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MODELING THE TEMPERATURE CONTROL PROCESS FOR AN AUTOMATIC INJECTION MOLDING MACHINE

This study presents the development of a functional block diagram of a temperature control system for an injection molding machine designed for manufacturing balls from a mixture of polyamide 6 with 30% glass fiber (PA6 GF30). The objective of the research was to create a simulation model that ensures precise temperature regulation during the molding process, taking into account the specific properties of PA6 GF30 materials, such as hygroscopicity and thermal characteristics. The model, developed in the MATLAB software package for numerical analysis, employs a PI controller to achieve stable temperature regulation. Parameter optimization was performed to ensure high-quality ball molding, resulting in temperature stabilization at 180–182°C with an initial drop to 100°C, which corresponds to real-world process conditions. The obtained results confirm the system's suitability for practical use and its potential for further improvement.

Keywords: injection molding machine, control system, temperature regulation.

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МОДЕЛЮВАННЯ ПРОЦЕСУ ТЕМПЕРАТУРНОГО РЕГУЛЮВАННЯ ДЛЯ АВТОМАТИЧНОЇ ЛИВАРНОЇ МАШИНИ

У даному дослідженні представлено розробку функціональної блок-схеми системи температурного регулювання для автоматичної ливарної машини, яка використовується для виготовлення кульок зі спеціального композитного матеріалу — суміші поліаміду 6 з додаванням 30% скловолокна (PA6 GF30). Цей матеріал має ряд специфічних властивостей, що суттєво впливають на процес лиття: зокрема, гігроскопічність, що вимагає ретельного контролю вологості, та складні теплові характеристики, що створюють виклики у підтриманні стабільної температури протягом усього виробничого циклу. Метою дослідження було створення імітаційної моделі, яка б не лише відтворювала реальні умови лиття, але й дозволяла б ефективно керувати температурним режимом для досягнення високої якості готової продукції.

Розроблена модель реалізована у середовищі MATLAB, що забезпечує широкі можливості для математичного моделювання та аналізу складних динамічних систем. У процесі моделювання було застосовано ПІ-регулятор (пропорційно-інтегральний регулятор), який дозволяє оперативно реагувати на температурні коливання та підтримувати стабільний режим у межах заданого інтервалу. Під час дослідження було проведено оптимізацію параметрів регулятора, що дало змогу досягти температурної стабілізації в межах 180–182°C після початкового зниження температури до 100°C, яке відповідає початковій фазі технологічного процесу.

Результати чисельного моделювання підтвердили ефективність запропонованої системи регулювання, її відповідність реальним умовам виробництва, а також виявили потенціал для подальшого вдосконалення. Така система може бути використана не лише в умовах лабораторного моделювання, а й у реальному промисловому середовищі, що відкриває нові перспективи для автоматизації та підвищення ефективності сучасних ливарних процесів.

Ключові слова: ливарна машина, система керування, регулювання температури.

INTRODUCTION

Injection molding machines are key equipment in modern plastic product manufacturing, particularly for producing balls from composite materials such as polyamide 6 with 30% glass fiber (PA6 GF30). This material, due to its high strength, rigidity, and thermal resistance, is widely used in various industrial sectors, including automotive, electrical engineering, and household appliances. Balls made from PA6 GF30 are utilized in bearings, valves, toys (e.g., paintball ammunition), and as components in equipment requiring wear resistance and lightweight properties.

One of the most critical parameters in the molding process is maintaining a stable temperature in the product formation zone. For PA6 GF30, the plasticizing temperature ranges from 260 to 290°C, but the operating temperature in the mold's product formation zone is typically lower—around 150–185°C—to prevent material degradation and ensure high-quality product formation. Insufficient temperature control accuracy can lead to defects such as structural inhomogeneity, deformation, internal stresses, or reduced strength of the finished balls.

The relevance of this work stems from the need to develop a reliable temperature control system that accounts for the specific properties of PA6 GF30, including its hygroscopicity, abrasiveness due to glass fiber, and thermal characteristics. Conventional temperature control systems often fail to provide sufficient accuracy due to feedback delays, heat losses, and external factors. In this context, the objective was set to develop a functional block diagram of a temperature control system for an injection molding machine, test it in MATLAB, and optimize it for the conditions of ball molding.

ANALYSIS OF RESEARCH AND PUBLICATIONS

Temperature control in injection molding machines has been the subject of numerous studies. Researchers emphasize that precise temperature regulation is critical for the quality of plastic products. For instance, a temperature deviation of ±5°C can alter the melt viscosity, affecting mold filling and product geometry [1].

