Optimal Design of the Roll Shape for the Roll-to-Roll Forming Process of Metal Micro-Patterns

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Abstract. Recently, the roll-to-roll (R2R) forming process has been employed in the manufacturing of micro-patterns for various electronic devices. While previous R2R forming stuides have mainly been applied to the micro-patterning on polymer films, the present study covers the R2R forming process of micro-patterns on a thin metal sheet. It is known that the wrinkling defects can be observed in the metal R2R forming process because the micro-dimples are formed by plastic deformation, which requires an adequate design of the forming roll to ensure a uniform material flow of the metal sheet. In this study, finite element (FE) analyses of the R2R process were applied to predict the material flow during the forming process from which the possibility of wrinkling can be estimated. Statistical analyses were performed from the FE analysis results by combining the design of experiments (DOE) and the response surface method (RSM). The roll shape was then optimized to get a uniform material flow, from which the wrinkling defects can be resolved.

Keywords: Roll-to-roll forming, Micro pattern, Wrinkling, Material flow, Finite element analysis, Design of experiments

1. INTRODUCTION

Recent demands for small size electric products have driven the creation of metal components containing micro-scale or sub-micron-scale features. To manufacture micro-sized metal parts, various processes such as micro-embossing [1], micro-punching [2], and micro-extrusion [3] processes have been developed. In these studies, the shape and size effects on formability were mainly investigated together with the effect of grain size. In addition to these micro-scale parts, the forming of macro-scale parts having micro-sized features also has become one of the major research topics: Micro-channels for fuel cells [4], a micro-reactor component containing miniature pins [5], barrier ribs in plasma display panels [6] and subminiature screws containing micro-scale threads [7] are examples of macro-scale parts having micro-features.

These days, micro-pattern forming on thin metal sheets using roll-to-roll (R2R) forming is popularly used in the printing process of display panels because of its high productivity [8]. The R2R forming process is similar to the roll forming process, in which a sheet strip is passed through a pair of rotating rolls and is formed incrementally by the two rolls [9]. The R2R forming process is different from the conventional roll forming process because a micro-patterned roll is used instead of a plain roll. Thus, micro-patterns are replicated on the metal sheet when it passes through two adjacent rolls.

In this study, the R2R forming process was applied to the forming of micro-dimple arrays on a thin metal sheet. Arrays of micro-dimples are formed by a pair of rotating rolls: One is a plain roll and the other roll contains micro-dimple arrays as convex patterns. As a result, concave micro-dimple arrays are replicated on one side of the metal sheet while the other side remains flat. For this reason, the forming of micro-patterns on a metal sheet by R2R forming is different from the conventional roll forming of a constant cross-section.

In the authors' previous studies, various defects were observed, such as micro-crack [10] and wrinkling defects [11], in the metal R2R forming process. To solve the wrinkling defects, a design change in the forming roll was investigated by adding a flow guide for a uniform material flow [11]. In this study, finite element (FE) analyses of the R2R process were further applied to predict the material flow based on the various design parameters of the flow guide. An optimal design of the flow guide was then obtained by combining the design of experiments (DOE) and the response surface method (RSM).

2. PREDICTION OF WRINKLING DEFECTS

2.1. Overview of the R2R forming process

Figure 1 shows the schematic view of the R2R forming process using a patterned upper roll and a plain lower roll. The diameter of each roll is 150 mm and the sheet thickness is 0.2 mm. A number of micro-dimples were engraved on the upper roll with a depth of 50 μm and a pitch of 200 μm. The pitch angle of the upper roll (θ) was 0.2° and the roller speed was set to 0.035 rad/s.

Figure 2 shows the upper roll and the detailed patterns (convex dimple arrays) engraved on the roll [11]. A patterned metal sheet through the R2R forming process is shown in figure 3. It can be seen that the interior region of the micro-dimples was well replicated while wrinkling defects were observed near the pattern edge. This wrinkling is caused by a non-uniform material flow, and should be eliminated or reduced for better product quality.

