Finite element modeling and durability evaluation for rubber pad forming process

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Abstract. Elastomer (or rubber pad) forming is a dieless forming process. The forming process has several advantages compared to general press forming process in terms of tool cost and scratch problem. However, when the elastomer is subjected to severe deformation during forming process, it can result in an expensive cost for the replacements of elastomer. Therefore, it is necessary to evaluate accurate tool life. In this study, the FE analysis was conducted for the rubber pad forming process and the fatigue life evaluation of the elastomer tool was investigated numerically using the reference experimental data. For the FE analysis, uniaxial and equibiaxial tension tests of natural rubber 50 were carried out in order to obtain the mechanical material properties of the elastomer. The hyperelastic behavior of the elastomer was characterized using Ogden model. The elastomer forming process was modeled using a commercial software LS-DYNA 3D. Two important factors of FE modeling were to calibrate the simulation conditions and to obtain the target product shape with a preformed elastomer. With the result of FE analysis, a durability of the elastomer was conducted focusing on fatigue life, because the elastomer is applied for repeated loadings during the forming process. Unlike general fatigue analysis, the fatigue life of the elastomer is predicted with respect to the strain measures due to Mullins effect. Furthermore, the Polar Effective Plastic Strain (PEPS) diagram [6] considering the strain path changes was used to check the failure of the blank during the forming process.

1. Introduction
Elastomer materials behave hyperelastic, and they have Mullins effect. The Mullins effect [1] is a phenomenon which the stress level decreases during repeated loads. Due to the Mullins effect the stress-strain behavior of elastomer material is different for each cycle depending on the maximum strain range. However, the stress-strain behaviors are not continuously changing but converging after 5 – 10 times of loading. In addition, the elastomer remains a permanent deformation such as common metallic material when an applied load is removed (or unloaded) at a certain level. Above phenomena are described in Figure 2.
Rubber pad forming process [2] is a forming process using elastomer as an upper die. The advantages of this process are no cost of die tooling, uniform load to the product, and no damage on the product surface. Whereas, the weakness is that it can result in expensive cost for the replacement of elastomer in case the elastomer undergoes severe deformation for the process. Despite this argument, the elastomer is regarded as a charming material related to the forming process. As recent works, Belhassen et al. [3] investigated a rubber-pad forming process of aluminum sheet metal focusing on numerical prediction. In addition, Kolahdooz et al. [4] studied 3D finite element model of the rubber pad forming process with damage concepts.

In this study, the mechanical behavior of the elastomer was investigated. Then, the finite element analysis of the forming process was modeled. In this simulation, the focuses is the correlation with the actual rubber forming process including the target shape and product failure. After the simulation, the durability of elastomer was evaluated in respect to the fatigue life using simulation results.

2. Material modeling for elastomer

2.1. Material properties test

To obtain the material properties of elastomer, uniaxial tensile and equibiaxial tensile tests were conducted. Five cyclic loadings were applied considering the Mullins effect and the tests were performed with 25%, 50%, and 100% of maximum strain ranges. In general, the equibiaxial tensile test is recognized as a uniaxial compressive test, because the both deformation modes are equivalent due to incompressible material. Specifically, when the hydrostatic load is applied, the incompressible materials such as elastomer have different stress states, but the deformation states are same as before. The specimens and experiment devices for the tests are shown in Figure 1. Figure 2 shows the results of the material property tests. As aforementioned, the stress-strain curves represent the characteristics of elastomer material: stress softening, permanent deformation, and different stress level with respect to the maximum strain ranges. The final stress-strain curves shown in Figure 3 are extracted from the last converged data in Figure 2. In this derivation, the permanent strains are shifted to zero in order to obtain the processed data for finite element analysis.

