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# Study of micro hydromechanical deep drawing of SUS304 circular cups by an ALE model

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**Abstract**

Accurate estimation of hydraulic pressure on the blank is important for micro hydromechanical deep drawing simulation. An Arbitrary Lagrange Eulerian (ALE) simulation model that considers strong fluid-solid interaction (FSI) was generated to accurately predict the hydraulic pressure on the blank. The changeable pressure significantly affects the drawn cup's quality regarding wall thickness. Both the minimum and the maximum wall thicknesses in the ALE model are significantly different from that in a conventional model with a simple pressure load. The relationship between the maximum thickness and the hydraulic pressure in the ALE model is similar to that from the experimental results while reverse to that from the conventional simulation model. The ALE model provides more precise hydraulic pressure on the blank and accurate prediction of the drawn cups' quality compared with the conventional model.


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*Keywords:* Micro hydromechanical deep drawing, ALE, FSI, Hydraulic pressure, Cup quality

## 1. Introduction

Due to an assistance of hydraulic pressure, deep drawing process is improved regarding metal's formability,

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frictional conditions and the drawn cup's quality [1–4]. Driven by growing requirement on micro-metal products, micro hydromechanical deep drawing (MHDD) has been developed to utilise potential of the hydraulic pressure [5,6]. Existing knowledge about influences of the hydraulic pressure on conventional hydromechanical deep drawing, however, cannot be directly applied in the micro hydromechanical deep drawing. Hydraulic path is simplified due to difficulty in hydraulic pressure control in tiny fluid domain during short processing time. Hydraulic pressure gradient, that drives fluid instead of the hydraulic pressure, significantly increases in the micro hydromechanical deep drawing. Interaction between fluid and solid (blank) becomes important and considerably different from that in conventional hydromechanical deep drawing process. Both frictional conditions and blank deformation are greatly affected by fluid in micro-scale. Therefore, accurate hydraulic pressure estimation is important for investigation of micro hydromechanical deep drawing. It generally simplifies hydraulic pressure in conventional hydro deep drawing simulation [7,8] and the simplified hydraulic pressure on the blank is constant, which is unsuitable for micro-scale due to strong fluid-solid coupling in tiny area. Inaccurate pressure estimation in micro hydromechanical deep drawing will result in unprecise prediction.

This study focuses on influences of the hydraulic pressure on micro hydromechanical deep drawing and the Arbitrary Lagrange Eulerian (ALE) method [9,10] with ability to simulate the fluid-solid interaction was selected for the MHDD simulation. Both an ALE model and a conventional model with a simple pressure load on the blank were employed in the simulation. Finally, simulation results were discussed and compared with experimental results.

**Nomenclature**

| | |
|---|---|
| $p$ | hydraulic pressure |
| $C_{i=0,1,2,\dots,6}$ | EOS coefficients |
| $E$ | internal energy per unit reference volume |
| $\mu$ | relative density change |
| $\gamma$ | material parameter for air |

## 2. Simulation model

### 2.1. Conventional model

A conventional model with a simple pressure load on blank was generated for comparison with the ALE model. The conventional model had the same size with that of the experimental micro hydromechanical deep drawing system. Fig. 1 shows the sketch of the micro hydromechanical deep drawing system and the conventional simulation model. Only a quarter of the drawing system was modeled and all parts were of high-quality quadrilateral shell elements. Only the blank was deformable and assigned the 3-Parameter-Barlat material model while the other parts were rigid. The forming surface-to-surface contact algorithm was selected for contact/friction monitor in simulation. Material parameters and friction coefficient were obtained from experiments. A constant hydraulic pressure load was set normal to the blank during whole drawing process. The shell thickness was updated based on the Lankford coefficient.

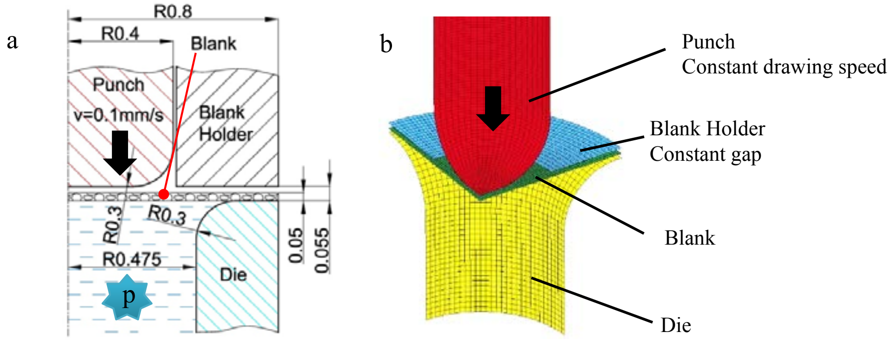


Fig. 1 (a) Sketch of micro hydromechanical deep drawing system (unit: mm); and (b) conventional simulation model

### 2.2. ALE model

The ALE model contained Lagrange and Eulerian modulus. The Lagrange module was the same as the conventional model without the hydraulic load and the Eulerian module represented fluid development and counted fluid-solid interaction. Fig. 2 shows the ALE model and the Lagrange and Eulerian modulus respectively.

