Numerical Simulation of Electrohydraulic Forming Using Coupling of ALE and Lagrangian Elements

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1 Abstract

Electrohydraulic forming is a high-speed forming process that employs high-pressure shock wave in fluid. When the electric energy is discharged from a capacitor bank, it is transferred to the water through the electrode bar and it makes the fluid into a high-pressure plasma state. Due to the high-pressure water, the sheet can be deformed into the die shape. Because the numerical model of electrohydraulic forming deals with fluid and structural models at the same time, it needs coupling mechanism for parts. Therefore, in this study, numerical model for electrohydraulic forming was developed using the coupling of ALE (Arbitrary Lagrange-Eulerian) and lagrangian mesh. The fluid parts, plasma, vacuum and water, were modelled with ALE elements and structural parts, die, chamber and sheet metal were modelled with general lagrangian mesh. The results of the numerical simulation showed that the plasma and water parts expanded due to the input energy, and the sheet metal was deformed with a speed above 100 m/s due to the pressure wave of the fluid parts.

2 Introduction

Electrohydraulic forming (EHF) is a sheet metal forming process that uses the high-voltage discharge in the fluid, typically a water, as the resources for forming a sheet metal in a closed die. From a capacitor bank, the electric energy is transferred to the fluid through two electrodes, and it creates the expansion of the plasma and high-pressure shock wave in the water.
Many researchers have found that the high-speed forming process can improve the formability of the materials due to high-strain rate effect or inertia effect[1-4]. In addition, the EHF has another advantage that the bouncing effect does not occur which happens in general high-speed forming process, so it is a process worthy to be researched.
Because the duration time of the EHF process at 1 discharge is less than 1 ms, the sheet metal is deformed with a velocity above 100 m/s and a strain rate of 10^3 s^{-1}. In addition, unlike other sheet-metal forming, the finite element model for EHF is not simple and requires a complex coupling mechanism because of the need to define the interaction between the fluid and the structure.
To implement the analysis for short duration and to reliably perform fluid-structure coupling, LS-DYNA program was used in this study.

3 Numerical model for electrohydraulic forming

3.1 Fluid parts

A 3-dimensional quarter numerical model for EHF developed in LS-DYNA is shown in Fig. 1. The fluid parts were modeled with arbitrary Lagrangian-Eulerian (ALE) multi-material elements because the ALE mesh can avoid the mesh distortion problem and can easily define the coupling mechanism with lagrangian mesh by using FSI (fluid-structure interaction) constraint keyword in LS-DYNA. The fluid parts are comprised of water, plasma, and the air. The energy resource for deforming the sheet metal is inputted in the plasma part through *EOS_ LINEAR_POLYNOMIAL_WITH_ENERGY_LEAK keyword. In this keyword, the energy deposition rate curve over time can be input through the *DEFINE_CURVE parameter. The energy for EHF process is an electric power obtained by multiplying the voltage and the current discharged from the capacitor bank as shown in Fig. 2. The current curve was obtained by Rogowski coil, and the voltage curve was assumed to be decreased linearly until the current curve reached the first peak.

