AIP | Review of Scientific Instruments

Hot roller embossing system equipped with a temperature margin-based controller

Seyoung Kim, Youngsu Son, Sunghee Lee, Sangyong Ham, and Byungin Kim

Citation: Review of Scientific Instruments **85**, 085117 (2014); doi: 10.1063/1.4893013
View online: http://dx.doi.org/10.1063/1.4893013
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/85/8?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in

Development of roll-to-roll hot embossing system with induction heater for micro fabrication
Rev. Sci. Instrum. **83**, 015108 (2012); 10.1063/1.3675574

Experimental study of influential process parameters in hot embossing for micropattern formation on low temperature cofirable ceramic green substrates
J. Vac. Sci. Technol. B **27**, 1437 (2009); 10.1116/1.3056175

Experimental and numerical analyses on recovery of polymer deformation after demolding in the hot embossing process
J. Vac. Sci. Technol. B **26**, 2399 (2008); 10.1116/1.2987956

Preparation Model Based Control System For Hot Steel Strip Rolling Mill Stands
AIP Conf. Proc. **1019**, 191 (2008); 10.1063/1.2952977

Temperature Controller System for Gas Gun Targets
AIP Conf. Proc. **845**, 1245 (2006); 10.1063/1.2263550

AIP | Journal of Applied Physics

Journal of Applied Physics is pleased to announce André Anders as its new Editor-in-Chief

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26

Hot roller embossing system equipped with a temperature margin-based controller

Seyoung Kim,[a] Youngsu Son, Sunghee Lee, Sangyong Ham, and Byungin Kim
Department of Robotics and Mechatronics, Korea Institute of Machinery and Materials (KIMM), Daejeon, South Korea

(Received 14 March 2014; accepted 2 August 2014; published online 19 August 2014)

A temperature control system was proposed for hot roller embossing. The roll surface was heated using induction coils and cooled with a circulating chilled water system. The temperature of the roll surface was precisely controlled by a temperature margin-based control algorithm that we developed. Implementation of the control system reduced deviations in the roll surface temperature to less than $\pm 2\,^{\circ}$C. The tight temperature control and the ability to rapidly increase and decrease the roll temperature will allow optimum operating parameters to be developed quickly. The temperature margin-based controller could also be used to optimize the time course of electrical power and shorten the cooling time by choosing an appropriate temperature margin, possibly for limited power consumption. The chiller-equipped heating roll with the proposed control algorithm is expected to decrease the time needed to determine the optimal embossing process. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4893013]

I. INTRODUCTION

Hot embossing, which makes fine structures on the surface of polymer substrate (e.g., PMMA) by patterning the polymer with an appropriate heat transfer, can be categorized into two general types of embossing process, i.e., roller embossing and plate embossing, depending on the patterning instrument.[1] Hot roller embossing has the advantages of larger area and faster speed compared to hot plate embossing. The reduction in force holding time is a disadvantage, which can result in a reduction in embossed pattern quality.[2–4] This potential disadvantage can be partially offset by optimizing the process parameters. Therefore, an optimum design of the processing condition is necessary to replicate high quality patterns using hot roller embossing.

Several factors (operating parameters) influence the pattern quality of hot roller embossing, including roller temperature, preheating temperature, roller speed, and applied force, which are generally considered to be major factors. In practice, the actual operating parameters are determined via optimization and/or the trial-and-error method.[5–8] The effects of changing the process parameters on embossed pattern qualities (e.g., embossed pattern depth ratio) have long been investigated by many research groups.[5–10] Unfortunately, parameter studies are typically carried out under limited conditions because taking all the parameters and corresponding ranges into consideration to find globally optimal values for obtaining the highest pattern quality is time consuming.

Design of Experiment (DOE) methodologies have often been employed to optimize the hot embossing parameters relatively quickly.[7,11] However, the number of process parameters for the optimization was limited to only three or four factors because the addition of an input parameter significantly increases the number of experimental trials. The number of trials is especially important because each experiment normally takes a considerable amount of time due to the time required to change and stabilize the roll temperature (i.e., heating and cooling).

