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Effects of Preheat Supply on Embossed Pattern Depth in Roll-to-Roll Process

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In this study, we examined the sensitivity of embossed pattern depth to preheat supply and cooling, and also tested how pattern type and density affect the embossed depth. The main factors such as roller temperature, roller speed, and applied force that mostly affect embossed pattern qualities of roll-to-roll hot embossing were determined based on the response surface methodology. Eight conditions were then added to know the time-dependent effects of heat transfer with custom designed preheating and cooling systems (Fig. 1). Extended preheat time for the PMMA substrate contributed to the significant change of the embossed depth, whereas the substrate-cooling showed no straightforward increasing or decreasing trend. Larger embossed depths were achieved in horizontal patterns with lower density compared to vertical patterns, and the lower pattern densities showed the greater embossed depths regardless of pattern types. We expect that this result may help to understand the effects of pre- and post-treatment of roll-to-roll (R2R) hot embossing by employing time duration factors of heat transfer, depending on mold pattern type and density.

The response surface methodology (RSM) was employed to optimize the main factors such as roller temperature, roller speed, and applied force that mostly affect embossed pattern qualities of R2R hot embossing. After we completed all of the experimental runs, pattern roll temperature, pressure roll temperature, rolling speed, and applied force were set to 105 °C, 30 °C, 0.5 m/min and 7 kN, respectively, where the averaged embossed pattern depth had a maximum value. To examine the time duration effects of heat supply on embossed pattern depth, eight conditions listed in Fig. 2 were tested with custom designed preheating and cooling systems (Fig. 1).

Embossed pattern profiles were captured by a 3CCD real color confocal microscope (OPTELICS H1200, Lasertec, Japan) and depth measurements were re-confirmed by a surface roughness tester (SJ-301, Mitutoyo, Japan). The depth measurements were used to calculate the pattern depth ratio (PdR) which was defined as follows: PdR = d_emb / h_mold x 100 %, where d_emb and h_mold are embossed depth on the substrate and pattern height on the mold structure, respectively. Differences in PdR corresponding to each R2R hot embossing condition were tested with two sample t-test with a level of significance of $p < 0.05$.

Extended preheating time between the pattern roll and PMMA substrate contributed to the drastically increasing PdR (Fig. 2(a) and (e)) and the increase in PdR was especially prominent in patterns with density of 33%. However, preheat supply to the substrate backside facing pressure roll contributed to the drops in PdR (Fig. 2(a) and (b)). By and large, the custom designed air injector was not effective in increasing PdR (Fig. 2(a) and (c)).

Larger embossed depths were achieved in horizontal patterns with lower density (Fig. 2). Horizontal patterns with densities of 10 and 33 % showed greater embossed depths compared to vertical patterns with densities of 10, 33, and 50 % ($p < 0.05$) however, horizontal patterns with higher density (50 %) showed smaller depths in compared to vertical patterns with the same density. The lower pattern density showed the larger embossed depth regardless of pattern types (Fig. 2). Horizontal patterns with a density of 10 % showed the largest embossed depths than any with higher density, whereas an averaged depth of vertical patterns with a density of 33 % showed greater embossed depth compared to a density of 50 %, but not a significant difference.

Longer contact time between the hot pattern roll and polymer substrate provoked sufficient heat transfer before an embossing, and this probably enhanced the polymer viscosity, resulting in an increase of pattern depth [1]. On the other hand, it might be better for the substrate's reverse side against the pressure roll to be untreated instead of preheated because it needs to be more solid to give proper support for greater polymer deformation.

Horizontal mold patterns, which are perpendicular to rolling direction, are likely to have more continuous polymer flow during the embossing stage compared to those for vertical patterns, maybe because the less dense pattern along the roller nip provided less resistance to the material flow [1]. Flexibility of the polymer behavior may be closely related to the pattern density [2]. It is thought that higher pattern density constrained material flow, whereas lower pattern density allowed the polymer to be more pliable [3].

References:

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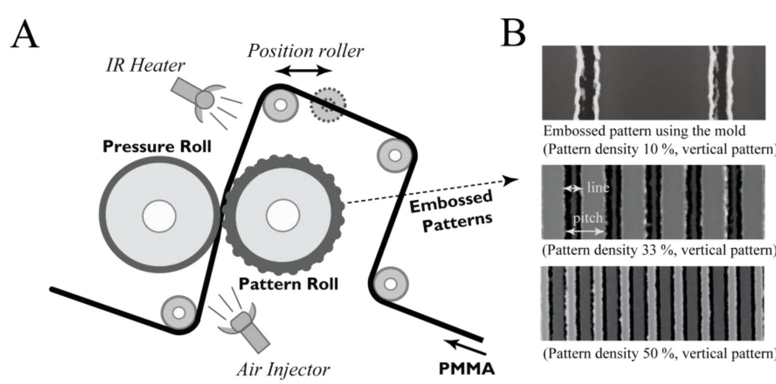

Figure 1. (A) Schematic of the hot roller embossing process including position roller, IR heater, and air injector. (B) Embossed vertical patterns with density of 10, 33, and 50 % captured by a 3CCD real color confocal microscope (OPTELICS H1200, Lasertec, Japan).

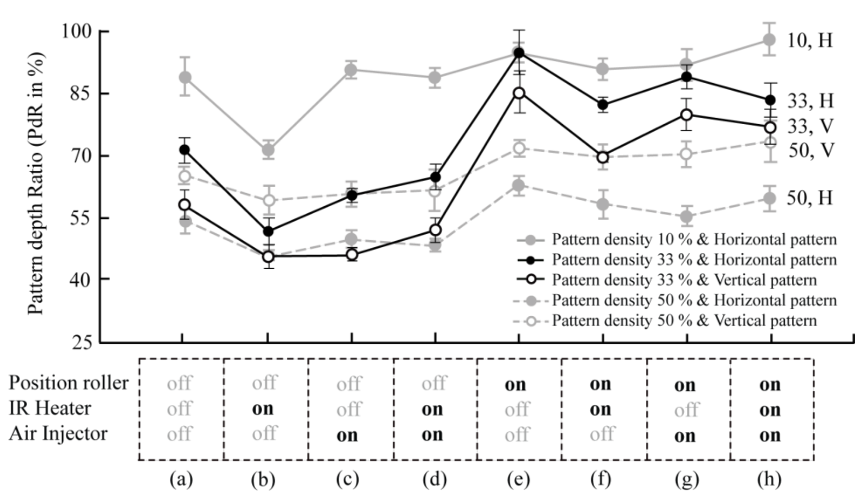

Figure 2. Sensitivity of pattern depth ratio (PdR) to preheating embossing and cooling. X-axis represents conditions, while Y-axis means PdRs in percentage.

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