Analytical study on web deformation by tension in roll-to-roll printing process

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Abstract Recently, flexible devices have gained high intentions for flexible display, Radio Frequency Identification (RFID), bio-sensor and so on. For manufacturing of the flexible devices, roll-to-roll process is a good candidate because of its low production cost and high productivity. Flexible substrate has a non-uniform deformation distribution by tension. Because the roll-to-roll process carries out a number of overlay printing processes, the deformation affects overlay printing precision and printable areas. In this study, the deformation of flexible substrate was analyzed by using finite element analysis and it was verified through experiments. More deformation occurred in the middle region in the direction parallel to rolling of the flexible substrate. It is confirmed through experiments and analysis that deformation occurs less at both ends than in the middle region. Based on these results, a hourglass roll is proposed as a mechanical design of the roll to compensate the non-uniform deformation of the flexible substrate. In the hourglass roll, high stiffness material is used in the core and low stiffness material such as an elastic material is wrapped. The diameter of the core roll was designed to be the minimum at the middle and the maximum at both ends. We tried to compensate the non-uniform deformation distribution of the flexible substrate by using the variation of the contact stiffness between the roll and the flexible substrate. Deformation distribution of flexible substrates was confirmed by finite element analysis by applying hourglass roll shape. In the analysis when using the hourglass roll, it is confirmed that the stress distribution is compensated by about 70% and the strain distribution is compensated by about 67% compared to the case using the hourglass roll. To verify the compensation of the non-uniform deformation distribution due to the tension, deformation measurement experiment when using the proposed hourglass roll was carried out. Experiments have shown that the distribution of deformation is compensated by about 34%. From the results, we verified the performance of the proposed.
1. Introduction
Roll-to-Roll printing technology has recently gained special interests in the field of printed electronics. Roll-to-roll printing technology is applicable to the production of flexible devices such as flexible displays, solar cells, RFID (Radio Frequency Identification) tags, and smart sensors.

The roll-to-roll process has the advantage of being capable of low cost manufacturing and high-speed printing because it is based on continuous rotary press process on flexible substrate. The roll-to-roll process is printed and processed on a flexible substrate between winding and rewinding rolls. Flexible substrates are thin and flexible like paper and have the advantage of lightweight and not breaking. Due to the continuous process, the tension acting on the flexible substrate changes in real time due to various factors. This tension distribution reduces the accuracy of the printed pattern.

In this study, we analyze the tension distribution of flexible substrate and propose a design to compensate the non-uniform tension distribution. First, the deformation by tensile force acting on the flexible substrate under static conditions is analyzed through finite element analysis and then the model is experimentally verified. The result of this analysis is essential to consider the deformation of the flexible substrate generated by the tension of each span. It proves that the conventional rolls have a limit to uniform tension control. A novel roll design with hourglass shape has been proposed to overcome the limit of uniform tension control. The performance of the hourglass rolls was also validated through analysis and experiments.

2. Tensile force measurement experiment
Experiments were conducted to measure the tension distribution of the flexible substrate. In order to analyze the tensile force acting on the flexible substrate under the load conditions, the measurement was carried out under static conditions. Reference marks were patterned on the substrates and then, the relative deformation between reference marks was measured to measure the tension distribution of the flexible substrate.

As shown in Figure 1, patterning was performed on a flexible substrate and measured using a vision camera. The vision camera is CREVIS's MX-BX30A (pixel size: 4.65 microns). The relative deformation was calculated by multiplying the displacement between the reference marks by the pixel size. The force acting on the flexible substrate was measured by the load cell at both ends of the Idle roller. The system for the measurement is shown in Figure 2.

Figure 3 shows the relative deformation of the flexible substrate against tension. The asymmetry of the measurement data is judged as a result of the misalignment of the guide rollers. The deviation of the 6th and 7th data in the middle region from the tendency is assumed as a result of the wrinkles of the flexible substrate, therefore they were eliminated from the following analysis.