Temperature adjustable rollers have been previously developed to change and stabilize the roll surface temperature, however most rollers were designed to have limited functions: active heating but passive (or natural) cooling. For example, a hot roller embossing system with induction heater was recently proposed by Yun *et al.*,[1] where induction heat coils were installed at the core of the roll and the surface temperature was adjusted with a closed-loop temperature control based on the induction heating technique. The proposed heating roll could achieve a more uniformly distributed temperature on the surface of the roll compared to that of other rolls heated by electric wires. However, due to the lack of appropriate cooling system, it still could not prevent the parameter optimization from taking a considerable amount of time (i.e., time of natural cooling), which results in the needs for the new heating roll system equipped with an active cooling mechanism.

In this study, a chiller-equipped heating roll system was developed and tested to determine whether a highly controlled embossing machine could be used to effectively shorten the search for the optimal processing parameters. The roll surface is heated by induction and cooled with circulating water. Temperatures were precisely controlled using a temperature margin-based control algorithm which is a combination of a standard Proportional-Integral-Derivative (PID) controller for the heating cycles and the simplest bang-bang controller for the cooling cycles. A simple on/off logic with a predefined margin value was added to switch between the heating and cooling cycles. The experiments determined whether (1) rapid heating and cooling were appropriately achieved, (2) whether uniform temperature distributions were obtained,

[a]Author to whom correspondence should be addressed. Electronic mail: seyoungkim@kimm.re.kr. Telephone: +82-42-868-7614.

 © 2014 AIP Publishing LLC

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26

and (3) whether the temperature margin-based controller contributed to the efficiency and reproducibility of the hot roller embossing process, depending on the margin value.

II. METHODS

A. Overall structure of the hot roller embossing system

The lab-scale hot roller embossing system was developed for use in microfabrication (Figs. 1(a) and 1(b)). Two rollers having the same radius, one for patterning (i.e., the pattern roll) and the other for pressuring (i.e., the pressure roll), were located horizontally and feedback controlled by servomotors to rotate at same speed but in opposite directions. The pattern roll was mounted on the frame, and the pressure roll was guided to push the pattern roll in a straight line, powered by an electro-hydraulic system. The roller surface temperature was adjusted using induction heat coils (Fig. 2), and several auxiliary products were equipped to appropriately fine-tune the embossing parameters. A position roller and electric infrared heater (IR heater) were used to preheat the polymer substrate before an embossing, while a custom-designed air injector rapidly cooled the polymer substrate after the embossing (Fig. 1(b)).

B. Chiller-equipped heating roll system

The surface temperatures of the pattern and pressure rolls were precisely controlled using the induction heating