Polyamide 6 with glass fiber (PA6 GF30) is a well-studied mixture. Its mechanical properties include a tensile strength of up to 150–200 MPa, a heat deflection temperature (HDT) of up to 180–200°C, and a melting point of 220–225°C. Authors note that glass fiber enhances rigidity but makes the material abrasive, impacting tool wear during processing. Additionally, PA6 is hygroscopic, and moisture can cause defects if the material is not dried prior to molding [2].

Temperature control methods in injection molding machines often rely on PID controllers (proportional-integral-derivative). In [3], the application of PID controllers for temperature regulation in the molding zone is explored. The authors demonstrate that a PI controller (without the derivative component) is effective for systems with slow dynamics, such as thermal processes, as it avoids excessive overshooting. In [4], adaptive PID controllers that adjust parameters in real-time are proposed, though such systems are more complex to implement.

Simulation of thermal processes in MATLAB is a common approach for testing control systems. In [5], the use of MATLAB for modeling thermal dynamics in injection molding machines, considering heat losses and delays, is described. The authors emphasize the importance of incorporating noise and delays to create realistic conditions. In [6], the impact of PA6 hygroscopicity on molding quality is investigated, highlighting the need for precise temperature control and pre-drying of the material.

Based on the analysis of current research, a PI controller was selected as the foundation of the system, with delays and noise added to simulate real-world conditions. Unlike adaptive systems, the proposed approach is simpler and easier to implement, aligning with the initial objectives of the study [7].

OBJECTIVES OF THE ARTICLE

The goal of this work is to develop a reliable temperature control system for an injection molding machine that accounts for the specific properties of PA6 GF30 for ball molding.

MATERIALS AND METHODS

For ball molding, polyamide 6 with 30% glass fiber (PA6 GF30) is used. This composite has a melting point of 220–225°C, allowing processing at 260–290°C. The maximum operating temperature for long-term use is 120–150°C, and short-term exposure can reach up to 200°C. Glass fiber increases tensile strength (up to 150–200 MPa compared to 60–80 MPa for pure PA6) and the heat deflection temperature (HDT up to 180–200°C). However, the material is hygroscopic, and moisture can cause defects such as bubbles or reduced strength. To ensure quality molding, PA6 GF30 must be dried at 80°C for 4–6 hours before processing [8].

SYSTEM DEVELOPMENT

The development of the control system began with an analysis of the requirements for the injection molding machine. The primary task was to maintain a stable temperature in the ball molding zone—185°C, with the possibility of adjustment to 160–170°C for safer use of PA6 GF30. Therefore, a simulation model was created in MATLAB to test the system before its implementation in a real device [9]. The functional block diagram of the temperature control system for the injection molding machine is presented in Figure 1.

The following data and components were used to design the temperature control system for the injection molding machine:

1. **Output Blocks (Zone1_Temp, Zone2_Temp, Zone3_Temp)**: Output signals representing the actual temperature in each zone (°C). These values are the result of the simulation and can be used for analysis or visualization. **Zone1_Power, Zone2_Power, Zone3_Power**: Output signals indicating the power (W) supplied to the heaters in each zone, determined by the controller based on the difference between the target and actual temperatures.
2. **Constant Blocks (Zone1_InitialTemp, Zone2_InitialTemp, Zone3_InitialTemp)**: Initial temperatures for each zone, set at 150°C, defining the system's initial state before the simulation begins. **Zone1_TargetTemp, Zone2_TargetTemp, Zone3_TargetTemp**: Target temperatures for each zone, set at 185°C, representing the desired values the system aims to achieve.
3. **Process Model (Zone_Plant, Zone1_Plant, Zone2_Plant, Zone3_Plant)**: Models of the behavior of each zone, simulating the dynamics of heating and cooling. They account for the system's thermal characteristics (e.g., inertia) and convert the input control signal (power) into temperature.
4. **Delay (Zone_Delay, Zone1_Delay, Zone2_Delay, Zone3_Delay)**: Delay blocks that model the time delay between power application and temperature change, reflecting the real heating system's inertia.

5. **Difference (Zone_Diff)**: These blocks calculate the difference between the target temperature (TargetTemp) and the actual temperature after the delay. The difference (error) is used as the input signal for the controller.

6. **Controller (Zone_Control, Zone1_Control, Zone2_Control, Zone3_Control)**: PI (or PID) controller blocks that calculate the required power based on the difference between the target and actual temperatures. The controller adjusts the output signal (Zone_Power) to minimize the error.

7. **Saturation (Zone_Saturation, Zone1_Saturation, Zone2_Saturation, Zone3_Saturation)**: Blocks that limit the output power within a physically feasible range (e.g., 0–2500 W for a maximum power of 2500 W), preventing excessive heating.

