Numerical Study of Incremental Sheet Forming Processes

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Abstract. In incremental sheet forming processes, materials are deformed by continuous local contact with a moving tool along predefined tool paths so that their stress or strain histories are significantly different from conventional forming processes such as stamping, drawing, and hydroforming. In this work, numerical conditions, e.g., a rigid surface type, an initial blank size, an element type, and a contact algorithm commonly assumed for the conventional forming, were re-investigated to confirm whether those assumptions are still valid for the incremental sheet forming. An aluminium alloy sheet, AA7075-O, with a thickness of 1.64mm was considered for this work. The simulation results were compared regarding stress or strain paths at the critical elements, an effective strain distribution, a thickness profile, and reaction forces and moments of the tool. The computational time was also compared, in order to identify optimum simulation conditions.

1. Introduction

The single point incremental forming (SPIF) process was developed several decades ago as a cost effective new forming technology for low volume and complex shape production [1, 2]. This process was further improved to the two-point incremental forming (TPIF) process, in order to produce better quality products in terms of geometric accuracy and surface roughness [3]. The sheet blank is formed by the single moving tool in the SPIF process while the supported die is additionally installed in the TPIF process. In addition, the more advanced process called the double sided incremental forming (DSIF) process was developed by replacing the die with the second moving tool [4].

In general, the deformation mechanism of the incremental forming processes is completely different from the conventional forming processes such as stamping, drawing and hydroforming where the plane stress state is commonly assumed for their simulations with the shell element. In the incremental forming processes, however, the additional hydrostatic pressure and the out-of-plane shear stresses are highly involved [5] so that not only the solid element should be considered but also the other finite element (FE) simulation conditions should be rigorously examined from the start. Therefore, in this work, the effect of the rigid surface type, the initial blank size, the blank element type, and the contact algorithm were investigated to determine the optimum FE simulation conditions.

2. Material characterization

An aluminium alloy sheet, AA7075-O, with a thickness of 1.64mm was considered as a base material and characterized based on the rather simple elastoplastic material model by ignoring the temperature and strain-rate sensitivities. The linear isotropic Hooke’s law was adopted for the elastic properties. The Young’s modulus and the Poisson’s ratio are 71.7 GPa and 0.33, respectively [6]. As for the plastic properties, the following yield criterion, \( \Phi \) was considered with the isotropic von-Mises stress yield function and the Voce type isotropic hardening law:
\[ \Phi(\boldsymbol{\sigma}, \varepsilon) = f(\boldsymbol{\sigma}) - \bar{\sigma}(\varepsilon) \leq 0 \]  

(1)

where

\[ f(\boldsymbol{\sigma}) = \left[ \frac{1}{2}(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 3(\sigma_{xy}^2 + \sigma_{xz}^2 + \sigma_{yz}^2) \right]^{1/2} \]  

(2)

\[ \bar{\sigma}(\varepsilon) = A + B \exp(-C\varepsilon) \]  

(3)

where \( f \) and \( \bar{\sigma} \) are the von-Mises yield function dependent on the Cauchy stress \( \sigma \) and the effective (or equivalent) stress as a function of the effective strain \( \varepsilon \), respectively. Here, \( A, B, \) and \( C \) are material parameters for the Voce type hardening law which is defined by the relation between \( \bar{\sigma} \) and \( \varepsilon \). Those parameters were calibrated to have a least mean square error for the stress-strain curves measured in the uniaxial tension test along the rolling direction [7]. The resulting parameters are as following: \( A=89.0 \text{ MPa}, B=149.34 \text{ MPa}, \) and \( C=26.71 \). For the AA7075-O sheet, the Voce type hardening law shows better prediction compared to the Swift type hardening law, as shown in Figure 1. Its density is 2.81 g/cm\(^3\) [6].

3. Parametric study on FE simulation conditions

For parametric study on FE simulation conditions, the two-point incremental forming (TPIF) process with a hemispherical-ended tool and a truncated cone shape die was considered, as shown in Figure 2 (a). The tool diameter is 12.7 mm, and for the die, the depth and the wall angle are 55mm and 67\(^\circ\), respectively. A spiral tool path with a step down of 0.5mm was generated based on thickness calculation from the cosine law, i.e., \( t = t_o \cos(\theta) \) where \( t \) and \( t_o \) are the final and initial thicknesses, and \( \theta \) is the wall angle [8]. The tool is rotationally fixed, and its feed rate is 50mm/s with a total forming process time of 717 seconds. The assumed friction coefficient is 0.1. The simulations were performed with the commercial software ABAQUS/Explicit. The fixed mass scaling of \( 10^7 \) was applied to increase the minimum required time increment. The computer cluster at Ohio Supercomputer Center was used with 112 cores of Intel Xeon E5-2680 v4 and 512 GB of memory.