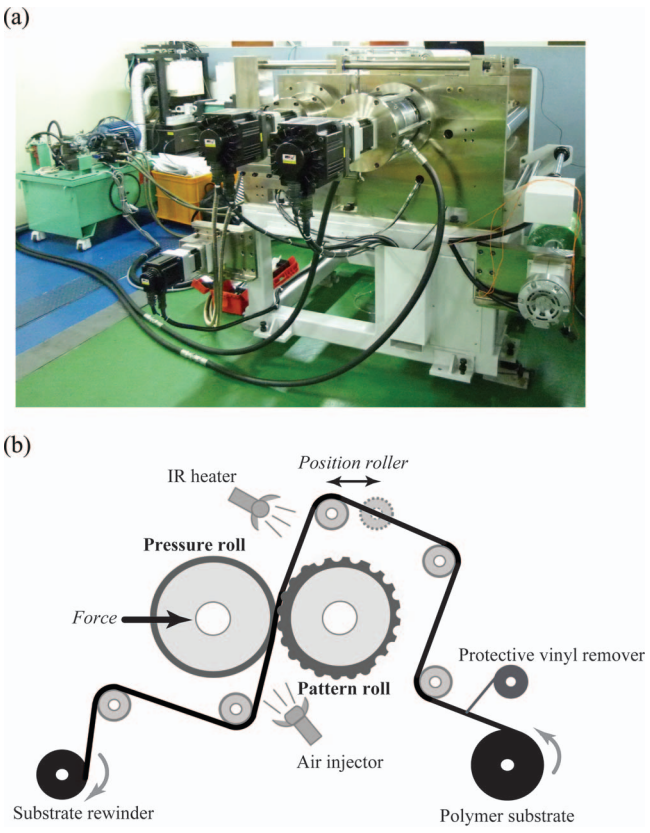


FIG. 1. (a) Lab-scale hot roller embossing system. (b) Schematic of the hot roller embossing system equipped with position roller, IR heater, and custom-designed air injector.

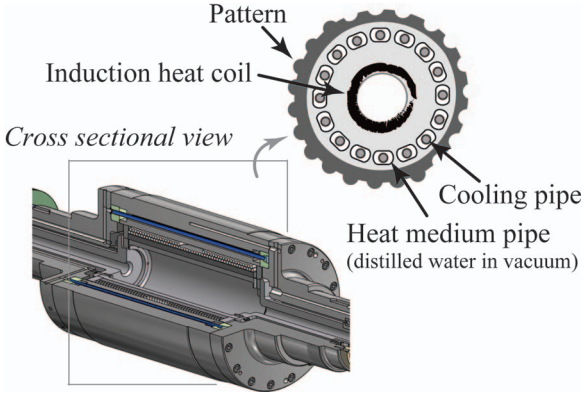


FIG. 2. Chiller-equipped heating roll system. Induction heat coils are located at the center of the pattern roll for heating, and cooling pipes are placed above the coils near the pattern circumference for cooling. Cooling water flows through the cooling pipe for heat transfer, while distilled water in a vacuum contributes to the important uniform distribution of the roller surface temperature.

methodology,[1,12,13] but only the pattern roll was equipped with the water-cooling system (Fig. 2). Induction heat coils were located at the core of the pattern roll to heat the surface, and cooling pipes were placed above the coils near the pattern circumference to decrease the temperature. Water flowed through the cooling pipe for heat transfer, while distilled water in the heat medium pipe contributed to the uniformly distributed surface temperature. The cooling water temperature was set at 10 °C with a discharge pressure of 2 bars to avoid condensation. Details of the induction heating methods have been reported previously.[1]

C. Temperature margin-based controller

The hot roller embossing controller (i.e., temperature margin-based controller) was newly designed to effectively control the roll surface temperature (Fig. 3). The desired temperature was reached by compensating the error ϵ between desired state T_d and current state T_c based on the PID control scheme. However, the error compensation value was limited to the valid range (4–20 mA) of a signal by upper and lower saturations due to the maximum allowable power flow. Then, the release of the control input power u, which was generated by a power regulator, and the coupling between the pattern roll and the chiller were continuously determined by the temperature margin-based control algorithm, where the margin was selected manually on the control panel. In the heating process, u was released to the induction heat coils, but the chiller was always switched off. However, during the cooling process, u was isolated and the chiller was switched on when ε + margin < 0, while u was released and the chiller was switched off when ε + margin ≥ 0.

D. Selection of PID gains

PID gains were selected using an on-line tuning method, i.e., relay feedback auto-tuning (Astrom-Hagglund Test),[14–17] which has several advantages over the ultimate cycle method (Ziegler-Nichols Test).[15,18,19] The on-line tun-