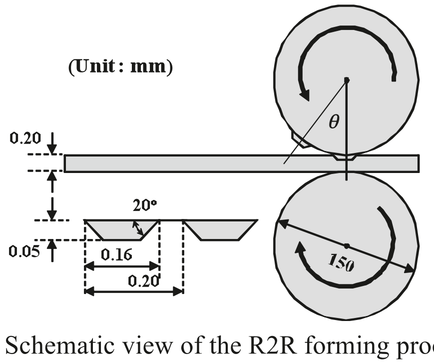


Figure 1. Schematic view of the R2R forming process.

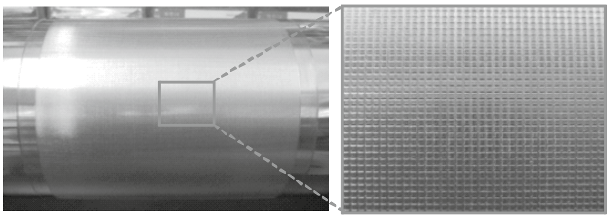


Figure 2. The upper roll containing micro-dimple arrays.

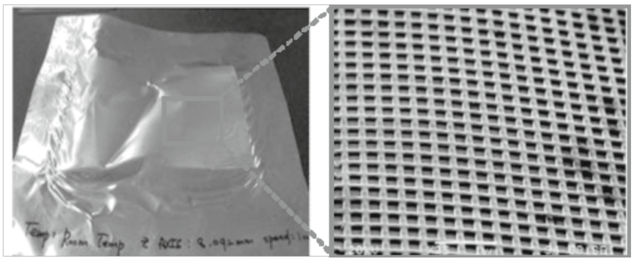


Figure 3. Patterned metal sheet through the R2R process.

2.2. FE analysis of the R2R forming process

To investigate the mechanism of the wrinkling phenomena in the R2R forming process, an FE analysis was carried out. The FE analysis was conducted using Deform-3D®, a commercial FE analysis software for metal forming processes. The metal sheet (Al6111-T4) was treated as a deformable body and the rolls were regarded as a rigid body. The Johnson-Cook plastic constitutive model [12] was used to describe the temperature dependent hardening effect. For efficient computation, a simplified analysis model was used by reducing the number of micro-dimples to the minimum numbers of rows and elements [10].

Figure 4 shows the results of the FE analysis, including the deformed shape and the enlarged velocity vector profile. It can be seen that the forefront edge does not show a uniform profile, but a convexly curved shape. This convex profile can be explained by the fact that the velocity shows its maximum value at the central region, and decreases as it moves to the outside region. As a result, this uneven material flow may cause instability during the R2R forming process. Considering that the current simplified model is for only a very small region of the full model, the non-uniform flow of material will accumulate and finally will cause wrinkling defects, as shown in figure 3.

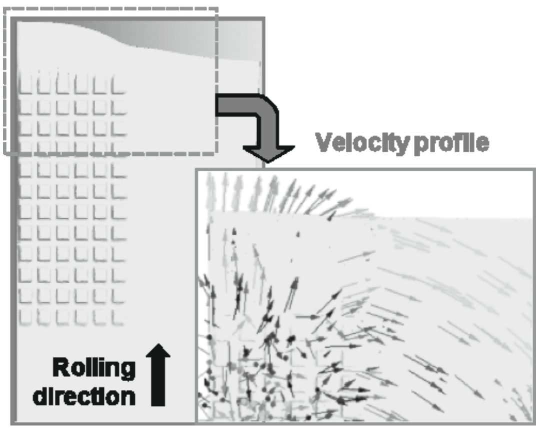


Figure 4. Deformed shape with detailed velocity vector profiles during the R2R process.

3. OPTIMAL DESIGN OF THE ROLL SHAPE

3.1. Design change of the patterned roll

To avoid wrinkling defects in the R2R forming process, the material flow should remain as uniformed as possible. In this study, a design change was proposed to add a flow guide on the patterned roll. A schematic illustration of the modified roll design is shown in Figure 5. The flow guide, which has a shape of a cylindrical bump outside the roll, was added on the patterned roll. Because the flow guide is located outside the patterned region, the material is expected to flow bi-directionally from the flow guide. Thus, a more uniform material flow can be obtained.