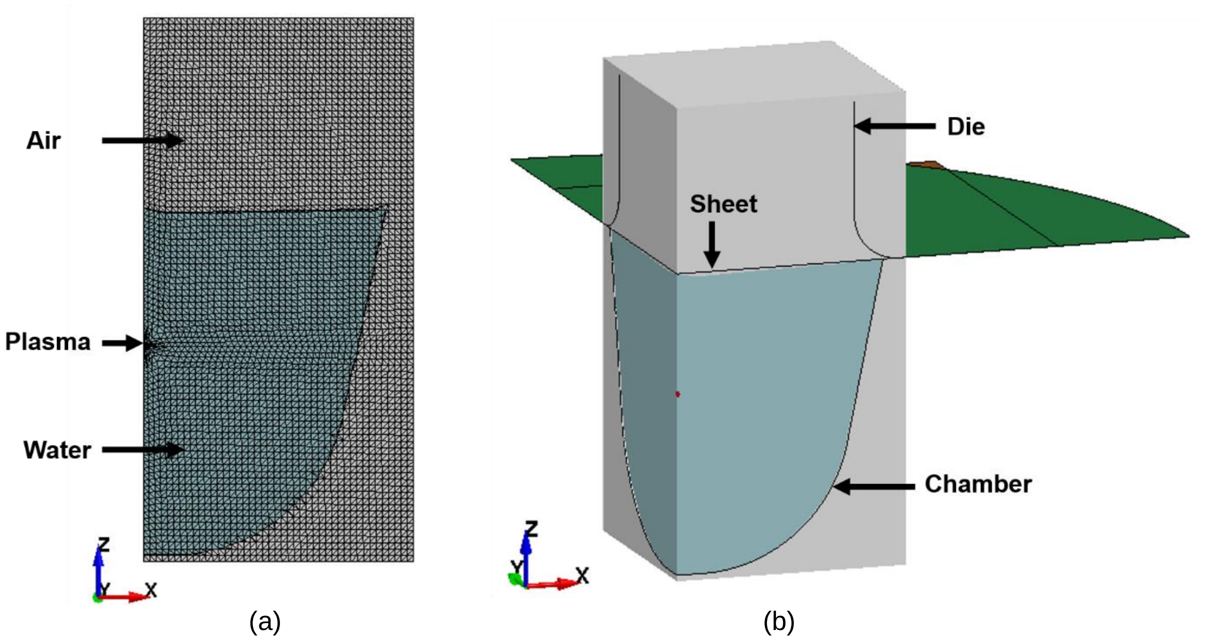

Fig.1: Numerical model for electrohydraulic forming process, (a) only fluid parts, (2) whole parts

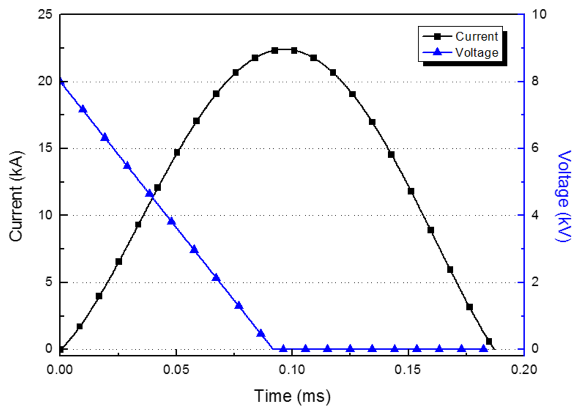

Fig.2: Current and voltage curves used in numerical simulation

In the EHF experiment, a very thin stainless wire is connected between two electrodes. When the voltage is discharged from the capacitor, the current is transferred into the electrodes, and the wire bursts because of the high electric energy. Because of this phenomenon, only one peak curve is generated as shown in Fig. 2.
The water part was positioned between a sheet metal and a chamber, so depending on the shape of the chamber, it may not be possible to generate a hexahedral element of the water part. Therefore, to reduce the difficulty of creating element in water parts, the air part was modeled bigger than the actual size and *INITIAL_VOLUME_FRACTION_GEOMETRY keyword was used as shown in Fig. 3. This keyword is a kind of volume-filling command which is valid only for ALE parts.
Among the elements of the air part(FMSID), specify the elements between the chamber and the sheet metal, which is to be replaced with the water part, as the segment set(SGSID), and input the physical properties of the water(FAMMG). By doing so, it is possible to reduce the inconvenience of generating all three elements of the fluid parts and to easily define the elements of the water part even if the shape of the chamber is complicated.

