"Taming" ultrasonic vibrations with ILC for controlled pre-heating of polymeric embossing process

Jun Liang Tan[1,2], Choon Meng Kiew[1], Puttachat Khuntontong[1], Guilin Yang[1], Yee Cheong Lam[2]
[1]*Singapore Institute of Manufacturing Technology, Singapore*
[2]*Nanyang Technological University of Singapore, Singapore*

junliang@simtech.a-star.edu.sg

Abstract

This paper presents a novel method of achieving temperature control in polymeric embossing process with ultrasonic vibrations. Heat is generated from mechanical vibration of polymer molecules which are activated by ultrasound. The controlled temperature rise of polymeric substrates is crucial to ensure quality components. For achieving the desired pre-heating temperature, consecutive short pulses of ultrasonic vibration, with pauses in between each pulse for temperature control, is proposed. An iterative learning control (ILC) method is employed to acquire the optimal vibration amplitudes so that the desired temperature can be achieved effectively.

1 Introduction

Although thermal embossing is a well established imprinting technique of transferring features from molds to polymer substrates, it has a long processing cycle time of more than 5mins [1]. Majority of the process time is spent on heating and cooling the system. Using ultrasonic vibrations is a rapid way of material processing as heating is localized at the feature region. Liu et. al. demostrated that such an imprinting technique could significantly reduce the process cycle time and energy comsumptions [2]. However, as heating is localised, the displaced heated polymer is unable to flow to its cooler surrounding region, resulting in severe feature defects. Temperature control is hence crucial during embossing. As such, Mekaru et. al. preheated the polymer using cartridge heaters and utilized ultrasonic vibrations at the final stage of the embossing process [3]. This investigation focuses on ultrasonic vibration preheating without the necessity of having cartridge heaters.

In ultrasonic embossing, the amount of heat generated is determined by both vibration amplitudes and durations. Consecutive pulses might have to be utilised for generating the appropriate thermal energy to achieve temperature control. However, to achieve this, the current limitations of commercial ultrasonic welding systems, which allow only a single pulse or at the most 2 pulses of ultrasonic vibrations during the process cycle, have to be overcome.

2 Methodology

The proposed method employs multiple consecutive short pulses at low vibration amplitudes with a short pause in between each pulse. Using a large vibration amplitude and long duration causes large thermal energy concentration which will damage the polymer substrate. Hence, an iterative learning control (ILC) scheme is implemented into the system for achieving the desired temperature. In the following experiments, single pulse and multiple pulses of ultrasonic vibration, with and without ILC, are investigated.

An ultrasonic welding module Rinco AGM35 coupled with a convertor, a booster and a titanium horn, was used in the experiments. The convertor converts electrical signals into mechanical vibrations. The booster amplifies the vibrations to larger amplitudes and the horn transmits the vibrations to the targeted area. The operating frequency is 35 kHz and the maximum achievable vibration amplitude is 24µm. A press force of 200N, generated by a pneumatic actuator, was applied to hold the sample between the horn and the mold. A 20mm x 20mm aluminium flat mold and Polycarbonate (PC) substrates of 48.25mm x 20.25mm x 2mm (length x breadth x thickness) were used. In addition, a K-type thermocouple was sandwiched between 2 pieces of PC which were to be hot embossed. National Instruments (NI) data acquisition modules and Labview software were used to acquire and generate the required signals. The samples were placed on the mold, and the horn was forced downwards to press onto the samples. With this experimental setup, preheating with ultrasonic vibrations was systematically investigated.

3 Results and Discussion

The pre-heating temperature required for subsequent ultrasonic embossing was estimated to be 100˚C, which is approximately 50˚C below the glass transition temperature (150 ˚C of PC). For this investigation, the precise determination of this pre-heating temperature is of less importance than the assessment if this temperature could be achieved and maintained for the development of the pre-heating strategy. Thus, the set-point (desired) temperature was set to 100˚C.

