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Mathematical modeling of the influence of technological parameters of rotary molding on the amplitude of the ultrasonic bottom signal

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Abstract. In recent years, the processing of polymer materials has undergone significant changes due to the introduction of digital technologies. This article discusses the integration of high-tech methods and tools that ensure reliability, flexibility and optimization of production processes. In particular, emphasis is placed on the choice of non-destructive testing methods to ensure product quality, especially in the production of polymer products by rotary molding. The article discusses the problems associated with incomplete sintering and thermal oxidative decomposition of polyethylene, which have a significant impact on the quality of products. Traditional methods of control, such as visual inspection and ultrasound control, are presented, and their limitations are discussed. The main attention is paid to the application of the ultrasonic method of non-destructive testing to detect incomplete sintering of polyethylene. The authors propose a formula based on probabilistic-deterministic planning, which takes into account the combined effect of temperature and plastic thickness on the amplitude of the ultrasonic signal. This formula demonstrates high reliability, estimated by the coefficient of nonlinear multiple correlation. The use of non-destructive testing methods in the production of polymer products by rotary molding allows us to ensure high quality products and prevent possible breakdowns and accidents during operation. This article represents an important contribution to the field of quality control of polymer products and opens up new opportunities for optimizing production processes.

1 Introduction

In recent years, the processing of polymer materials has changed significantly due to the introduction of digital technologies. One of the trending directions of development is the integration of high-tech technologies, methods and tools that can ensure reliability, flexibility and optimization of production processes. In the context of product quality control methodologies, the choice of non-destructive testing methods is considered progressive, since they guarantee a great economic effect due to the absence of the likelihood of damage to non-defective parts, devices and mechanisms. The production of hollow plastic parts by rotary molding also requires more effective methods of detecting defective products.

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The quality of polyethylene parts significantly depends on two unfavorable factors: incomplete sintering and thermal oxidative degradation. Incomplete sintering is associated with insufficient sintering of polyethylene powder. Thermal oxidative degradation occurs when products overheat. In the process of melting polyethylene powder, liquid bridges arise between the particles that trap air bubbles. These bridges should disappear during the subsequent sealing stage at moderate temperatures above the melting point of the plastic (more than 135 degrees Celsius). If the bubbles are not removed, the manufactured parts will have poor mechanical properties. In case of overheating of the product, thermal oxidative degradation of polyethylene occurs, as a result, mechanical properties also deteriorate significantly. Thermal oxidative degradation leads to discoloration, and a decrease in the service life of hollow polyethylene structures.

Currently, destructive quality control tests are still convenient and affordable for technologists of many enterprises engaged in the manufacture of plastic products by rotary molding, despite the wasted resource consumption. Impact strength is the most important property, an indicator of product defects due to two factors - incomplete sintering and thermal degradation of the material. Other similar parameters are tensile strength, modulus of elasticity, elongation at fracture, yield strength. But no testing of these parameters guarantees a high-quality result, instead a small number of parts from the batch of the production cycle are shipped as test samples. The check takes several hours before information is given about the acceptability of the plastic manufacturing conditions. In this regard, in order to increase the reliability, accuracy, and speed of quality control of polyethylene products, it is necessary to use non-destructive methods.

Non-destructive testing methods include: magnetic (based on the analysis of the interaction of the magnetic field with the controlled object), electric (based on the registration of the parameters of the electric field interacting with the controlled object or arising in the controlled object as a result of external influence, eddy current (based on the analysis of the interaction of the electromagnetic field of the eddy current converter with the electromagnetic field of eddy currents induced in controlled object), radio wave (based on registration of changes in the parameters of electromagnetic waves of the radio range interacting with the controlled object), thermal (based on registration of changes in thermal or temperature fields of controlled objects caused by defects), optical (based on registration of parameters of optical radiation interacting with the controlled object), radiation (based on registration and analysis of penetrating ionizing radiation after interaction with a controlled object), acoustic (based on the registration of elastic wave parameters, excited or arising in the controlled object), vibroacoustic (based on the registration of the parameters of the vibroacoustic signal that occurs during the operation of the controlled object). In general, the use of non-destructive testing methods for the control of plastic products obtained by rotary molding allows us to ensure high quality products and prevent possible breakdowns and accidents during operation.

