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Temperature Control Algorithm for Roll-to-Roll Embossing

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Abstract

In this study, a temperature control algorithm based on PID control scheme was proposed for roll-to-roll embossing. The roll surface was heated using induction coils and cooled with circulating water, where the temperature of the roll surface was feedback controlled by the control algorithm that we proposed. Proportional band (PB), integral time, and derivative time components of the PID controller were calculated by the relay feedback method and the reaction curve method. The release of the controller output and connection between the roll and chiller were both simply switched on/off based on the margin between desired temperature and current temperature. The temperature controller rapidly raised roll temperature and shortened the cooling time by choosing an appropriate temperature margin. Consequently, the roll-to-roll embossing system equipped with the proposed controller may decrease the time required to find the optimal embossing process parameters.

Keywords: *Roll-to-roll embossing, Temperature control algorithm, Relay feedback method, Reaction curve method*

1. Introduction

Roll-to-roll embossing has advantages of larger area and faster speed compared to plate embossing. However, the reduction in force holding time due to the smaller contact area between two rollers can result in a reduction in pattern quality [1-3]. This potential disadvantage can be partially compensated by optimizing the process parameters (e.g., operating parameters such as roll surface temperature). There are several operating parameters that influence the pattern quality of roll-to-roll embossing, including roller temperature, preheating temperature, roller speed, web tension, and applied pressing force which are generally considered as major factors. Practically, those operating parameters were determined using process optimization or simply trial and error method. For example, the effects of changing process parameters on embossed pattern qualities have been investigated by a number of research groups [4-9]. However, unfortunately the parameter studies are typically carried out under limited conditions because it is not technically possible to take all the parameters and corresponding ranges into consideration to find globally optimal values for highest pattern quality. Moreover, each experiment normally takes a considerable amount of time due to the time needed to raise and decrease the roll temperature. In this study, roll-to-roll embossing system equipped with a temperature controller was developed and tested whether the embossing system could be used to effectively shorten the search for the optimal processing parameters by reducing the time required to change and stabilize the roll temperature by manually choosing an appropriate temperature margin.

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2. Methods

2.1. Roll-to-Roll Embossing System

The lab-scale roll-to-roll embossing system was developed for use in micro-patterning process (**Fig. 1**). Two same size rollers (i.e., pattern roll and pressure roll shown in **Fig. 1**) were located horizontally and feedback controlled by servomotors to rotate at same speed but in opposite directions to keep substrate moving forward. The pattern roll was firmly mounted on the frame structure, and the pressure roll was guided to push the pattern roll straightly, powered by an electro-hydraulic system.

The pattern roll surface was heated using induction heat coils and cooled with a circulating water system (i.e., chiller). Induction heat coils were located at the core of the pattern roll to heat the surface, and cooling related pipes were placed above the coils below the pattern circumference to rapidly decrease the pattern temperature. The cooling water temperature was set to 10 °C with a discharge pressure of 2 bars. Details of the induction heating methodologies have been reported in previously published paper [10].

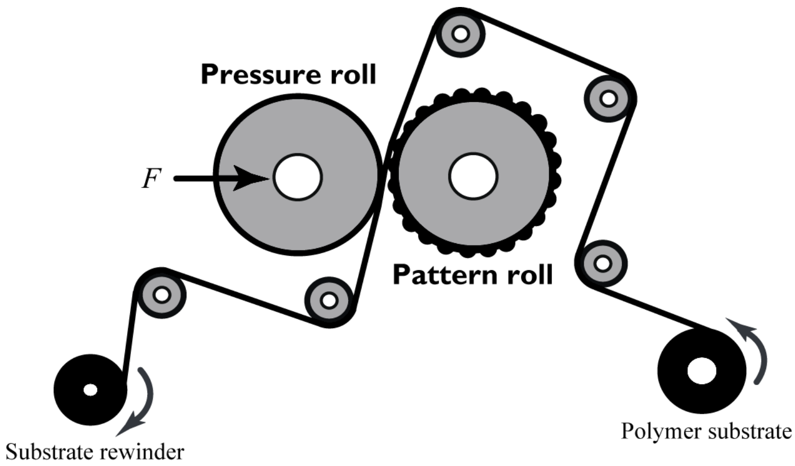

Figure 1: Schematic of the lab-scale roll-to-roll embossing system

2.2. Temperature Control Algorithm

The roll temperature controller was newly designed to achieve the target temperature (**Fig. 2**). The desired temperature was basically reached by compensating the state error ε between desired temperature T_d and current temperature T_c based on the proportional-integral-derivative (PID) control scheme. However, the error compensation was strictly limited to the valid range of a control signal due to the maximum allowable power flow.