An FE analysis was performed to investigate the effect of the flow guide. The guide width (w) and depth (h) were set to be 0.2 mm and 0.05 mm, respectively. The guide distance from the end of micro-dimples (d) was set to 0.5 mm, and the remaining flange length (l) was set to 0.5 mm.

Figure 6 shows the results of the FE analysis when the modified roll was used. It can be seen that the forefront edge shows a more uniform profile than the previous result in figure 4. For a quantitative comparison, the order of non-uniformity (δ) is defined by the deviation of the forefront profile from the center to the end of the micro-dimples as marked in figure 6. The order of non-uniformity was calculated to be 64.5 μm while it was 142.8 μm in the previous case. This indicates that the proposed flow guide helps to prevent the wrinkling defect by improving the uniformity in the material flow.

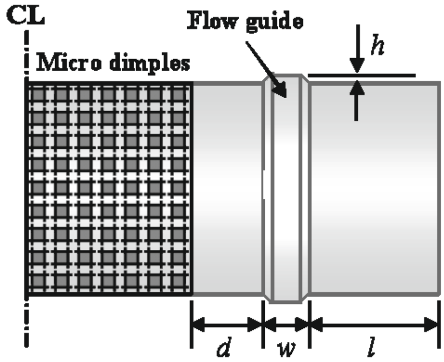


Figure 5. Schematic illustration of the flow guide with its design parameters.

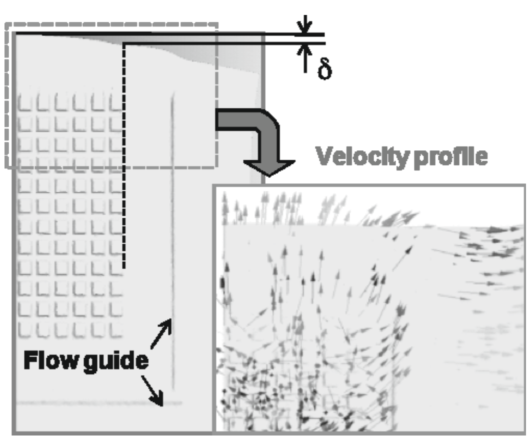
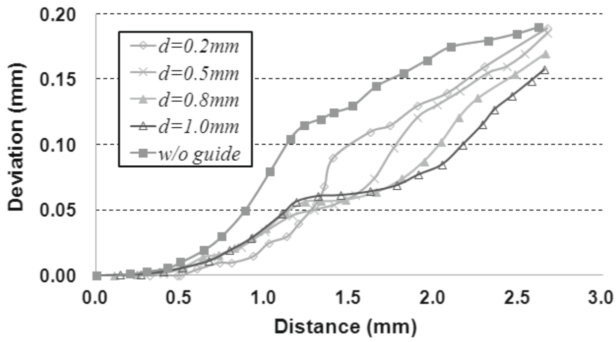


Figure 6. Deformed shape with detailed velocity vector profiles during the R2R process with the flow guide.

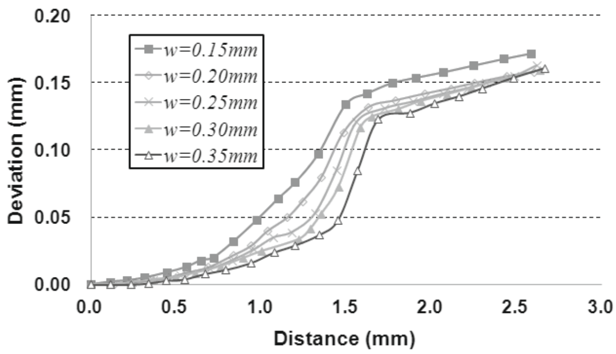
3.2. FE analyses for various design parameters

In this section, the effect of design parameters of the flow guide is investigated. Among the four design parameters denoted in figure 5, the guide depth (*h*) was fixed to the same value as the dimple depth (50 μm), and FE analyses were performed with variations of the other parameters. Figure 7 plots the variations of the front profiles for three design parameters. The vertical axes in these graphs are defined by the deviations of the forefront profile from the center.

