount of the used compressed air. The 1-d analysis code can be widely used in the design of a thermoforming cooling system, and the parameters of the thermoforming process can be modified based on the recommended data suitable for a cooling system of thermoforming.

Chapter 5: The total contents described in this book were summarized.

The analysis and optimization method for thermoforming processes described in this book have made a theoretical basis for designing thermoforming system, and recommended a scheme of thermal management for thermoforming process to improve the quality of final products.

Nomenclature

A	area, m^2
B	coefficient matrix
C_P	specific heat of ABS sheet, J/kg.K
c_i	i^{th} coefficient of response surface
D_{eff}	D-optimal assessment index
D	distance between center of coolant channel and upper surface of mold, m
d	diameter of coolant channel, m
E	emitted heat flux, W/m^2
e	error
F_{k-j}	view factor from k surface to j surface
G	irradiation, W/m^2
g	acceleration of gravity, m/s^2
g	i^{th} inequal constraint
H	error matrix/thickness of total sheets, m
h	convective heat transfer coefficient, $W/m^2{\cdot}K$
h_i	i^{th} equal constraint
h_{fg}	latent heat of water, kJ/kg
J	radiosity, W/m^2
k	thermal conductivity of ABS sheet, W/m·K
k_{eq}	thermal conductance, W/m·K
L	half of sheet thickness/half of total thickness/total length of coolant channel, m
L	characteristic length, m
M	moment matrix

m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N	number of total sheets
P	length of circumference/distance between channels, m
q/Q	heat flow rate, W
q''/q	heat flux, W/m^2
R	resistance, mK/W
Ra_L	Rayleigh number
S	shape factor
T	temperature, K
T_∞	environmental temperature, K
t	time, s
T_h	thickness, m
V	volume of ABS sheet, m^3
υ	dynamic viscosity of air, m^2/s

Greek Symbols

α	thermal diffusivity, m^2/s
β	volume expansion coefficient of air, K^{-1}
β_m	eigen vector
ρ	density, kg m^{-3}
ρ_k	kth surface reflection coefficient
σ	Stefan-Boltzmann constant, 5.67×10^{-8}W/m$^2\cdot$K^4
ε	emissivity
η_n	eigen value

Subscripts

a	air/average
c	contact/center
cl	cooling
conv	amount caused by convection
e	environment
elec	electric power
f	final
h	heater/heating
in	input
ini	initial
inf	infinite
l	lower
m	mold
p	sheet
rad	amount caused by radiation
req	requirement
s	ABS sheet
u	upper
w	water

1. Introduction

1.1 Research background

Currently, the properties of the composite materials have been improved with development of the materials science and engineering. The study on the composite materials in the past was mainly focused on the chemical components and the physical structures. There is a trend that the composite materials take the place of the original metal materials in some engineering field with development of the properties of the composite materials. Therefore, the study on the forming performance of the composite materials is also important.

Thermoforming is a method of manufacturing plastic parts by preheating a flat sheet of plastic to its forming temperature, then bringing it into contact with a mold whose shape it takes. The sheet is held against the mold surface unit until cooled. The formed part is then trimmed from the sheet. [1-8]

A lot of composite materials have been used for thermoforming including ABS (Acrylonitrile-Butadiene-Styrene).[9-13]

Thermoforming is one of the most versatile and economical processes available for shaping polymer products, but obtaining a uniform thickness of final products using this method is difficult. Thermal management of thermoforming processes is very important because the thickness distribution strongly depends on the distribution of the sheet temperature.

In order to improve the performance of final products and decrease the manufacturing cost, the design variables of thermoforming system and the operating parameters should be optimized. For realizing the optimization, the processes of thermoforming should be simulated. But, the simulation models for these processes of thermoforming have not been systematically constructed well. Therefore, the engineers only depend on trial and error. The design efficiency is too low, and design and manufacturing cost can not be decreased significantly when using the method based on trial and error.

Thermoforming has 4 nonlinear characteristics which can be expressed as the geometry nonlinear problem (nonlinear between the strain and the displacement), the material nonlinear problem (nonlinear between the stress and the strain), the boundary nolinear problem (the contact status nonlinear between the sheet and the mold) and the tempeature nonlinear problem (the unsteady temperature distribution of the sheet).[14] So, the simulation models for the processes of thermoforming can not be easily constructed.

According to the nonlinear characteristics described above, kinds of simulation and optimization methods were used for simulating the stage of storing, the preheating process and the cooling process of thermoforming under the condition of neglecting the effect of deformation of the sheet.

1.2 Review of research for thermoforming

The study on the processes of thermoforming mainly can be divided into several sections as follows.

◆ **Study on material properties**

In order to improve the quality of final products, Muenstedt and etc have studied the effect of the material properties to the performance of thermorming.[15-17] Selecting the material suitable for thermorming is very important when the size, the operating conditions, etc. are changed according to the users' requirements.

Zappala et al have commented about selecting the material suitable for thermoforming.[16-19] Erchiqui et al have compared the materials used for thermoforming.[20]

◆ **Study on simulating thermoforming processes**

Many researchers have studied the effects of the parameters, the operating conditions, etc. for optimization of thermoforming processes.[21,22] Nam et al have studied the parameter effect using experimental method, but numerical simulation have been mainly studied by a lot of researchers for decreasing the design cost and the iterative design or manufacturing process.[23] Although the method based on analytic solution developed by Lim et al is very important for setting up theoretical basis for thermoforming. Many numerical methods such as finite element method, finite difference method, etc. have been widely used for more accurate simulations.(24-32) The simulation studies have mainly focused on the preheating and the forming processes because the parameters of them have significant effects on the thickness distribution of final products. Generally, the simulations of thermoforming processes are difficult due to the temperature-dependent material properties.

For simulating the preheating process of thermoforming, the complex phenomenon such as phase change. should be considered. Many researchers have studied the preheating process of thermoforming using many kinds of techniques.[33-43] The material used for thermoforming have their own absorption bands, and the ceramic heaters can be considered that only the surfaces of the sheet are heated by the heaters. Therefore, the temperature between the surface and the center of the sheet is significantly different. In order to solve this problem, Jeffery