Of all the variety of existing methods of non-destructive testing in the scientific and technical literature for the control of plastic products made by rotary molding, the use of only acoustic (ultrasonic) and visual inspection is described. Visual inspection is one of the fastest and simplest non-destructive testing methods that can be performed on the production line without interrupting the production process. However, it does not allow to detect hidden defects, such as internal cracks and inhomogeneities of the material.

The ultrasonic method of non–destructive testing is used everywhere to control the thickness of manufactured products - barrels, pools, etc. For these purposes, ultrasonic thickness gauges from various manufacturers are used. Ultrasonic flaw detection is a set of non-destructive testing methods that use ultrasonic waves to find defects in products. The obtained data are then analyzed, the shape of defects, size, depth of occurrence and other characteristics are found out.

There is an ultrasonic method for detecting incomplete sintering of polyethylene in parts made by rotary molding, through the analysis of the amplitude of the bottom signal. This method, implemented using the USD-60 flaw detector, consists in transmitting a control and measuring probing ultrasonic signal by means of tight contact with the plastic contact pad [4]. The reflected bottom signal, which is a radio pulse with frequency deviation, carries several information parameters: the thickness of the product, the speed of passage of the ultrasonic signal, the amplitude. The amplitude of the signal is determined in the time domain of the flaw detector through the percentage of overlap of the waveform scale, as well as in dBm/W. It is not possible to determine the branching of chains and the formation of cross-links between crystallites characteristic of the thermooxidative degradation of polyethylene due to the equivalence of the amplitudes of the bottom signal in both normal and baked samples. In [4], the dependences of the amplitude of the bottom signal on the thickness and temperature of polyethylene were not studied. It is possible to identify the dependence and derive equations for calculating the amplitude of the bottom signal on the temperature and thickness of plastic with a high quality of reliability using the probabilistic deterministic planning (VDP) method. This method, like the Taguchi method, allows you to create multifactorial mathematical models that take into account the contribution of several different parameters to the processes under study. Similar to Taguchi, this method is used in chemical technology to optimize the compositions of various composite materials (plastics, paints, etc.) and the parameters of their processing (injection rate, temperature, etc.) [5-8]. A detailed description of the process of applying the VDP method for modeling multiparametric processes is presented in [8-15].

2 Materials and methods

The material used was rotary polyethylene "DOWLEX 2629UE" (hereinafter "DOW") with a density of 935 kg/m3 from Dow Chemical Company (Dow Europe GmbH, Horgen, Switzerland).

"DOWLEX 2629UE" refers to a series of high-molecular polyethylene, which have high resistance to shock loads and good tensile strength. This polyethylene is also characterized by good processing and weldability, which makes it a suitable material for the production of various products, including containers, barrels, pipes and other products that require high resistance to mechanical loads and chemicals.

For the rotary molding process, a model F D 4.0 machine from Yantai Fengda Rotary Molding Co. was used. Ltd (Yantai, China), which was equipped with three cubic steel molds and two axes of rotation. After the introduction of the required amount of polymer, the mold was closed and placed in a machine preheated to 300 °C. The mold was kept in rotation for 25-35 minutes at a temperature of 300 ° C. During the entire process, the internal air temperature was controlled by a thermocouple through the mold vent. After heating the mold to the required values (from 170 to 245 ° C) of the maximum internal air temperature, the cooling process began. The samples were removed from the mold at a decrease in the internal air temperature to 90 °C. The rotation speed of the main axis (lever speed) and the minor axis (plate speed) were set to 5 and 9 revolutions per minute, respectively. A steel mold with a size of 500 mm × 500 mm × 500 mm was used.

The amplitude of the bottom signal (A, %) was determined by the echo pulse method during ultrasonic control of the samples. An industrial ultrasonic flaw detector USN 60 from Kropus (Russia) was used in the research. Before conducting studies of the surface of the plastic sample, a layer of glycerin was applied to it to improve the transmission of the ultrasonic signal. The piezoelectric transducer was placed on the surface of the sample treated with glycerin. An electric pulse with an amplitude of 200 V, a filling frequency of 2.5 MHz and a repetition frequency of 20 Hz was supplied from the flaw detector to the piezoelectric converter. After reflection from the opposite plastic wall, the bottom signal was recorded on the flaw detector screen, which is an important informative parameter.