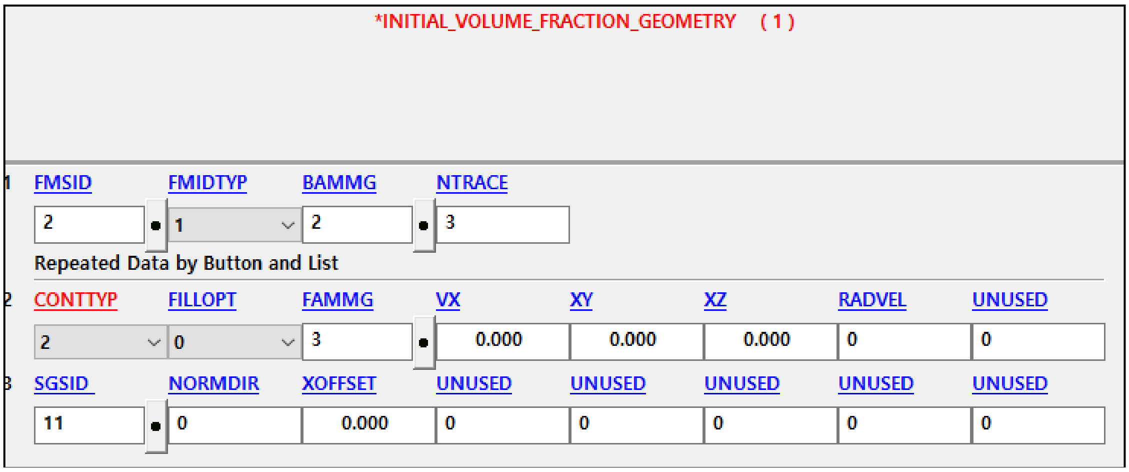

*Fig.3: * INITIAL_VOLUME_FRACTION_GEOMETY keyword in LS-PrePost software*

3.2 Structure parts – material properties for Al 6061-T6

Structure parts for EHF numerical simulation are composed of a chamber, die and sheet metal. Al 6061-T6 was used for this simulation and the 4-node shell element was employed because the sheet is very thin with a thickness of 1 mm compared to its size (250X250 mm^2). The chamber and the die were modelled as rigid-bodies.

Because the EHF is a high-velocity forming process, the material properties for the sheet metal obtained under conventional quasi-static test is not valid. Therefore, the constitutive equation that can consider the strain rate effect must be used. Cowper-Symonds constitutive model, as shown in Eq. (1), has been widely used to show the strain-stress curves for various strain rates of the material.

$$\sigma = \sigma_{y,0}\left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}\right] \quad (1)$$

Here, $\sigma_{y,0}$ is a yield strength in quasi-static condition, $\dot{\varepsilon}$ is a strain-rate, C and p is the strain-rate index. In case of Al 6061-T6, C =12266 and p =19.19

3.3 Fluid-structure interaction

It is very important to define the contact condition between fluid and structural parts for EHF numerical simulation. If the contact condition is not described adequately, the fluid part leaks out through the structure part, which causes inaccurate simulation result. In LS-DYNA, by using *CONSTRAINED_LAGRANGE_IN_ SOLID keyword, the definition of the coupling mechanism between two parts can be performed easily. In this keyword, the structure part is generally slave set, and the fluid aprts are the master. For the contact condition, the number of the coupling poinrts and the direction of the coupling must be defined for the numerical model. If a small number of coupling point is defined, leakage of the water occurs, and in the opposite case, the analysis beecomes instable and it needs high computational costs. Therefore, In this study, 4-coupling points are chosen.

4 Results of the numerical simulation for electrohydraulic forming

Fig. 4 shows the pressure distribution of the fluid and the deformation process of a sheet at once. From the input of electric energy, the pressure waves reached at the sheet and the chamber wall at about 0.05 ms, and they were reflected and mixed with other waves. And then from 0.2 ms, quite high pressure occurs near the clamping area and it results in large deformation of the sheet in the one specific direction. The final bulge shape of the deformed material was shown in Fig. 5, and the bulge height(a) and the strain rates(b) at different location were plotted in Fig. 6. Due to the high-strain rate near the clamping area(x = 40mm~) at 0.2~0.4 ms, the rapid deformation occurred that area. This phenomenon not always happen in EHF process because the pressure distribution in the fluid depends on a shape of the chamber and the input energy.