3.1 Rigid tool type and initial blank size

To investigate the effect of the rigid surface type and the initial blank size on the simulation results, the discrete rigid tool and the analytical rigid tool were considered, and the initial blanks with three different radii of 85mm, 100mm, and 115mm were generated in the cylindrical shape with a thickness of 1.64mm. Figure 2 shows the schematic view of the FE simulation conditions considered in this section. The linear solid 8 node element with reduced integration, the so called C3D8R in ABAQUS, was used for the sheet blank. The average element size is 0.7mmX0.7mmX0.5467mm with 3 integration points through the thickness. The kinematic contact algorithm was adopted to calculate the frictional force and the hard contact pressure between the rigid tool and the sheet blank.
ABAQUS provides two different types of rigid surfaces for the tool and the die. In the discrete method, the rigid surface is discretized with multiple rigid elements in a similar way to the deformable shell element, while in the analytical method, the rigid surface is defined by revolving or extruding the profiles including the straight and curved line segments. The analytical method generally provides a smoother surface description with better approximation to the physical contact constraint and the reduced contact noise, while the discrete method is highly dependent on the element size [9]. The discrete method is usually applied to the conventional forming simulation because the analytical method has limitation for application to complex shapes, as well as that the discrete method shows similar simulation results to the analytical method. The incremental forming, however, has completely different contact procedure, i.e., simultaneous overall contact in the conventional forming, while continuous local contact in the incremental forming. Therefore, it should be confirmed whether the discrete method is still valid for the incremental forming. Firstly, for this work, the tool and the die were discretized with the rigid elements of which average sizes are 0.5mm and 2.5mm, respectively. In Figures 3 and 4, the reaction forces of the tool and the die in the normal direction, $F_z$, and the radial direction, $F_r$ or $\sqrt{(F_x^2 + F_y^2)}$, were compared. The abnormal force peaks, regarded as a numerical error, were frequently observed in Figure 3 (a). This is because the sharp edge between coarse rigid elements leads to the unstable contact calculation. In addition, for the same reason, materials are severely deformed when the discrete tool is used for the simulation. Its maximum effective strain is 13.605 which is approximately 4 times higher than the analytical tool. However, the reaction forces of the die with the relatively extensive contact are less sensitive to the rigid surface type, as shown in Figures 4 (a) and (b). The computational time was also compared in Table 1. As a result, the analytical rigid surface should be used at least for the tool.

The clamping process with the holder or the screw pin was simplified by applying the fixed boundary condition to the edge region of the blank, in order to reduce computational time with the less number of elements. For simplified boundary conditions, the initial size and shape of the blank should be optimized. Here, the initial blanks were considered as cylindrical with a thickness of 1.64mm and radiuses of 85mm, 100mm, and 115mm. It was confirmed that the initial blank size has a minor effect on the simulation results except for the reaction force of the die. In Figures 4 (b), (c) and (d), as the initial blank size becomes larger, the peak value of the reaction force $F_z$ in the beginning region decreases and eventually converges. The computational time was compared in Table 1, which is highly dependent on the total number of elements. This implies that the larger blank requires the more computational time. Note here that the 100mm radius is the optimum value for the initial blank size.
Figure 3. Reaction force curves of the tool: (a) the discrete tool and the 85mm blank, (b) the analytical tool and the 85mm blank, (c) the analytical tool and the 100mm blank, and (d) the analytical tool and the 115mm blank

Figure 4. Reaction force curves of the die: (a) the discrete tool and the 85mm blank, (b) the analytical tool and the 85mm blank, (c) the analytical tool and the 100mm blank, and (d) the analytical tool and the 115mm blank

Table 1. Comparison of the computational time for the rigid tool type and the initial blank size

| Condition (a) | Condition (b) | Condition (c) | Condition (d) |
|---------------|---------------|---------------|---------------|
| Rigid tool type | Discrete      | Analytical    | Analytical    | Analytical    |
| Initial blank size | R85mm         | R85mm         | R100mm        | R115mm        |
| Total elements | 85,122        | 85,122        | 108,912       | 131,443       |
| Process time   | 717sec        | 717sec        | 717sec        | 717sec        |
| CPU time (2.40GHz, 112 cores) | 55hr 50min | 55hr 12min | 70hr 42min | 85hr 20min |