The release of the controller output power u, which was generated by a power regulator, and the connection between the pattern roll and the chiller (i.e., circulating water cooling system) were continuously being monitored and determined by the temperature control algorithm (i.e., integration of PID controller and simple on/off controller; **Fig. 2**). In the heating process, u was fully released to the induction heat coils but the chiller was always switched off. However, during the cooling process (i.e., the desired temperature is lower than the current temperature), u was thoroughly isolated from being released and the chiller was switched on when ε + margin < 0, whereas u was released and the chiller was switched off when ε + margin ≥ 0. While chiller was switched on, cooling fluid circulated through the cooling pipes, resulting in a reduction in the pattern temperature (i.e., roll surface temperature).

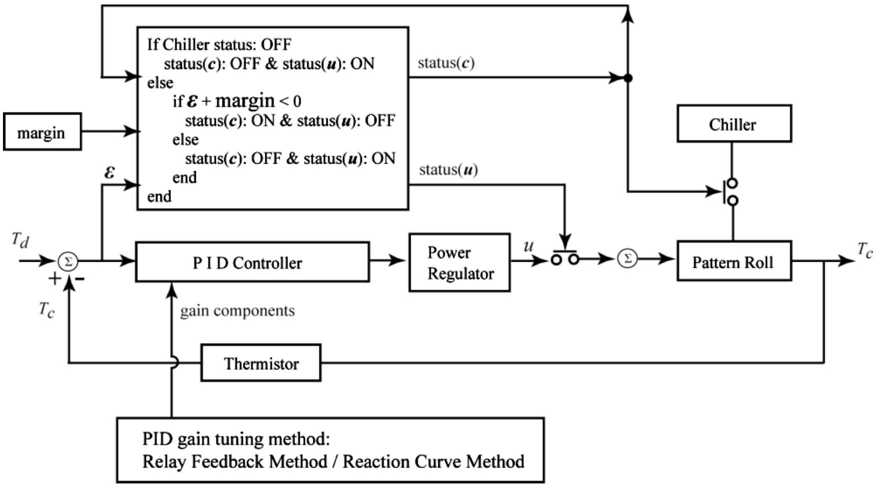

Figure 2: Control block diagram of the roll-to-roll embossing system equipped with the temperature controller.

2.3. Selection of PID Gain Components

Control gains were selected using PID gain tuning methods, i.e., relay feedback method and reaction curve method suggested by Astrom-Hagglund and Ziegler-Nichols, respectively [11-16]. These tuning methods required only a single experimental test rather than a trial-and-error procedure, therefore the experimental data of the single trial was employed to quickly calculate the gain components of the PID controller. To ensure the values, the experiment and the calculation were repeated.

2.3.1. Relay Feedback Method: The amplitude of the controller output (relay output) was set to 50 % and controlled the amplitude of oscillations in the temperature measurement where a desired temperature was 100 °C. Roller temperature and relay output were sequentially recorded for approximately 1000 s, and then, proportional band (PB), integral time (τ_i), and derivative time (τ_d) components of the PID controller were calculated as follows: PB = $100/(0.6K_u)$, $\tau_i = T_u/2$, and $\tau_d = T_u/8$, where K_u (= $4d/\pi a$) and T_u are ultimate gain and ultimate period, respectively (**Fig. 3**).