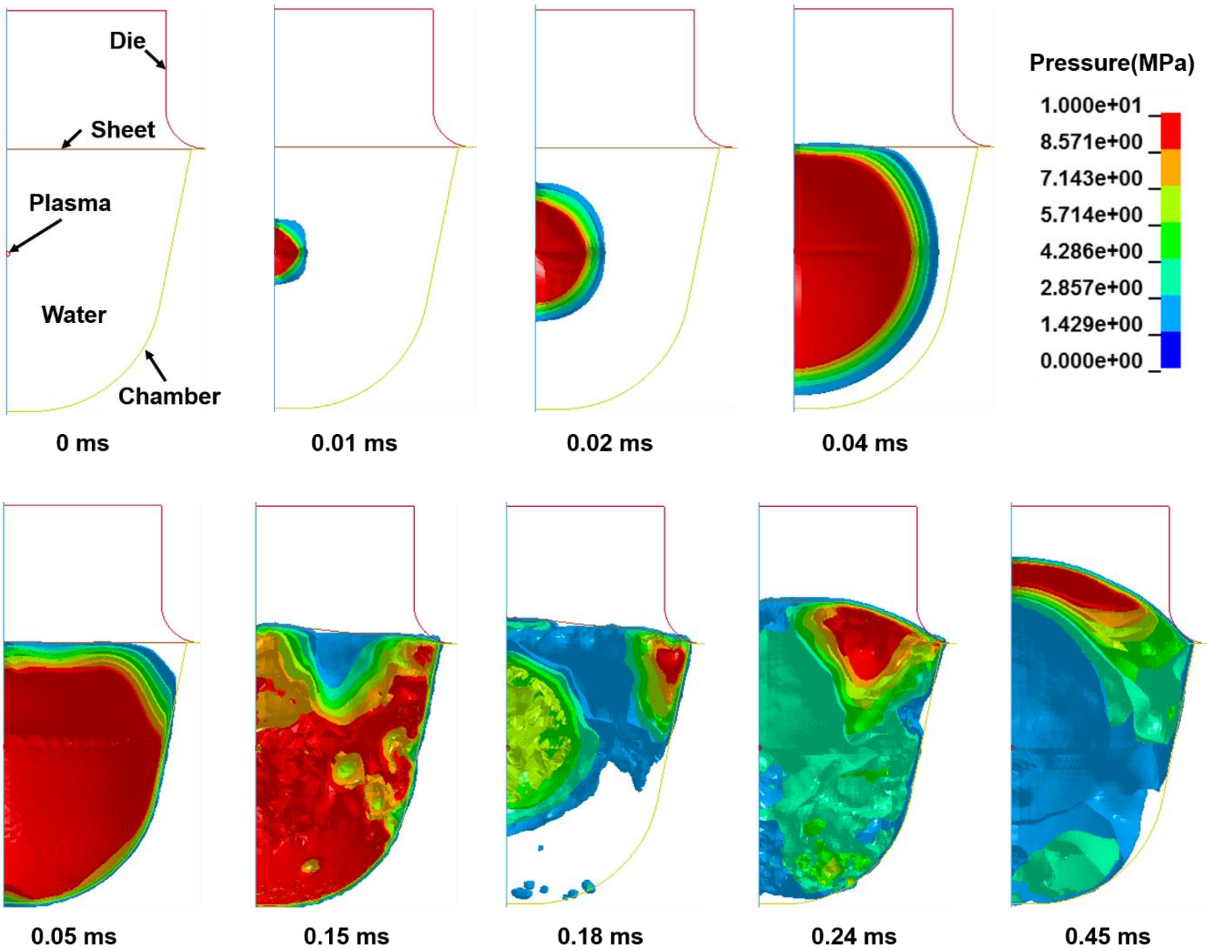

Fig.4: Pressure distribution of fluid and the deformation process of sheet in electrohydraulic forming process