To create different ambient temperature conditions for test samples of polyethylene of different brands, they were placed for 4 hours in a drying oven SPU SHS-80-01. This time interval was chosen taking into account the brand of polyethylene and its thickness to ensure high-quality heating of all layers of plastic. To assess the dependence of the optimization parameters on temperature, four different values were selected: 20°C, 40°C, 60°C and 80°C.

The amplitude of this signal (A) in the time domain was determined by the percentage of overlap of the flaw detector display with the lower signal in percent (%). For optimal display of the signal on the display, the internal amplifier of the flaw detector was set to 20 dBm.

The following experimental input factors were chosen: thickness (S, mm: 7.5, 8.5, 9.5 mm) and temperature (T, oS: 20, 40, 60 and 80). The numerical values of the levels for each factor are presented in Table 1.

Table 1. Numerical values of levels for each factor.

Number of sample	Thickness, mm	Temperature, °C	Amplitude of ultrasonic signal, %
1	7.5	20	43
2	7.5	40	30
3	7.5	60	20
4	7.5	80	19
5	8.5	20	19
6	8.5	40	13
7	8.5	60	6
8	8.5	80	6
9	9.5	20	19
10	9.5	40	14
11	9.5	60	13
12	9.5	80	5

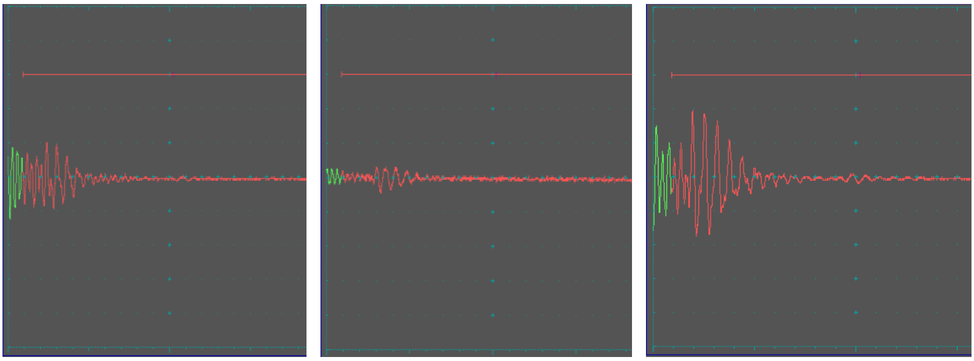
Then we compiled an orthogonal plan matrix of a two-factor experiment 3×4 table.2. Taking into account the different number of levels of the two input factors, the total number of experiments will be 3*4=12. The amplitude of the bottom signal was taken as the response function (here i is the ordinal number of the experiment).

Table 2. Orthogonal plan-matrix of a two-factor experiment.

Factor levels Thickness, mm	Factor levels Temperature, °C			
	20	40	60	80
7.5	y_1	y_2	y_3	y_4
8.5	y_5	y_6	y_7	y_8
9.5	y_9	y_{10}	y_{11}	y_{12}

3 Results

The effect of temperature and thickness on the amplitude of the bottom signal is shown in Fig.1.



a b c

Fig.1. Effect of temperature on the amplitude of the bottom signal of rotary polyethylene, 8.5mm thick (a - 40°C; b - 60°; c - 80°C).

As the temperature increases (Pic.1), the amplitude of the bottom signal decreases. With an increase in temperature from 20 to 80 ° C, the amplitude of the bottom signal decreases by almost 2.2 times (from 43 to 19) for samples with a thickness of 7.5 mm. Moreover, this depression of the amplitude of the bottom signal is characteristic of all three studied polyethylene thicknesses. For a thickness of 8.5mm, depression was 3.1 times, and for a thickness of 9.5mm, depression was 3.8 times. Therefore, according to the depression of the amplitude of the bottom signal, a number of thicknesses can be built: 9.5 < 8.5 < 7.5 mm.

Then the experimental array was sampled for each level of each factor according to Table 3.

Table 3. Sampling an experimental array.

Factor levels Thickness, mm	**Selection**	**Factor levels Temperature, °C**	**Selection**
7.5	$(y_1+y_2+y_3+y_4)/4$	20	$(y_1+y_5+y_9)/3$
8.5	$(y_5+y_6+y_7+y_8)/4$	40	$(y_2+y_6+y_{10})/3$
9.5	$(y_9+y_{10}+y_{11}+y_{12})/4$	60	$(y_3+y_7+y_{11})/3$
		80	$(y_4+y_8+y_{12})/3$

Based on a sample of an experimental data array (Table. 3) the construction of partial dependencies of the response functions on the thickness and temperature of the plastic was carried out.