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26

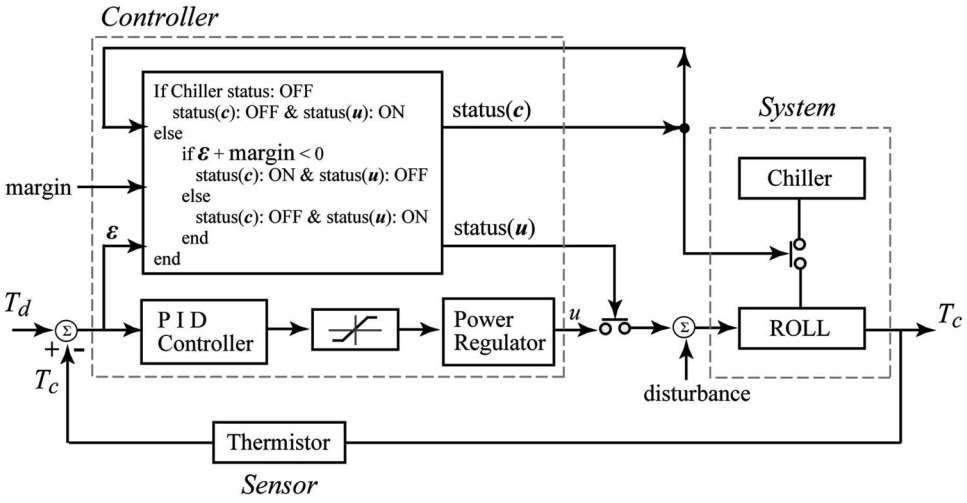


FIG. 3. Control block diagram of the hot roller embossing system. The desired temperature is reached by the PID closed-loop control, whereas release of the control input power and coupling between the roll and chiller are both switched on/off by the temperature margin-based controller. The margin is selected manually on the control panel.

ing method required only a single experimental test rather than a trial-and-error procedure, and the experimental test was simply automated using a digital temperature controller (NX4, HANYOUNG NUX, Korea). Proportional band, integral time, and derivative time components of the PID controller were set to 0.1%, 113 s, and 28 s, respectively.

E. Roller performance testing and data analysis

To determine whether PID gains were appropriately found, the roll surface temperature was regulated at 80 °C for 20 min and then continuously heated to 100 °C for approximately 30 min. During the experiment, the trajectories of the roll surface temperature and control input percent were recorded as functions of time (the experimental plan is shown in Table I).

To examine the uniform temperature distributions that contribute to the embossing quality, both the pattern and pressure rolls were continuously heated from 30 °C to 100 °C, and the lengthwise-distributed surface temperatures were measured using a digital thermometer (Testo 720, Germany) when the temperatures were 30, 50, 80, and 100 °C. Two rolls were then cooled from 100 °C to 30 °C, and the surface temperatures were measured again in the same way, but with different intervals.

To examine the efficiency of the temperature margin-based controller depending on the margin value, the pattern roll was cooled from 100 °C to 95 °C and 85 °C. The temperature, control input percent, and time-integrals of the control input power corresponding to various margin values were recorded sequentially. One-way ANOVA with post-hoc tests were performed on the data to examine the significant differences in the integrated control inputs corresponding to each temperature margin, with a level of significance of $p < 0.05$.

III. RESULTS

A. Heating and temperature regulation

The roll surface temperature was well regulated at 80 °C with a small change of ±1 °C, and the roller was also able to reach a target temperature of 100 °C with a steady

TABLE I. A detailed experimental plan.

Phase 1	Phase 2	Phase 3	Phase 4
Embossing machine setup • Pattern roll - Heating: induction heat coils - Cooling: water cooling system - Rotation: servomotor • Pressure roll - Heating: induction heat coils - Cooling: natural cooling - Rotation: servomotor - Pushing for pressurization: electro-hydraulic system	Controller design • Temperature margin-based controller - Heating cycles: standard PID control - Cooling cycles: simple bang-bang control	Roller performance testing • Roll heating from 80 to 100 °C • Temperature regulation at 80 °C • Uniform temperature distribution in lengthwise, at 30, 50, 80, and 100 °C • Control input power efficiency depending on margin values of 0, 3, 6, and 9 °C - Roller cooling-A: 100–95 °C - Roller cooling-B: 100–80 °C	Data analysis • One-way ANOVA With post hoc tests With a level of $p < 0.05$