In order to correct the misalignment error of the guide rollers, the relative deformation amount by the first order trend line was eliminated. It can be seen that more deformation occurs at the center in the direction perpendicular to the direction in which the tensile force is applied as shown in Figure 4. These results adversely affect the accuracy of the printed pattern.
3. Finite element analysis

The finite element analysis for the deformation of the flexible substrate was performed under the same conditions of the experiments results. Analysis software was ANSYS version 17.0, commercial software for structural analysis.

The boundary conditions were fixed at the left end and applied force at the right end. The applied force was 50 N. The analytical modeling was set to 200 mm in length, 100 mm in width, and 0.2 mm in thickness. Numbers of elements were 6,670 and Nodes were 6,844. CPU time was about 10 seconds.

The physical properties used in the analysis are shown in Table 1. Figure 5 shows the equivalent strain for the 100 mm area in the analytical model. Because the experiment was performed in the middle area away from the fixed end, we focused on the middle region of the analytical model. In the analysis results, it can be seen that more deformation occurs in the middle region. For a 100 mm area, the maximum strain is 73 and the minimum strain is 68 microns, which were 6 microns of difference.

| Table 1 Physical Properties in FEA for material. | Young’s Modulus | Poisson’s ratio | Density |
|-------------------------------------------------|-----------------|----------------|---------|
| Flexible substrates                             | 3.5 GPa         | 0.34           | 1320 kg/m³ |
| Roll                                            | 71 GPa          | 0.33           | 2770 kg/m³ |

Figure 5. Principal strain for central 100 mm area from the substrate of 200 mm width.

Figure 6. Result of principal strain of roller which have the minimum in the middle contact stiffness.
4. Tension compensation of a flexible substrate

4.1 Verification through finite element analysis
Static analysis and experiment of flexible substrate showed that more deformation occurred in the middle region in the width direction. If we can control and correct such a deformation, the precision of the printing pattern is enhanced, and the printing area is expanded, so that the productivity of the flexible substrate will be improved.

Finite element analysis was performed for a model in which the tension was uniform on the flexible substrate and the contact stiffness between the roller and the flexible substrate varied. Because more deformation occurs in the middle region, the finite element analysis is performed so that the stiffness of the roller is minimized in the middle. Figure 6 shows the result of finite element analysis under the above conditions. For comparison, the case when using a conventional roller with uniform stiffness is analysed under the same condition. The maximum strains were 72.3 microns and the minimum strains were 71.0 microns. The difference was about 1.3 microns, resulting in a reduction of about 67% when compared to the conventional rolls.

4.2 Verification through experiments
In order to implement the change of stiffness, the core of the roll was made as shown in Figure 7. The roll was designed with compliant elastic material at its periphery as shown in Figure 7. These rolls were named hourglass rolls. In order to verify the performance of the hourglass roll, we compared the tension distribution of the flexible substrate of the conventional roll and the hourglass roll. The relative deformation was measured when a load of 85 N was applied under the same boundary condition as the previous experiment as depicted in Figure 8. As in the previous experiments, the linear components were eliminated and the relative deformation was compared in order to correct the misalignment errors of the rollers. The difference between the maximum value and the minimum value of the relative deformation was 2.08 microns in the conventional roll test and 1.37 microns in the hourglass roll. It was confirmed that the relative deformation of the hourglass roll was reduced by about 34% when compared with the conventional rolls. Figure 9 is a graph showing the measurement results.
5. Conclusion
The tension distribution on flexible substrate in the roll-to-roll process changes in real time. This tension distribution adversely affects on the accuracy of the printing pattern. In this study, we analyzed the tension distribution on the flexible substrate and proposed an hourglass roll as an improvement design to compensate the tension’s non-uniforming. Compared with conventional rolls, the difference of the principal strain was reduced by about 67% under the load condition of 50 N in finite element analysis. Experimental results show that the difference of the deformation is reduced by about 34% under the load condition of about 85 N.

This research was analyzed the deformation of flexible substrate only static conditions. But in reality, roll-to-roll process proceeds while rotating rolls. Therefore we plans to study deformation of flexible substrate when hourglass roll is rotated. If the hourglass roll is applied, the accuracy of the print pattern can be improved, and the expansion of the print area is expected to be expected.

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