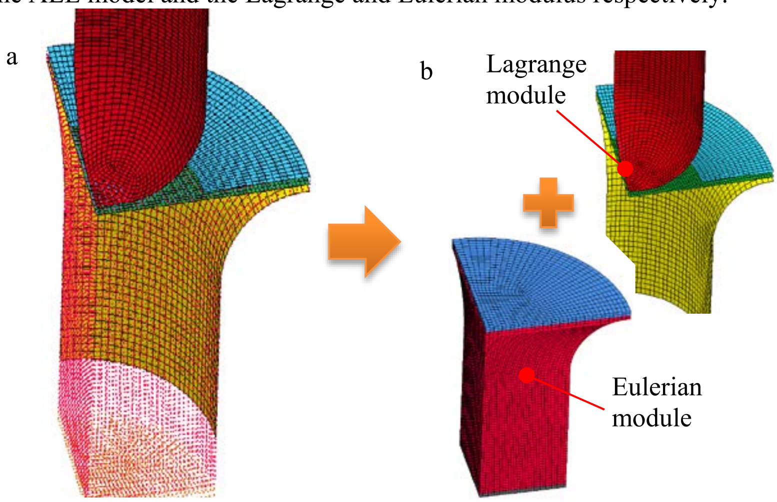


Fig. 2 (a) ALE model; and (b) Lagrange and Eulerian modulus

There were an inlet, an outlet and fluid domain in the Eulerian module and all were meshed with high quality hexagon elements with a similar elemental edge size to the shell size of the blank. The inlet and fluid domain were initially filled with pressured mechanical oil while the outlet was occupied by the air under atmosphere pressure (0.101325 MPa). The pressure generation of liquid phase was governed by linear polynomial equation of state (EOS) as shown in Eq. (1). The pressure updating of the air was controlled by $\gamma$-law EOS as shown in Eq. (2). All outer surfaces of Eulerian parts were set wall boundary condition.

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (1)$$

$$P = (\gamma - 1)(1 + \mu)E \quad (2)$$

The null material model and one-point ALE multi-material elemental model were applied to all the Eulerian parts. Thus, the fluid development can be calculated and solid parts can enter fluid domain interacting with the fluids. Four coupling points were assigned along the edge of each coupled element. Ten percent volume change of Eulerian coupling elements was set as the advection criterion, and the second order accuracy advection method was adopted. Compared with the influence of the oil, the impact of the air with a short activating time and low hydraulic pressure was ignorable and thus was not considered in the simulation. The air domain was still used for the oil development. Although the punch also interacted with the oil in a quite short time at the end of the drawing process, the interaction between the punch and the fluid was not of interest and did not affect the blank-fluid interaction significantly. Therefore, to accelerate computational speed and to increase robustness of the simulation program, only the interaction between the punch and the oil was considered in the ALE model. Additionally, the time step in the simulation was reduced to improve the computational stability.

## 3. Results & discussion

SUS304 sheets with a thickness of 50±2 μm were annealed at 975℃, 1050℃ and 1100℃ for two minutes respectively, and therefore, called 'H975', 'H1050' and 'H1100' sheets accordingly. All the sheets were then drawn under hydraulic pressures from 5 MPa to 30 MPa at an interval of 5 MPa. All the experimental cases were modelled and simulated in LS-DYNA. Fig. 3 displays the hydraulic pressure in fluid domain at four typical drawing stages with an inlet pressure of 25 MPa. Due to pre-bulging, the blank deformed upwards and hydraulic pressure decreased. As the blank was gradually drawn through the die, the hydraulic pressure was re-built and increased over the inlet pressure due to significant oil domain compression. At the final stage, the hydraulic pressure returned stable as oil domain compression compensated oil leakage.