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26

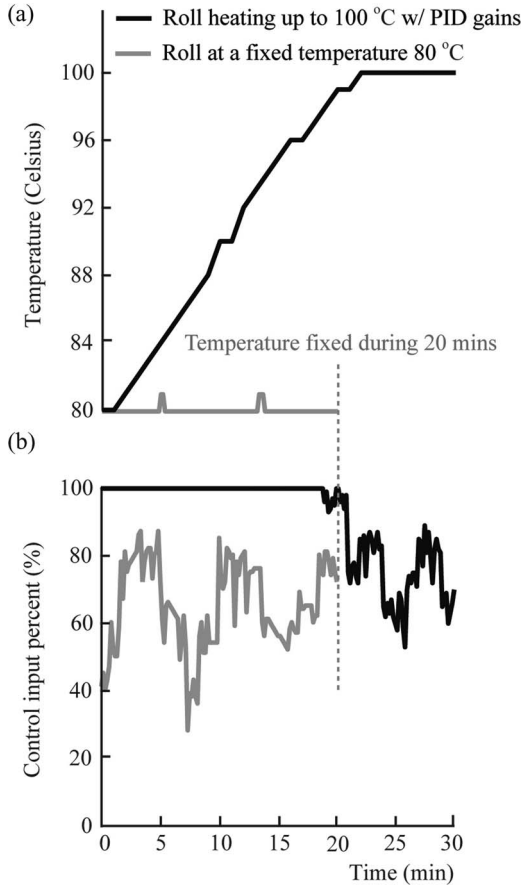


FIG. 4. Roll heating with the selected PID gains: Trajectories of (a) roll surface temperature and (b) control input percent when the pattern roll was continuously heated to 100 °C (black solid) and the temperature was maintained at 80 °C (gray solid).

rate of increase, without overshoot (Fig. 4(a)). During the regulation at a given temperature, the control input percent continuously changed within the range of 40%–80% (Fig. 4(b)), which could prevent the surface temperature from falling due to the difference between the roller and room temperature.

B. Temperature trajectories and lengthwise distributions

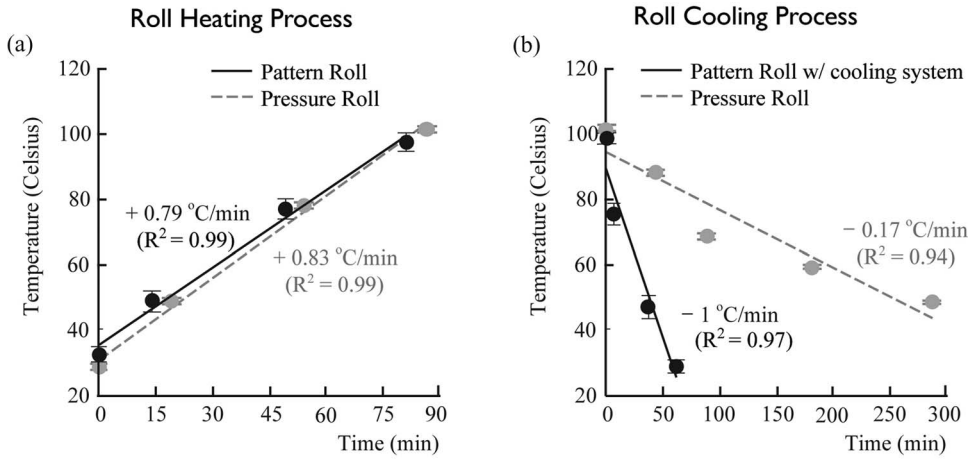
The rate of temperature increase of the (chiller-equipped) pattern roll was similar to that of the pressure roll (Fig. 5(a)), whereas the decreasing slope of the pattern roll was approximately 6 times steeper than that of pressure roll (Fig. 5(b)) because the chiller (water cooling system) greatly accelerated the cooling process. Both rollers required approximately 85 min to increase from 30 °C to 100 °C during the heating process, but the cooling rates between chiller-accelerated cooling and natural cooling were −1 °C/min and −0.17 °C/min, respectively.