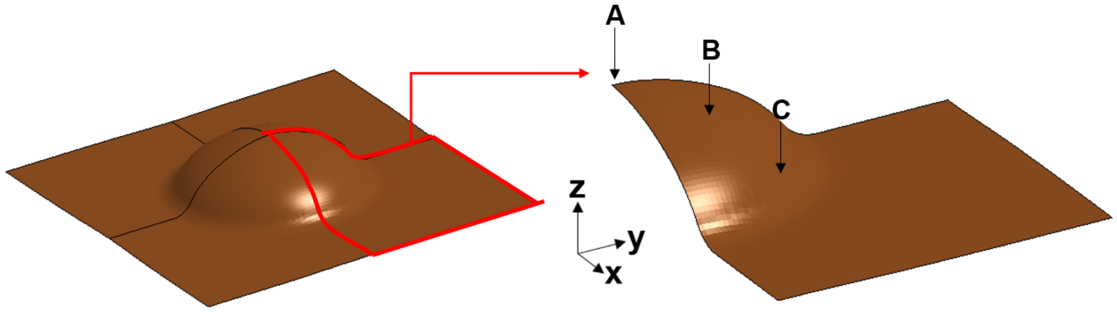

Fig.5: Final deformation shape of the blank

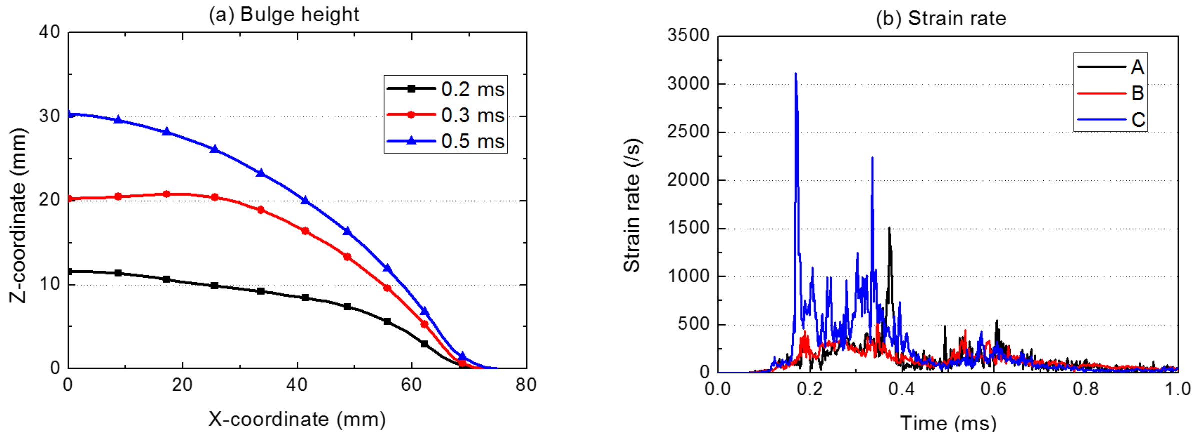

Fig.6: (a) Bulge height at 0.2, 0.3 and 0.5 ms and (b) strain rate distribution of a sheet

5 Summary

In this study, the numerical model for electrohydraulic forming (EHF) process was developed using LS-DYNA. The fluid parts (plasma, water and air) were created with arbitrary Lagrange-Eulerian (ALE) technique, and the structural parts (sheet metal, chamber, and die) were modeled as lagrangian mesh. 4-coupling points per segment were selected for definition of the coupling mechanism between fluid and structure part, and the volume fraction keyword was used to simplify construction of the water parts.
The results of numerical simulation showed the deformation mechanism of the sheet metal, and the information such as strain rate of sheet metal, and the pressure distribution of the water.
The developed numerical model can be used to predict the final deformation shape of the sheet, and to optimize the experimental equipment for EHF process by using various process parameters such as fluid, chamber geometry, and the blank holder force.

6 Acknowledgement

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7 Literature

[1] Balanethiram VS, Daehn GS (1994) Hyperplasticity: increased forming limits a high workpiece velocity. Scr Met Mater 30(4).

[2] Smerd R, Winkler S, Salisbury C, Worswick M, Lloyd D, Finn M (2005) High strain rate tensile testing of automotive aluminum alloy sheet. Int J Impact Eng 32(1–4):541–560.

[3] Altan TA, Tekkaya E (2012) Sheet metal forming: processes and applications. ASM International

[4] Imbert BJ (2005) Increased formability and the effects of the tool/sheet interaction in electromagnetic forming of aluminumalloy sheet.Master’s thesis, University of Waterloo. http://hdl.handle.net/10012/857