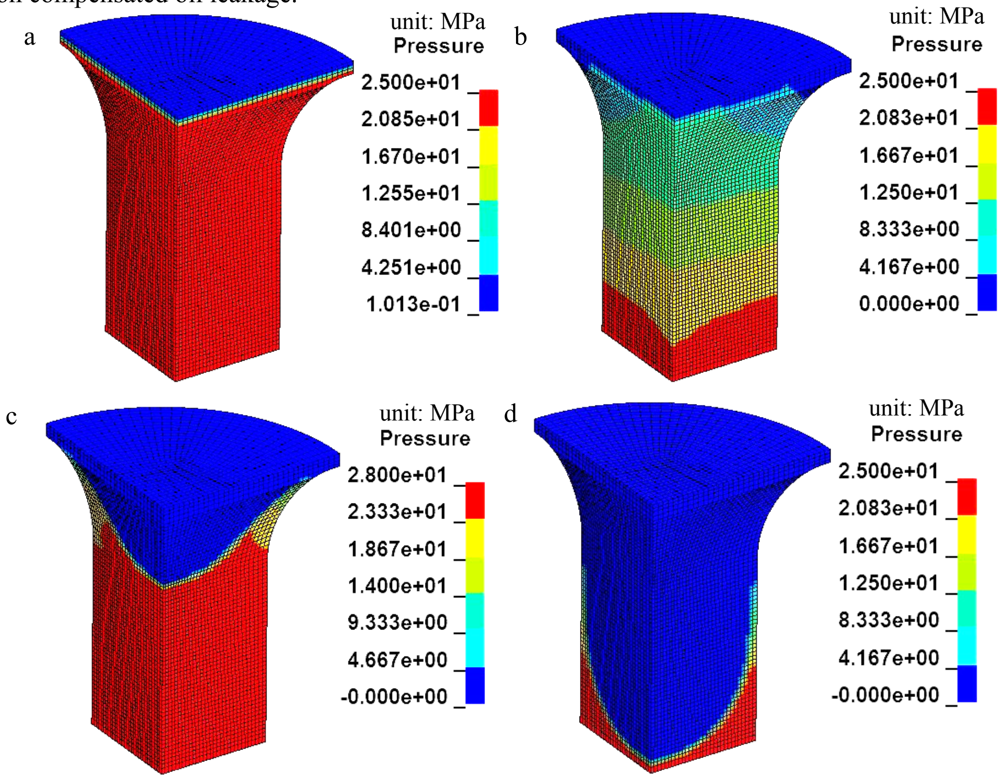


Fig. 3 Fluid pressure development at different drawing stages: (a) initial; (b) pre-bulging; (c) middle; and (d) final stage (inlet pressure: 25 MPa)

The hydraulic pressure developments on four special points of the blank were monitored, as shown in Fig. 4. For the points 1 and 2, as they were located under the punch, hydraulic pressure on these points were relatively stable and remained slightly below inlet pressure (15 MPa). Regarding point 3 on the drawn cup wall area, hydraulic pressure reduced sharply when it entered die wall area and sealing was failed. For the point 4, due to lack of effective sealing, the hydraulic pressure was low during the whole drawing process.

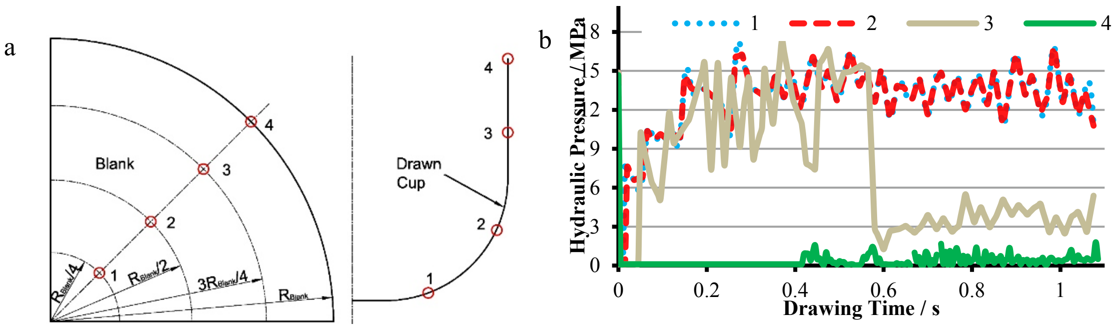


Fig. 4 (a) Four special positons on the H1050 blank; and (b) their pressure development (inlet pressure: 15 MPa)

All these hydraulic pressure developments were ignored in the conventional model. Thus, the difference in hydraulic pressure will result in difference in drawing process and drawn cups' quality. The maximum and the minimum cup wall thickness were studied. Fig. 5 displays the maximum and the minimum drawn cup wall thickness from the ALE and the conventional models. The minimum thickness occurred at the drawn cup corresponding to the punch fillet area and the maximum thickness can be found at the mouth of the drawn cup. The minimum wall thickness decreased with the hydraulic pressure in all models, however, the minimum wall thickness predicted by the conventional model reduced faster than that in the ALE model. The maximum wall thickness was decreased in the ALE simulation while increased in the conventional simulation models. Their difference became large with an increase of the inlet pressure.