The standard deviations of the lengthwise-distributed surface temperature were approximately ±3 °C and ±1 °C at a given specific temperature in the pattern roll and pressure roll, respectively; however, the deviations in the pattern roll became smaller (within ±2 °C) when the temperature was maintained for approximately 3 min.

C. Temperature, control input percent, and integrals of control input power

Natural cooling required more time to reach the desired steady state (95 °C) but showed no undershoot in the temperature trajectory (Fig. 6(A)). The induction heater instantly switched on with the control input power of 60%–70% when the temperature reached the desired value to maintain the steady state (Fig. 6(C)). The time-integral of the control input power was the smallest of all conditions ($p < 0.05$; Fig. 6(E)).

Cooling with zero margin (margin temperature = 0 °C) showed a nearly −4 to −3 °C undershoot and required more time to reach the desired steady states (95 and 80 °C) than the



*Error bars indicate standard deviations of roll surface temperatures in lengthwise

FIG. 5. Continuous roll heating and cooling to the desired temperature with zero margin: (a) Pattern roll (black solid) and pressure roll (gray dotted) were continuously heated from 30 °C to 100 °C , and lengthwise distributed surface temperatures were measured when the temperatures were 30, 50, 80, and 100 °C. (b) Two rolls were then cooled from 100 °C to 30 °C, and the roll temperatures were again measured in the same way, but with different intervals. The solid lines indicate the linear regression slopes of the measurement data as a function of time, with R^2 values above 0.9 in all cases. The error bars indicate standard deviations. The deviations become smaller (±2 °C) when the specific temperature would be maintained at a certain degree for over 3–4 min.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26