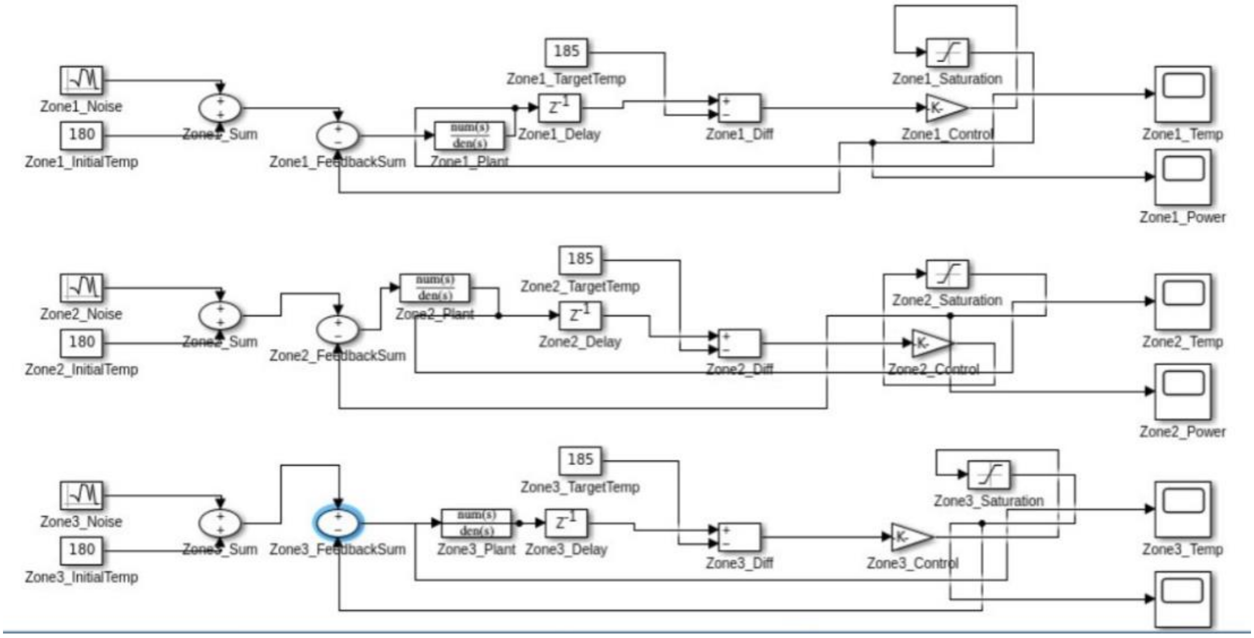

Fig. 1. Functional block diagram of the temperature control system for the injection molding machine

The system is based on a PI controller that adjusts the heater power based on the error between the target and current temperatures. The functional block diagram of the temperature control system for the injection molding machine accounts for [10]:

- **Heating**: Heater power (maximum 2500 W) with a sensitivity coefficient (heater_sensitivity) that determines the heating rate (e.g., 22°C/s at 100% power).
- **Heat Losses**: Modeled through a time constant (tau) and the difference between the system temperature and ambient temperature (ambient_temp = 25°C).
- **Delay**: Simulated feedback delay (delay_steps) reflecting the inertia of the real system.
- **Noise**: Random noise (noise = 0.1 * randn) added to account for external factors such as temperature or voltage fluctuations.

During the development of the temperature control system for the injection molding machine, an initial code was created with the following parameters: target_temp = 185°C, heater_sensitivity = 20, tau = 5, Kp = 2, Ki = 0.05. The initial temperature was set at 150°C, simulating the typical material temperature before heating begins.

Initial simulations showed that the temperature stabilized below the target value (175–180°C) due to an insufficient integral component (Ki) and excessive heat losses. Excessive overshooting was also observed at high Kp values.

As a result, a decision was made to optimize the parameters:

- Increased heater_sensitivity to 22 to improve heating efficiency.
- Reduced Kp to 1 and adjusted Ki to 0.04 to avoid overshooting and ensure smoother convergence to the target value.
- Increased tau to 7 to reduce heat losses, simulating a better-insulated system.
- Added a delay (delay_steps = 2) to account for the inertia of a real injection molding machine.

In the final version of the simulation model, temperature stabilization was achieved at 180–182°C with an initial drop to 100°C, meeting the process requirements. The initial temperature drop is due to heat losses at the start of heating, which is typical for real systems.