For the investigation of a single ultrasonic vibration pulse, 80% of the maximum amplitude was applied for 0.2secs. The temperature increased to 55˚C but dropped to room temperature in less than a second, see Figure 1. By changing the pulse duration to 4.5secs, a higher temperature of 180 ˚C was achieved but this required temperature could not be maintained. The temperature dropped rapidly once ultrasonic vibrations ceased.

To minimise rapid temperature decrease, the application of multiple pulses instead of a single pulse was investigated. Pulses were applied one after another, with a short interval (2ms) between these pulses. By applying 30 pulses each with 40% maximum amplitude and 150ms duration, the resulted overall rate of temperature increase was more gradual, but it could not reach the required set-point temperature see, Figure 2. However, a higher vibration amplitude (60%), but with the same burst duration (150ms), resulted in temperature overshoot. Thus, although this method is promising, there is a need of a system to control and achieve the desired temperature profile.

As ultrasonic embossing is a repetitive process, an iterative learning control (ILC) can be implemented. It allows the system to learn from its previous control trials. Through such ILC scheme, a suitable control input is determined as follows [4]:

$$\mathrm{u}_{\mathrm{i+1}}(\mathrm{t}) = \mathrm{u}_{\mathrm{i}}(\mathrm{t}) + \mathrm{q}\Delta\mathrm{y}_{\mathrm{i}}(\mathrm{t}) \qquad (1)$$

where *i=1, 2, 3 ...* is the iteration index, $\mathrm{u}_{\mathrm{i}}(\mathrm{t})$ is the input, *q* is the learning rate and $\Delta\mathrm{y}_{\mathrm{i}}(\mathrm{t})$ is the error which is governed by Equation 2.

$$\Delta y_i(t) = y_d(t) - y_i(t) \qquad (2)$$

By having the vibration amplitude as the control input, Figure 2 shows the temperature of the substrate can be maintained approximately at a preheating temperature of 100˚C for more than 3 seconds using ILC. This optimal amplitude was obtained on the 8th process run with ILC.

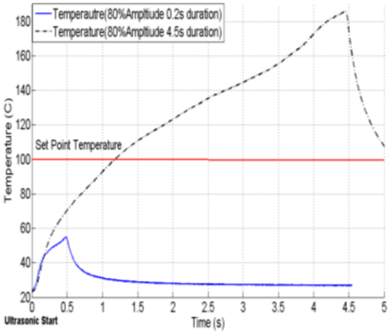

Figure 1 Temperature profile of a single ultrasonic vibration pulse

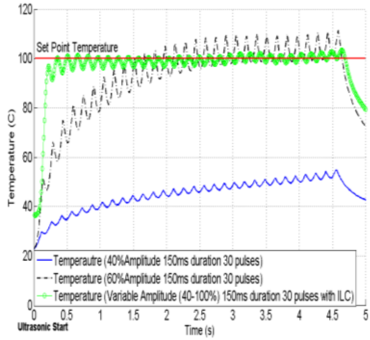

Figure 2 Temperature profile of multiple ultrasonic vibration pulses

4 Conclusion & Future Works

Controlled temperature increase in a polymer substrate can be achieved by ultrasonic vibration together with ILC, without any other additional heating element. Embossing tests, with the determined optimum process parameters, will be conducted in the future to determine the quality of the ultrasonic embossed features on various polymeric materials.

5 References:

[1] C. M Kiew, J. L Tan, T. J Teo, W Lin, G.Yang; A Precision Thermal Press for Polymer Processing. Proceedings 26th ASPE Conference 2011

[2] S.J Liu, Y.T Dung; Hot embossing precise structure onto plastic plates by ultrasonic vibration Polymer Engineering & Science Volume 45, Issue 7, pages 915–925, July 2005

[3] H. Mekaru, O. Nakamura, O. Maruyama, R. Maeda and T. Hattori; Development of precision transfer technology of atmospheric hot embossing by ultrasonic vibration. Microsystem Technologies, Vol13, No 3-4, Pages 385-391, 2007

[4] J.X Xu, Y. Tan; Linear and Nonlinear Iterative Learning Control. Springer March 2003