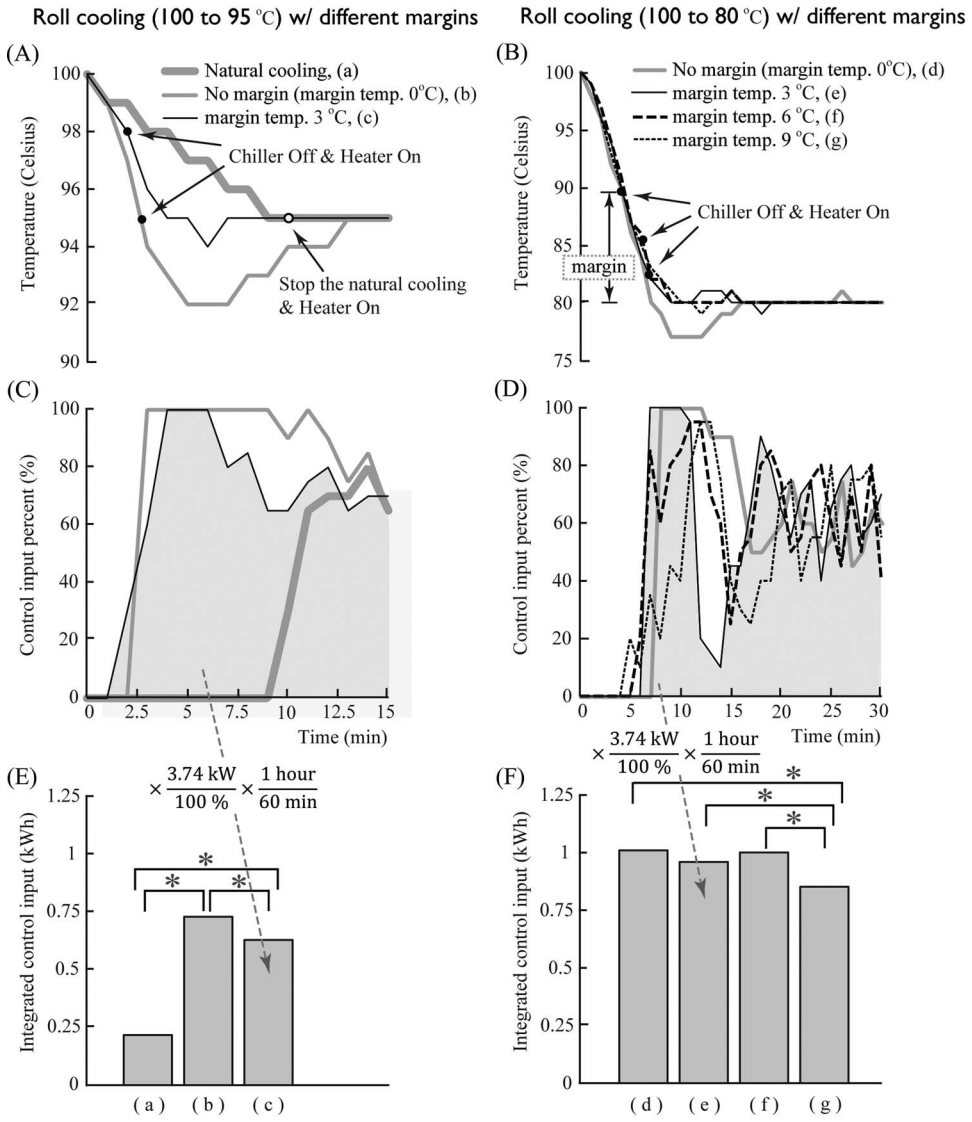


FIG. 6. Roll cooling with different margins: Pattern roll equipped with a temperature margin-based controller was cooled from 100 °C to (A), (C), and (E) 95 °C or (B), (D), and (F) 85 °C. The (A) and (B) temperature, (C) and (D) control input percent, and (E) and (F) time integrals of control input corresponding to (a) natural cooling, (b) and (d) zero margin, (c) and (e) 3 °C margin, (f) 6 °C margin, and (g) 9 °C margin are shown above with different line styles. One hundred percent control input equals to 3.74 kW of electrical power. *: Statistical significance is $p < 0.05$.

other conditions (Figs. 6(A) and 6(B)), even longer than natural cooling in the case of a slight drop such as 5 °C (Fig. 6(A)). The heater immediately switched on with 100% control input power when the temperature first passed through the desired value and continued until the error ε was reduced to approximately 1–2 °C. Thereafter, the amount of control input percent became smaller (Figs. 6(C) and 6(D)). The time-integrals of the electric power showed the largest values among all conditions ($p < 0.05$; Fig. 6(E)) but were not significantly different (Fig. 6(F)).

Cooling with non-zero margins such as 3, 6, and 9 °C showed minimum (±1 °C) undershoot and required less time to reach the desired steady state compared to cooling with zero margin (Fig. 6(B)). The chiller switched off when the temperatures reached 83, 86, and 89 °C (Fig. 6(B)), and the control inputs corresponding to each condition were released to the induction heater to avoid undershoot due to the existing momentum (Fig. 6(D)). The cooling with a 9 °C margin showed the minimum value in the list of integrated control inputs, with statistical significance ($p < 0.05$; Fig. 6(F)).

IV. DISCUSSION

A. A chiller-equipped heating roll system has the advantages of a faster and more efficient process on hot roller embossing

A chiller-equipped hot roller embossing system may hasten the establishment of an optimal embossing process. Differences in cooling times corresponding to the existence of the chiller (pattern roll vs. pressure roll) were considerable, even 6 times faster in our experiment, and the standard deviations of the roll surface temperature were within ±2 °C, which is suitable for hot roller embossing. The temperature

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26

TABLE II. Causes and effects for the temperature margin-based controller.

Causes		Effects
Factors that influence the outcomes • Temperature adjustable roller with a circulating water system • Temperature margin-based controller, which is a combination of a standard PID controller and the simplest bang-bang controller • Selecting an appropriate temperature margin	→	Given outcomes • Optimizing the time course of electrical power • Shortening the process time (i.e., it allows optimum operating parameters to be developed quickly)

margin-based control algorithm, which is a combination of a standard PID controller for the heating cycles and the simplest bang-bang controller for the cooling cycles, could also be useful for optimizing the time course of electrical power and shortening the process time by selecting an appropriate temperature margin, possibly for limited power consumption (causes and effects for the temperature margin-based controller are shown in Table II).