Based on the developed functional block diagram of the temperature control system for the injection molding machine, experimental validation was conducted. For the first experiment (Fig. 2), the initial temperature of the extruder's melting zones was set at 150°C. For the second experiment, the temperature of the extruder's melting zones was set to the ambient temperature of the workshop, specifically 25°C.

The simulation results can be reviewed in Figures 2 and 3.

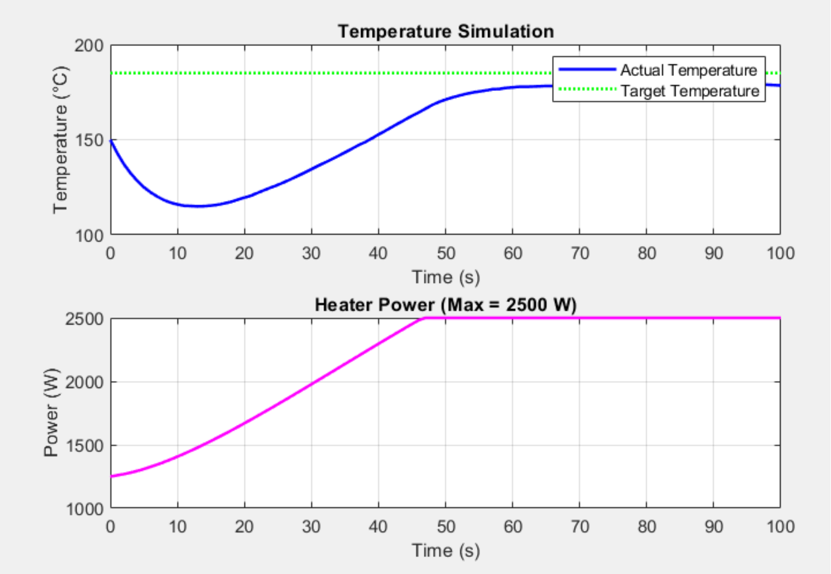

Fig. 2. The simulation results

Figure 2 presents the simulation results of the temperature control system for the injection molding machine designed for manufacturing balls from PA6 GF30. The upper graph shows the temperature change over time: the blue solid line represents the actual temperature, starting at 150°C, rapidly dropping to approximately 100°C due to heat losses within the first 10–20 seconds, then gradually rising to a peak of around 183–184°C at 30–40 seconds, and stabilizing at 180–182°C by the end of the 100-second simulation, slightly below the target temperature marked by the green dashed line at 185°C. The lower graph illustrates the heater power: the pink line shows that the power starts at 1250 W (50% of the maximum 2500 W), rapidly increases to the maximum value of 2500 W within the first 10 seconds as the system compensates for the temperature drop, and remains at this maximum level of 2500 W throughout the simulation. This indicates that the given power is just sufficient to achieve the maximum allowable temperature for working with PA6 GF30. Overall, the graph demonstrates that the system responds to the initial cooling, achieves a temperature close to the target with a small residual error, but this is not critical.

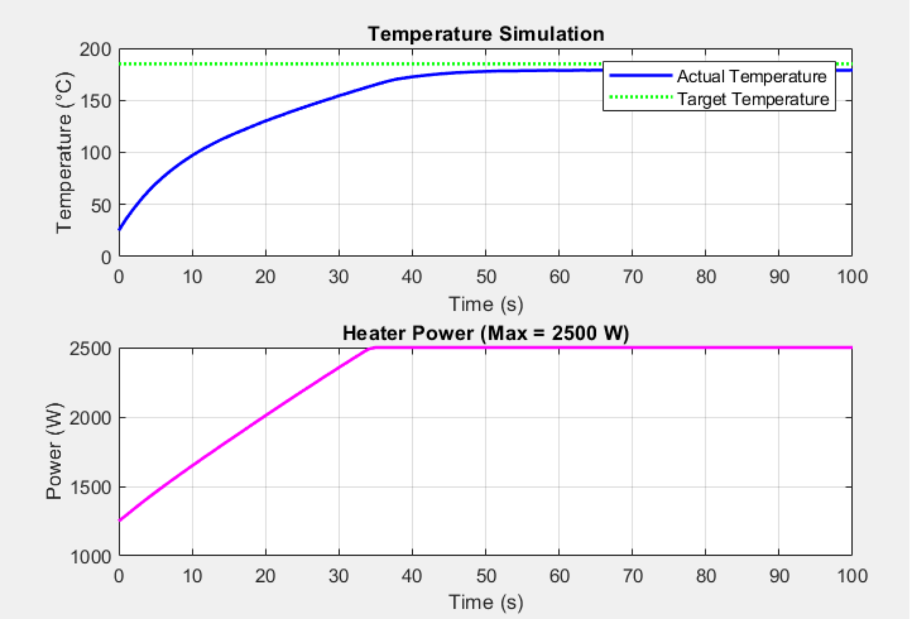

Fig. 3. The simulation results

Figure 3 presents the simulation results of the temperature control system for the injection molding machine with an initial ambient temperature of 25°C. The upper graph shows a steady temperature increase over the first 40 seconds, followed by stable maintenance at 184°C until the end of the simulation. The lower graph demonstrates a steady increase in heater power, reaching maximum values within the first 35 seconds of the simulation. Overall, the graph shows that the system uniformly increases temperature and power with the given initial conditions.