![Figure 1. Specimens and experiment devices: (a) for uniaxial tension, (b) for equibiaxial tension](image)

![Figure 2. Raw experiment data: (a) for uniaxial tension, (b) for equibiaxial tension](image)
2.2. Hyperelastic material model

The elastomer uses hyperelastic material for constitutive model. With hyperelastic material model, it can be described nonlinear and large elastic deformation of material. For hyperelastic materials, the stress-strain relationship is derived from a strain energy density function as shown in Equation (1). In this equation, \( W \), \( T \), \( \lambda \) and \( F \) stand for the strain energy density function, engineering stress, stretch, and deformation gradient, respectively.

\[
T = \frac{\partial W(F)}{\partial \lambda}
\]  

As a hyperelastic material model, Neo-Hookean, Mooney-Rivlin and Ogden are popular constitutive models. In this study, Ogden model [5] was modeled to fit the experiment data accurately. Equation (2) represents the simplified Ogden model. In Equation (2), \( n \), \( \mu \) and \( \alpha \) are material constants and \( i \) means the direction of axis. \( K \) represents the bulk modulus and \( J \) refers the determinant of deformation gradient. For a fully incompressible material, \( J \) becomes zero and the second term can be removed.

\[
W = \sum_{i=1}^{3} \sum_{j=1}^{n} \frac{\mu}{\alpha_j} (\lambda_i^j - 1) + K (J - 1 - \ln J)
\]  

As shown in Figure 4, the experiment data was fitted with Ogden model, Equation (2). These results shows good agreement. The material parameters are summarized in Table 1.

Figure 3. Processed experiment data: (a) for uniaxial tension, (b) for equibiaxial tension

Figure 4. Comparison between experiment and simulation: (a) for uniaxial tension, (b) for equibiaxial tension
Table 1. Material constants for Ogden model (n = 5)

|   | 1   | 2   | 3   | 4   | 5   |
|---|-----|-----|-----|-----|-----|
| μ | 7.90E-01 | 6.94E-01 | 4.51E-01 | -6.20E-01 | -6.78E-05 |
| α | 7.33E-07 | 4.55E-07 | 2.61E-15 | -7.75E-03 |

3. Finite element modeling for elastomer forming process

As the first study, the elastomer was designed with a simple cylinder shape. However, in an actual test, the blank sheet was fractured with the cylinder shape of elastomer. Finite element simulation is introduced to obtain the target shape without any fracture by designing an optimized rubber die shape. To construct the finite element model for elastomer forming process, the shape of elastomer was iteratively modified to get the target product. Finally, it was investigated whether the product is free from the fracture, using the PEPS diagram proposed by Stoughton and Yoon [6]. The initial concept of FE modeling is shown in Figure 5. The metal sheet is located between blank holder and die. Commercial software LS-DYNA 3D was used for FE modeling. Stainless steel and natural rubber 50 was used as a blank sheet and an elastomer.

3.1. Adjustment of analysis conditions

In order to model the elastomer, the element type and Poisson’s ratio were determined. ELFORM 13 (1 point nodal pressure tetrahedron), not hexahedron, was selected as an element formulation option for elastomer, because the punch shape is complex and the contact surface of elastomer is deformed flexibly during forming process. A hexahedron element has a limitation to handle severe distortion. The ELFORM 13 with the nodal pressure reduces the element stiffness compared to general tetrahedron.

In practice, the Poisson’s ratio for incompressible material is defined between 0.49 and 0.4999. However, the two bounds, 0.49 and 0.4999, showed the different results at the edge of blank as shown in Figure 6. For Poisson’s ratio of 0.4999, the elastomer showed much incompressible behavior. Actually, it is not possible to measure the correct value from 0.49 to 0.4999. From the sensitive studies for different Poisson’s ratios, the value is set to 0.4995. With this result, it exhibits good agreement with an actual test. Figure 7 shows the comparison between the simulation and the actual test, and the locations of crack and wrinkling were similar with actual test. In this comparison, the strain based forming limit diagram was applied for the post processing.