B. Future perspectives

Experimental design methods (e.g., response surface methodology) have often been employed to optimize the main process factors, such as roller temperature, roller speed, and applied force, which mostly affect embossed pattern qualities of hot roller embossing. However, the number of process parameters for the optimization was limited to only 3 or 4 factors because the addition of an input parameter could drastically increase the number of experimental trials.[11] Each experiment normally requires a substantial amount of time to begin the embossing process because of the time required to change roll temperature. Therefore, the chiller-equipped heating roll with the suggested control algorithm is expected to optimize those parameters by significantly reducing the time required to change the experimental conditions.

ACKNOWLEDGMENTS

This research was supported by the research fund of the Korea Institute of Machinery and Materials (NK179E). The authors thank Sungwon Lee for his contribution to data collection.

[1]D. Yun, Y. Son, J. Kyung, H. Park, C. Park, S. Lee, and B. Kim, Rev. Sci. Instrum. **83**, 015108 (2012).
[2]S. H. Ahn and L. J. Guo, Adv. Mater. **20**, 2044–2049 (2008).
[3]Y. He, J.-Z. Fu, and Z.-C. Chen, J. Micromech. Microeng. **17**, 2420–2425 (2007).
[4]Y. Cho, S. Kwon, J.-W. Seo, J.-G. Kim, J.-W. Cho, J.-W. Park, H. Kim, and S. Lee, Microelectron. Eng. **86**, 2417–2422 (2009).
[5]S.-J. Liu, C.-C. Huang, and C.-T. Liao, Polym. Eng. Sci. **52**, 1395–1401 (2012).
[6]L. P. Yeo, S. H. Ng, Z. Wang, Z. Wang, and N. F. de Rooij, Microelectron. Eng. **86**, 933–936 (2009).
[7]L. P. Yeo, S. H. Ng, Z. F. Wang, H. M. Xia, Z. P. Wang, V. S. Thang, Z. W. Zhong, and N. F. de Rooij, J. Micromech. Microeng. **20**, 015017 (2010).
[8]T. Velten, H. Schuck, W. Haberer, and F. Bauerfeld, Int. J. Adv. Manuf. Technol. **47**, 73–80 (2010).
[9]N. Ishizawa, K. Idei, T. Kimura, D. Noda, and T. Hattori, Microsyst. Technol. **14**, 1381–1388 (2008).
[10]K. Metwally, S. Queste, L. Robert, R. Salut, and C. Khan-Malek, Microelectron. Eng. **88**, 2679–2682 (2011).
[11]R. H. Myers, D. C. Montgomery, and C. M. Anderson-Cook, *Response Surface Methodology: Process and Product Optimization Using Designed Experiments* (Wiley, 2009).
[12]C. J. Erickson, *Handbook of Electrical Heating for Industry* (IEEE Press, 1995).
[13]J. Davies and P. Simpson, *Induction Heating Handbook* (McGraw-Hill, 1979).
[14]K. J. Åström and T. Hägglund, Automatica **20**, 645–651 (1984).
[15]M. Yuwana and D. E. Seborg, AIChE J. **28**, 434–440 (1982).
[16]K. J. Åström, T. Hägglund, C. C. Hang, and W. K. Ho, Control Eng. Pract. **1**, 699–714 (1993).
[17]C. C. Hang, K. J. Astrom, and Q. G. Wang, J. Process Control **12**, 143–162 (2002).
[18]J. Ziegler and N. Nichols, Trans. ASME **64**, 759–768 (1942).
[19]K. J. Åström and T. Hägglund, J. Process Control **14**, 635–650 (2004).

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitationnew.aip.org/termsconditions. Downloaded to IP: 203.241.104.23 On: Tue, 19 Aug 2014 20:17:26