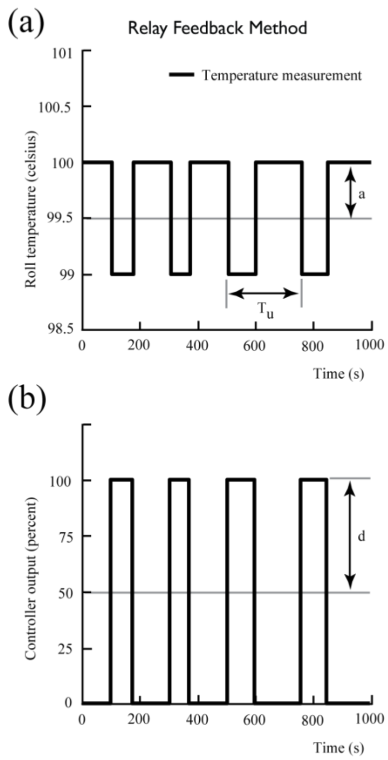

Figure 3: (a) Process output (roll temperature) and (b) relay output (controller output) were recorded for approximately 1000 s when the desired temperature was set to 100 °C. "a", "T_u", and "d" indicate process output amplitude, ultimate period, and relay output amplitude, respectively.

2.3.2. Reaction Curve Method: A step change (Δu = 25 %) of controller output from 60 % to 85 % was applied, and the roll temperature measurement, which is called the reaction curve, was used to calculate the maximum slope (N) and the delay (D) (**Fig. 4**). Proportional band (PB), integral time (τ_i), and derivative time (τ_d) of the PID controller were calculated as follows: PB = ND/1.2Δu, τ_i = 2D, τ_d = 0.5D, where ND was then normalized by total range.

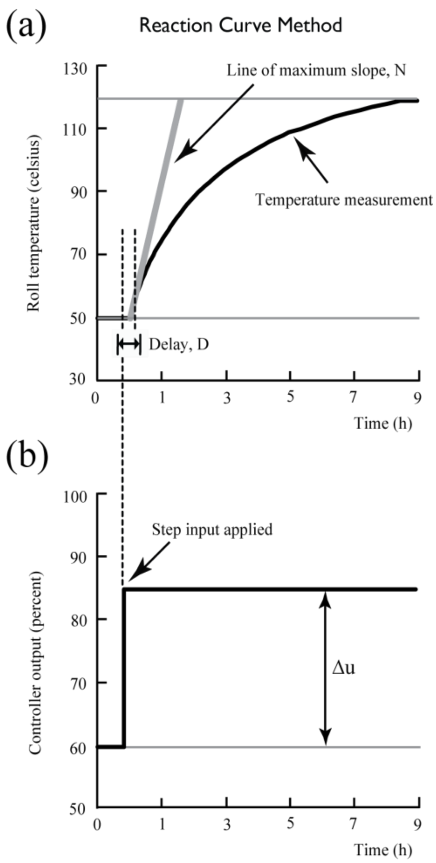

Figure 4: The Ziegler-Nichols reaction curve method based on an open-loop step response. (a) Process output (roll temperature) and (b) step input (controller output) were recorded for about 9 hrs until the roll temperature was saturated at 119 °C. "N" and "D" indicate maximum slope and delay, respectively.

2.4. Roller Performance Testing

To examine whether PID gains were appropriately found by the gain tuning methods, the roll surface temperature was regulated at 80 °C for 20 mins and then heated to target temperature 100 °C. During the experiment, the trajectories of the roll surface temperature and controller output percent were recorded as functions of time. To examine the performance of the suggested temperature controller depending on the manually selected margin value, the pattern roll was cooled from 100 °C to 95 °C. The temperatures corresponding to different margins (i.e., natural cooling, zero margin, and 3 °C margin) were recorded as functions of time sequentially and were plotted on the same graph for comparison.

3. Results

3.1. Selected Gain Components

Proportional band (PB = 0.1 %), integral time (τ_i = 115 s), and derivative time (τ_d = 29 s) of the PID controller were calculated by the relay feedback method, whereas PB = 0.2 %, τ_i = 184 s, τ_d = 46 s were obtained by the reaction curve method. Because process output responses with gains derived from the relay feedback method were not significantly different from those with gains from the reaction curve method in heating and temperature regulation tests, finally, proportional band, integral time, and derivative time components of the PID controller were set to 0.1 %, 115 s, and 29 s, respectively, by accepting the gains from the relay feedback method.