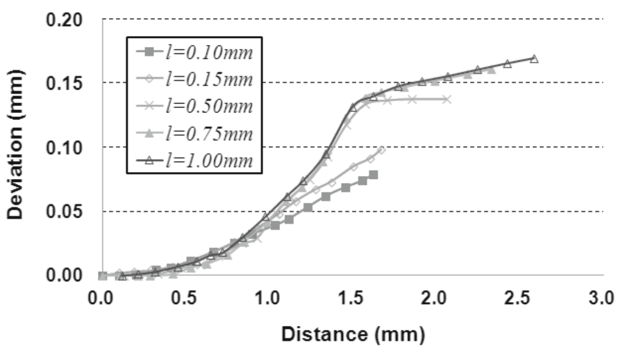
Figure 7(a) plots the effect of the guide distance (*d*), showing that the material flow becomes more uniform as the guide distance decreases, that is, as it gets located more closely to the micro-dimples. Figures 7(b) and **(c)** represent the effect of the guide width (*w*) and the flange length (*l*), respectively. These results indicate that the material flow becomes more uniform as the guide width increases and the flange length decreases.



(a)



(b)



(c)

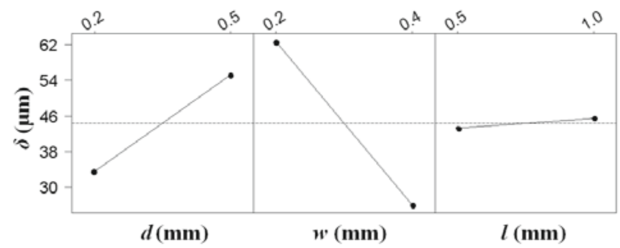
Figure 7. Comparison of deformation profiles with variations of: (a) the guide distance, (b) the guide width, and (c) the flange length.

3.3. Optimization for the roll design parameters of the flow guide using DOE and RSM

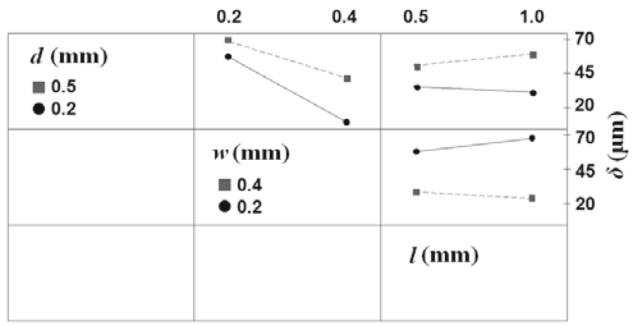
In this section, the design of experiment (DOE) was applied to systematically investigate the effects of the three parameters by considering their mutual interaction [13]. The first screening DOE was performed for the three parameters with two levels, as listed in table 1. A full factorial DOE with two levels (8 experiments) was conducted. Figure 8(a) presents the main effect plot for the order of non-uniformity (δ). It can be seen that the guide distance shows a positive effect while the guide width shows a negative effect. In contrast, the flange length does not demonstrate a significant effect while it shows a slight positive effect. Figure 8(b) represents the interaction plot between each design parameter. It can be seen that the flange length does not have a remarkable interaction with other design parameters. Thus, the flange length could be screened out in the next DOE by fixing it as 0.5 mm in order to obtain a more uniform profile.

Table 1. Design parameters for the first screening DOE.

Design parameter	Low level	High level
Guide distance (mm)	0.2	0.5
Guide width (mm)	0.2	0.4
Flange length (mm)	0.5	1.0



(a)



(b)

Figure 8. DOE results for the order of non-uniformity: (a) the main effect plot and (b) the interaction plot.