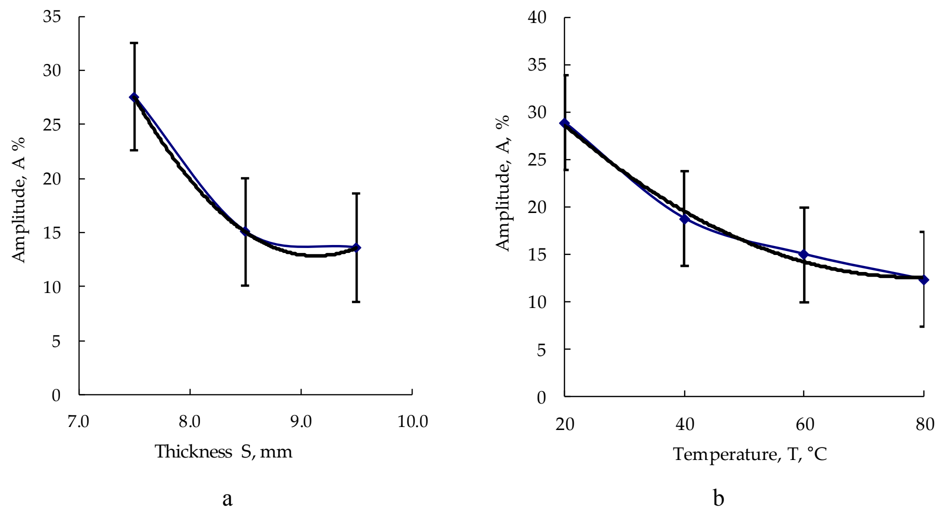


Fig 2. Partial dependences of the response functions of the bottom signal amplitude (a – from thickness; b – from temperature).

Further, these functions were combined into a multifactorial statistical mathematical model (generalized equation) based on the proposed [13] semi-empirical formula (1):

$$Y_0 = \frac{\prod_{i=1}^{p} Y_i}{Y_{av}^{p-1}}, \tag{1}$$

where Y_o – generalized equation; Y_i – private function; $\prod_{i=1}^{p} Y_i$ – the product of all partial functions; p – the number of partial functions equal to the number of input factors; Y_{av}^{p-1} – the arithmetic mean of all the experimental values of the response function taken into account (the general average) to a degree one less than the number of partial functions.

Each particular dependence was approximated by a function of one variable, then these functions were combined into a multifactorial statistical mathematical model (generalized equation) based on the proposed semi-empirical formula (1) [13]:

$$A = \frac{\left(5.5 \cdot S^2 - 100.5 \cdot S + 471.96\right) \cdot \left(0.0047 \cdot T^2 - 0.7325 \cdot T + 41.417\right)}{17.25}, \%. \tag{2}$$

where A- the amplitude of the bottom signal, %; S – plastic thickness, мм; T – temperature, °C

The accuracy of the obtained multivariate statistical mathematical model was evaluated by calculating the coefficients of nonlinear multiple correlation (R) by (2):

$$R = \sqrt{1 - \frac{(n-1) \cdot \sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2}{(n-p-1) \cdot \sum_{i=1}^{n} \left(y_i - \bar{y}\right)^2}}, \tag{3}$$

where n – number of experiments; p – number of input (independent) parameters; i – serial number of the experiment; y_i – the actual value of the output parameter in the i - th experiment; $\hat{y}_i$ – the calculated value of the output parameter, calculated using a multifactorial mathematical model, for the conditions (values of input parameters) of the i - th experiment; $\overline{y}$ – the average value of the actual value of the output parameter for all n experiments (the general average).

As a result of the calculation according to the equation (3) R=0,905, what is acceptable.

4 Conclusion

By the method of probabilistic-deterministic planning, a formula is derived that takes into account the combined effect of temperature and plastic thickness on the amplitude of the ultrasonic signal. For the proposed formula, the coefficient of nonlinear-multiple correlation is calculated equal to (0.905), which is the criterion for the reliability of the proposed mathematical model.

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