3.2. Heating and Temperature Regulation Tests

The roll surface temperature was well maintained at 80 °C with a small deviation of 1 °C, and the roller was also able to reach the target temperature of 100 °C with an almost steady rate of increase (**Fig. 5A**). During the regulation at a given temperature (i.e., 80 °C), the controller output percent continuously changed within the range of 35 to 85 % (**Fig. 5B**), which could prevent the surface temperature from falling due to the difference between the roller surface temperature and laboratory temperature.

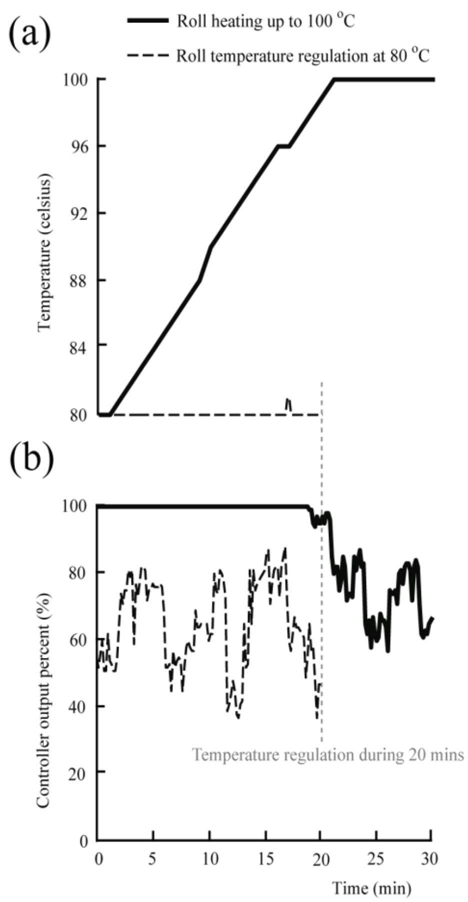

Figure 5: Roll heating tests with the selected proportional-integral-derivative (PID) gains from the relay feedback method: Trajectories of (a) roll surface temperature and (b) controller output percent with the time change.

3.3. Temperature Trajectories depending on the Margins

Cooling with zero margin showed a nearly −3 °C undershoot and took a longer time to reach the desired steady states (95 °C) than other conditions, even slower than natural cooling (**Fig. 6**). Cooling with 3 °C margin showed small undershoot, −1 °C, but took the shortest time to reach the desired steady state (**Fig. 6**).

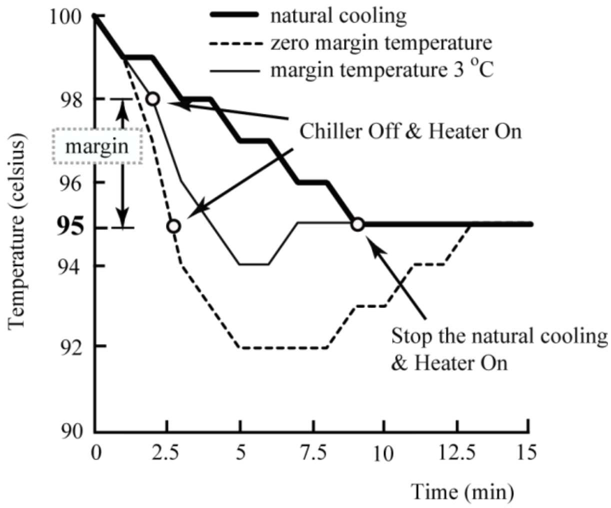

Figure 6: Roll cooling tests with different margins: Pattern roll equipped with the temperature controller was cooled from 100 °C to 95 °C. The cooling temperature trajectories corresponding to natural cooling, zero margin, and 3 °C margin are shown below, with different line styles.

Conclusion

It is expected that the roll-to-roll embossing system equipped with the proposed control algorithm could reduce a considerable amount of time required to change and stabilize the roll temperature by manually selecting an appropriate temperature margin, resulting in the reduction of the time needed to find the optimal embossing process parameters, assuming that heating/cooling performances do not change (i.e., settings for both heater and chiller are fixed with limited power consumption).

ACKNOWLEDGEMENTS

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Conflicts of Interest

The authors declare no conflict of interest.

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