The second DOE was scheduled using the central composite design (CCD) table to conduct the response surface method. Thirteen experiments were scheduled based on the orthogonal array of the two remaining design parameters (*d* and *w*), and the resulting response contour is plotted in figure 9. Through the statistical analysis, the quadratic regression model for the response surface of the order of non-uniformity (δ) was obtained as shown in Eqn. (1):

$$\delta = 0.289w^2 - 0.786d^2 - 0.017dw - 0.358w + 0.478d + 0.058 \quad (1)$$

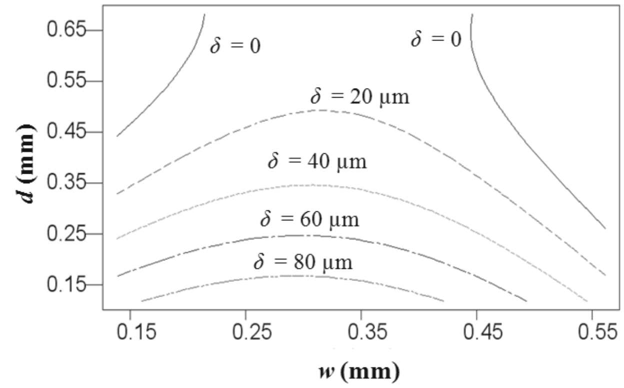
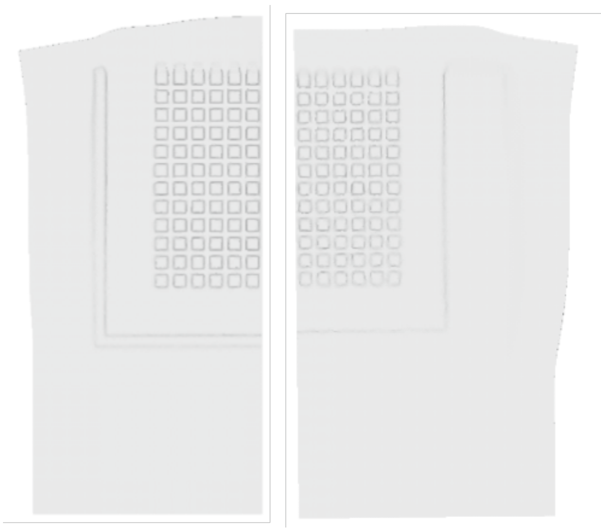


Figure 9. Response contour for the order of non-uniformity.

The optimal processing parameters can be found based on this regression model. The guide distance was restrained to 0.45 mm by considering the limitation in roll machining tolerance. The optimal guide width to minimize δ was then obtained as 0.56 mm. Additional FE analysis was conducted under this optimal condition, and the resulting non-uniformity was further reduced to 5.1 μm. This result means a great improvement in uniformity because δ was reduced to 1/12 in comparison with the previous result from the originally designed guide. Figure 10 compares the deformed shapes for the initial guide design and the optimal guide design, showing the optimized design provides a remarkably improved profile in uniformity.



(a) (b)

Figure 10. Comparison of the deformed shape for the: (a) original guide design and (b) optimal guide design.

4. CONCLUSION

The present study focused on the R2R forming process of micro-dimple arrays on a metal sheet. To replicate micro-dimples on a thin metal sheet, the wrinkling defect should be avoided. In this study, FE analyses were performed to predict the possibility of the wrinkling defect. The analysis results indicated that the non-uniform material flow, which was evaluated to be 144.8 μm, could be the main reason for the wrinkling defect.

To reduce this non-uniform material flow, a design change to the patterned roll was proposed by adding a flow guide to separate the material flow. From the FE analysis on the R2R forming process adopting the flow guide, it was shown that the non-uniformity could be reduced to 65.4 μm. The effects of the guide design parameters (*d*, *w*, and *l*) were then numerically investigated, from which we could obtain conditions for a more uniform material flow: a shorter guide distance, a wider guide width, and a shorter flange length.

Finally, the FE analyses were connected to DOE in order to investigate the effects of each design parameter with mutual interactions. Statistical analyses were then followed based on the RSM, and the optimal design parameters were determined from the quadratic regression model. Through the final FE analysis using the optimized design parameters, the order of non-uniformity was remarkably reduced to 5.1 μm.

5. REFERENCES

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