![Figure 5. Initial concept design of the elastomer forming process](image)

![Figure 6. The simulation result with respect to the Poisson’s ratio: (a) for 0.4999, (b) for 0.49](image)
3.2. Preformed design of elastomer

With cylinder shape of the elastomer, the crack was observed in both experiment and simulation as shown in Figure 7. To solve this problem, the preformed elastomer was proposed from an aspect of the contact. The contact among the elastomer, blank, and punch could induce the constraint that seizes the blank sheet and could result in local severe deformation of the blank sheet. As shown in Figure 8, the first concept design of the preformed elastomer was simulated. With this concept design, it could delay the onset of second contact. Herein, the first contact refers the contact between blue part of punch in Figure 9 and blank sheet, and the second contact means the contact between green part of punch and blank sheet. In the simulation with this design, the deformation of the sheet was more uniformly distributed than the original model and cracks were not observed. However, the edge of elastomer did not sufficiently press the blank sheet and the wrinkling occurred. Consequently, the final design was developed as shown in Figure 10. With this preformed shape, the contact between elastomer and blank was delayed and it reduced the friction on the contact surface. In addition, the target shape for product was successfully obtained from the simulation. Figure 11 shows the formability evaluation of final preformed elastomer case. The cracks were not observed on the surface of the product.
3.3. **Forming limit analysis with Polar EPS (PEPS) diagram**

Strain based forming limit diagram cannot cover the strain path changes and it uses the final status. Stoughton and Yoon [6] proposed the PEPS diagram which consider nonlinear strain path changes during forming process. As more advanced approach compared to the conventional strain-based forming limit diagram, the PEPS diagram was applied to the results of previous FE analyses. Figure 12 shows the failure evaluation using PEPS diagram for the initial and final die setups. The results are compatible for this example (fail for the initial die setup and safe for the final die setup)

![PEPS Diagram](image)

**Figure 12.** Failure evaluation using conventional strain based FLD and PEPS diagram

4. **Durability estimation**

In terms of fatigue, the tool life of elastomer was evaluated. In general, the fatigue life is related to materials performance defined with stress and number of cycles to reach failure. However, the stress of hyperelastic material including elastomer decreases during repeated loads because of the Mullins effect. Therefore, in case of hyperelastic material, the strain function is defined as a major parameter of the fatigue life. Woo [7] carried out the fatigue test about various natural rubbers and studied the relationship between fatigue life and strain function. The material behavior of this study was compared with the reference data. According to Figure 13, the behavior of natural rubber 50 (NR 50) showed good agreement with the elastomer used in this study. The average difference percentage of stress between NR 50 and the used elastomer was almost 15%. Equation (3) from reference [7] is the relationship between fatigue life and Green–Lagrange strain, for NR 50. In more conservative aspect, the relationship for NR 55 was described in Equation (4).

\[
N_f = 741300 \times [Green – Lagrange strain]^{-2.77}
\]

(3)

\[
N_f = 457088 \times [Green – Lagrange strain]^{-2.55}
\]

(4)
Figure 13. Comparison of mechanical behavior between reference data and the elastomer

From the simulation result, the Green-Lagrange strain was investigated as shown in Figure 14, assuming that the failure may take place at the region of severe deformation. From this contour, the regions A and B showed the high levels of Green-Lagrange strain, and the values of each region were 2.59 and 2.11. Figure 15 describes the locus of each region among fatigue life related to NR 50 and 55. The fatigue life was evaluated as 53,107 cycles for NR 50 and 41,962 cycles for NR 55. From this figure, the stronger hardness of elastomer the shorter fatigue life. The durability estimation with reference NR 50 is enough to obtain reliable result, because the final strain of the elastomer is important in the fatigue life estimation and the stress level of the used rubber is lower than the reference NR 50. Therefore the fatigue life might be longer than 53,107 cycles.

Figure 14. Contour of maximum principal strain

Figure 15. Fatigue life relation of NR 50 and NR 55, and locus of each regions

5. Conclusion
In this study, the elastomer forming process was investigated for elastomer material modeling, FE forming analysis, and durability evaluation. From the investigation, it was found that the FE model simulated the actual elastomer forming process accurately and the proposed elastomer shape for die is able to form the target product shape without failure on product. In addition, the life of elastomer was predicted as 53,107 cycles. Therefore, it is concluded that this elastomer process is feasible for elastomer forming process in views of accuracy and cost.
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