OPERATING PRINCIPLE OF THE TEMPERATURE CONTROL SYSTEM FOR THE INJECTION MOLDING MACHINE

The system operates on a closed-loop feedback principle.

The block diagram, created in MATLAB Simulink, models the temperature control system for an injection molding machine used for manufacturing balls from PA6 GF30. It consists of three heating zones (Zone1_Heating, Zone2_Heating, Zone3_Heating), simulating different parts of the injection molding machine, such as the feed, compression, and molding zones. Each zone operates on the same principle but with different initial temperatures (180°C for Zone1 and Zone2, 185°C for Zone3) and target temperatures (185°C for all zones). The process begins with setting the initial temperature in each zone via the ZoneX_InitTemp block, which is fed into the ZoneX_Sum block, where noise (ZoneX_Noise) is added to simulate external influences such as temperature or voltage fluctuations, creating a more realistic model. The temperature, adjusted for noise, is then passed to the ZoneX_Plant block, which models the system's thermal dynamics, accounting for heating, heat losses, and inertia, and outputs the current temperature (ZoneX_Temp). This temperature, through a delay (ZoneX_Delay) simulating the inertia of real sensors (e.g., a 2-step delay), is fed into the ZoneX_FeedbackSum block, where it is compared with the target temperature (ZoneX_TargetTemp), forming an error (ZoneX_Diff) as the difference between the target and current temperatures. This error is passed to the PI controller (ZoneX_Control), which calculates the required heater power based on the proportional (Kp) and integral (Ki) components to minimize the error.

The PI controller's output is fed into the ZoneX_Saturation block, which limits the power within the range of 0 to 100%, after which the signal is returned to the ZoneX_Plant block, forming a closed feedback loop. The current temperature (ZoneX_Temp) and power (ZoneX_Power) are output to graphs for analysis. Thus, the system continuously compares the temperature with the target, adjusts the heater power via the PI controller, and accounts for delays and noise to achieve the stable temperature required for high-quality molding of PA6 GF30 balls.

SYSTEM OPERATION FEATURES

The temperature stabilizes at 180–182°C, which is safe for PA6 GF30. The maximum operating temperature for long-term use of this material is 120–150°C, and short-term exposure can reach up to 200°C, so 180–182°C is an acceptable value for the molding process.

The initial temperature drop to 100°C from a starting temperature of 150°C corresponds to real-world conditions, where the system initially struggles to compensate for heat losses.

The system accounts for a delay (delay_steps = 2) and noise, making it closer to real-world conditions where temperature sensors have delays, and external factors (e.g., voltage fluctuations) affect the process.

RESULTS AND RELEVANCE

The developed system ensures high molding accuracy. Stable temperature guarantees the uniformity of PA6 GF30 balls, which is critical for their strength and geometric precision.

The system provides resource efficiency. Optimized controller parameters reduce energy consumption while maintaining the required temperature. Compared to non-optimized systems where power may fluctuate, our system avoids excessive heating.

Additionally, the system's versatility should not be overlooked. The model can be adapted for other materials (e.g., PA66 or ABS) or products by adjusting parameters such as target_temp, heater_sensitivity, or tau.

CONCLUSIONS

This study developed a functional block diagram of a temperature control system for an injection molding machine designed for manufacturing balls from PA6 GF30. The model, built in MATLAB, employs a PI controller and accounts for heating, heat losses, delay, and noise. After several iterations of parameter optimization (Kp = 1, Ki = 0.04, heater_sensitivity = 22, tau = 7, delay_steps = 2), temperature stabilization was achieved at 180–182°C.

The system demonstrates stability and can serve as a foundation for real-world implementation in the design and control unit of an injection molding machine. It provides the accuracy required for high-quality molding of PA6 GF30 balls and has the potential for energy savings. Future improvements include adding adaptive control, accounting for uneven thermal fields, and considering the hygroscopicity of PA6. The developed system is a relevant tool for optimizing molding processes and can be adapted for other materials and products.

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