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Optimal two-stage single-screw design for polymethyl methacrylate extrusion by taguchi technique

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ABSTRACT

The optimal screw design for polymethyl methacrylate (PMMA) extrusion was studied. The Taguchi method was used to determine the optimal screw geometry and processing conditions for the extrusion of PMMA sheet and/or film. To get the high quality of sheet and/or film, perfect melting, adequate melt temperature, and enough metering pressure were necessary. The six factors relating screw geometry and processing condition were chosen with three levels for each factor. The orthogonal array was selected as the most suitable for fabricating the experimental design, $L_{27}3^6$, with 6 columns and 27 variations. The smaller-the-better was used as an optimization criterion. The optimal values of these parameters were 8D of feeding zone length, 15 mm of feeding zone depth, 4D of melting zone length, 3 of compression ratio, 49 rpm of screw speed, and 165/180/200/250/260/2660/260 of barrel temperature. Under these conditions, the completeness of melting of solid bed, the stability of solid bed, the melt pressure at vent zone, and the melt temperature at the end of screw were 0, 0, 0 bar, and 279.5 °C, respectively.

1. Introduction

Extrusion has been one of promising technologies in many industries over many years. It can be applied in polymer, food, and cosmetic processing, and its importance is still increasing. Among all kinds of extrusion technologies, single screw extrusion is the cheapest processing method, has the longest history, and is still playing an important role. The theories of a single screw extruder have been significantly developed during the last few decades [1]. However, the theories have many complicated analytical problems very difficult to be solved without many assumptions. Recently, as numerical simulation technology advances, solving a whole extrusion process is becoming possible with fewer assumptions. A complete solution can provide more detailed information of the effect of screw geometry parameters and processing conditions on the performance of the screw extruders. Some commercial software packages for single screw extrusion are available [2].

Transparent plastics are not only used for lenses but also used in precision optics because of their light weight, possibility of mass production, and low prices [3–5]. Among these kinds of plastics, polymethyl methacrylate (PMMA) has been a good optical polymer because of its good light transmission and has been used as good diffusing plates and as diffusing beads. However, PMMA has low thermal stability and low mechanical properties due to high moisture absorption by containing hydrophilic group such as a carbonyl group [6–8]. During a melt processing of PMMA for sheet or film production, troubles like fish-eye and poor product surface could be found even in mild processing condition. It was believed due to the incompleteness of melting of PMMA solid and the improper melt temperature inside extruder. Commercially, production of goods in good quality has very important meaning and the optimum processing condition should be found to solve the problems during manufacturing. However, there are so many process parameters that can affect the properties of final product and a great number of experiments are required to figure out the optimum condition.

As an optimization technique, design of experiment (DOE) is a technique of defining and investigating all possible conditions in an experiment involving multiple factors. By using "partial" information obtained from the selected experiments, we can predict an entire picture. Analyzing the experiment results is based on analysis of variance (ANOVA), whose fundamental concept is to determine an "average value" from all the responses, and their variations. The contribution of each factor and the interaction between various factors of an experiment can be quantitatively evaluated and the best condition set which gives the best response can be determined by using ANOVA [9]. In recent years, the Taguchi method, also called the robust design method, has greatly

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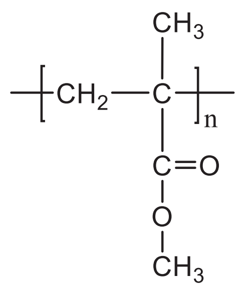

Scheme 1. Chemical structure of polymethyl methacrylate.

improved engineering productivities. By consciously considering the noise factors and the cost of failure in the field, it helps ensure customer satisfaction. The complex systems with many variables could have been investigated by the Taguchi method, explained successfully, and optimized at the best conditions [10,11].

In this study, PMMA was extruded for the purpose of sheet or film production by taking into consideration the experimental parameters on the screw geometry (feeding zone length, feeding zone depth, melting zone length, compression ratio) and processing conditions (screw speed, barrel temperature). Taguchi experimental design method was employed to determine optimum screw design and processing conditions.

2. Theory and experimental

2.1. Materials

The basic material properties and viscosity behavior of polymethyl methacrylate (PMMA, SUMIPEX, G5126, Sumitomo Chemical) were used for numerical simulation of extrusion. The chemical structures of PMMA used and its characteristics are shown in Scheme 1 and listed in Table 1, respectively.

2.2. Rheological behavior

A stress-controlled rheometer (AR-G2, TA Instruments) was used to measure the complex viscosity and modulus. Parallel-plate fixture of diameter 25 mm with gap size of 1 mm was used. The frequency range was 0.05–500 rad/s and strain amplitude was kept enough value (5%) to ensure a linear viscoelastic response of the polymers. A capillary rheometer (Rheograph 2003, Goettfert) was also used to measure the viscosity in high shear rate region.

Table 1
Properties of polymethyl methacrylate used in this study.

	Properties	Unit	Values
Density	Solid bulk	kg/m^3	800
	Solid phase	kg/m^3	1180
	Melt phase	kg/m^3	1050
Thermal properties	Melting temperature	°C	160
	Heat of fusion	J/kg	–
	Heat capacity	J/kg-°C	1700
	Thermal conductivity	W/m °C	0.19

2.3. Extrusion

An industrial two-stage single screw extruder (Fig. 1) which has mixing and vent zones was operated to plot a calibration curve between screw speed, head pressure and throughput. The screw speed and the throughput are necessary as basic input variables for screw simulation.

2.4. Experimental design

To find optimum conditions a list of six factors, thought to be most important, was chosen, all of which were screw geometry and processing condition. The three levels for each factor were set using information from material supplier and knowledge from personal experience. The factors and their levels were listed in Table 2. The orthogonal array was chosen as the most suitable one to make up the experimental design, $L_{27}3^6$, with 6 columns and 27 variations given in Table 3. From the L27 array and the factor list, the test schedule was drawn up in Table 4. Performance characteristics chosen as the optimization criteria were divided by three categories, the larger-the-better, the nominal-the-best, and the smaller the-better. Among these, the smaller-the-better was calculated by using Eq. (1) [12].

$$SN = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (1)$$

2.5. Software packages

As a tool for applying Taguchi method, MINITAB software (MINITAB release 14.20, Minitab Inc.) was used. Simulation software (NEXTRUCAD ver 2.10.0, Polydynamics Inc.) for single

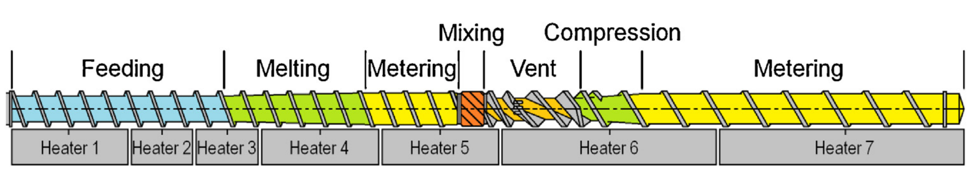

Fig. 1. Two-stage single screw with mixing and vent zone.

Table 2
Factors and levels of the experiments.

Level	Screw geometry				Processing condition	
	Feeding zone		Melting zone	*C/R*	Screw speed (rpm)	Barrel temperature (°C) B1/B2/B3/B4/B5/B6/B7
	Length, *L* (L/D)	Depth, *h* (mm)	Length, *L* (L/D)			
1	7.0	14.0	4.0	2.8	49	165/180/200/250/260/260/260
2	8.0	15.0	5.0	2.9	56	180/195/215/255/260/260/260
3	9.0	16.0	6.0	3.0	63	195/210/230/260/260/260/260