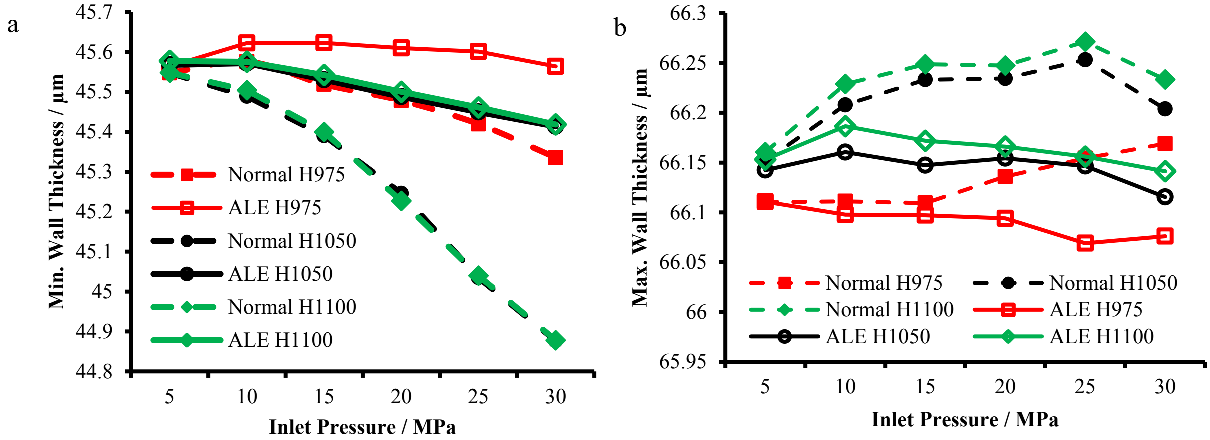


Fig. 5 (a) The minimum; and (b) the maximum wall thicknesses of drawn cups

The ALE simulation results were compared with the experimental results. Fig. 6(a) displays a drawn cup from H1050 sheet under inlet pressure of 20 MPa and Fig. 6(b) compares with the maximum cup wall thickness between the ALE simulation and experimental results. A decreasing trend of the maximum thickness with the hydraulic pressure was observed in both ALE simulation and the experiments. The maximum wall thickness in the ALE model, though was not the same, was quite close to the experimental results. By contrast, the maximum thickness development trend predicted by the conventional simulation model (Fig. 5(b)) was opposite to that in the ALE simulation and experimental results. This indicated more precise hydraulic pressure estimation in the ALE model than that in the conventional simulation model.

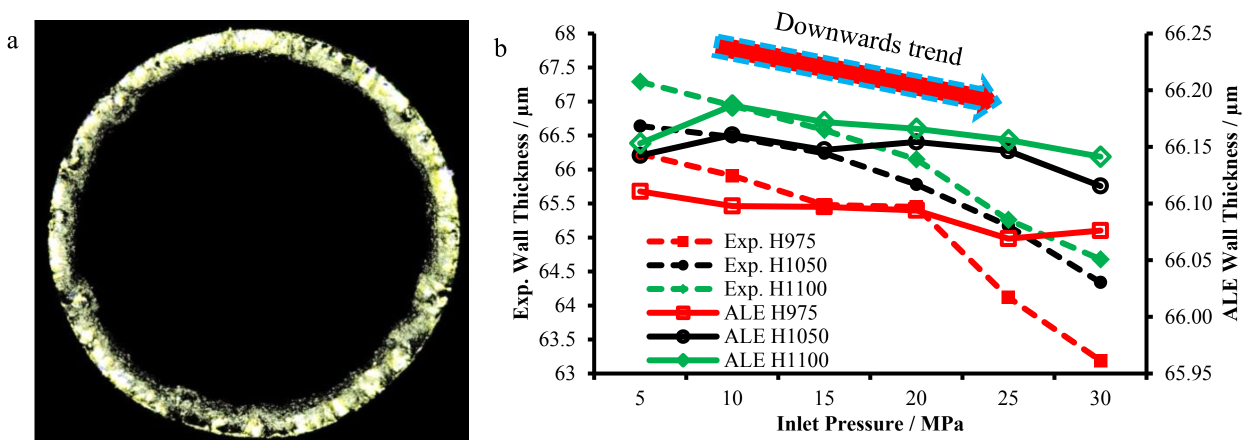


Fig. 6 (a) Drawn cup from H1050 sheet under 20 MPa; and (b) the maximum wall thickness from experiments and ALE simulation results

## 4. Conclusions

The developed ALE model can accurately present the strong fluid-solid interaction and the hydraulic pressure on the blank. The hydraulic pressure distribution and its development can be represented by the ALE model, which cannot be considered in the conventional model. Hydraulic pressure difference between the ALE and the conventional models resulted in different drawn cup wall thickness. Although both the conventional and the ALE models predicted the decreasing minimum wall thickness trend with increase of the hydraulic pressure, the greater thinning is obtained by the conventional model than that of the ALE model. Regarding the maximum wall thickness, the conventional model predicted a reverse trend to that in the ALE model and the experimental results. The ALE model provides more precise pressure distribution on the blank than that of the conventional simulation model for the MHDD simulation.

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