3.2 Blank element type and contact algorithm

In this section, the blank element type and the contact algorithm are the major FE simulation conditions to be studied. Three types of 8-node hexahedral solid elements, the so-called C3D8I, C3D8, and C3D8R available in ABAQUS/Explicit, were considered. The C3D8R element uses the reduced integration with 1 Gauss point per element while the C3D8 and C3D8I elements are fully integrated with 8 Gauss points per element. The C3D8R and C3D8I elements were developed to remedy the over stiffness or shear locking problem occurring in the bending dominated simulation with the C3D8 element. On the other hand, the reduced integration element, C3D8R, intrinsically has its own drawback called the hourglass mode where the part of the strains cannot be detected as the actual strains. This often leads to the severely distorted elements even with low strain energy. In the C3D8R element, there are several hourglass control methods such as the relax stiffness, enhanced strain, stiffness, and viscous methods. Here, the relax stiffness method was only considered by default. As another approach for reducing the shear or volumetric locking, the incompatible mode-controlled element, C3D8I, were introduced by adding the bubble function to the conventional shape function [9]. Therefore, the C3D8I element is expected to be the most accurate with the highest computational cost. For this work, the shell element, in which the plane stress state is only accommodated, is not considered since the out-of-plane stresses are important in the incremental forming processes.

In addition, two different contact algorithms including the kinematic and penalty methods were considered. In the kinematic method, the contact force and the nodal position are iteratively calculated
in the implicit manner while in the penalty method, they are explicitly calculated by assuming the artificial spring between the slave and master surfaces. The more accurate kinematic method has the higher computational cost than the penalty method especially for the contact related simulations. The FE simulation conditions were summarized in Table 2. To save the computational time, the simulations were partially conducted up to the process time of 150 seconds out of total 717 seconds.

Figure 6 shows ratio of the hourglass energy to the internal energy with respect to the forming depth. It is recommended that the artificial hourglass energy is less than 1% of the internal energy [10]. In Figure 6 (d), however, the hourglass energy of the C3D8R element is more than 4% of the internal energy. Furthermore, the unrealistic zig-zag patterns are found in a lot of elements on the outer surface. This numerical error was also observed in Figure 7 (d), showing the oscillated thickness profile. It was concluded that despite low computational cost, the C3D8R element is not suitable for the incremental forming simulation. Secondly, to quantify the locking problem of the C3D8 element, the reaction forces of the tool were compared in Figure 5. The force values of the C3D8 element are similar to the C3D8R and C3D8I elements which are considered as the element types without the locking problem. In conclusion, the C3D8 element which is slightly faster than the C3D8I element in Table 2, is the optimum element type to be used for the incremental forming simulation.

The choice of the contact algorithm has a significant effect on the computational time. The kinematic method is 7 times slower than the penalty method as listed in Table 2. However, both methods show the similar results, e.g., the reaction forces in Figure 5 and the thickness profiles in Figure 7. Consequently, the penalty method is the recommended contact algorithm for the incremental forming simulation.

Figure 5. Ratio of artificial hourglass energy to internal energy: (a) C3D8I and kinematic, (b) C3D8I and penalty, (c) C3D8 and penalty, and (d) C3D8R and penalty

Figure 6. Reaction force curves of the tool: (a) C3D8I and kinematic, (b) C3D8I and penalty, (c) C3D8 and penalty, and (d) C3D8R and penalty

Figure 7. Thickness profiles: (a) C3D8I and kinematic, (b) C3D8I and penalty, (c) C3D8 and penalty, and (d) C3D8R and penalty
Figure 7. Thickness profiles along the initial rolling direction: (a) C3D8I and kinematic, (b) C3D8I and penalty, (c) C3D8 and penalty, and (d) C3D8R and penalty

Table 2. Comparison of the computational time for the Element type and the contact algorithm

| Condition (a) | Condition (b) | Condition (c) | Condition (d) |
|---------------|---------------|---------------|---------------|
| Element type  | C3D8I         | C3D8I         | C3D8          | C3D8R         |
| Contact algorithm | Kinematic     | Penalty       | Penalty       | Penalty       |
| Total elements | 108,912       | 108,912       | 108,912       | 108,912       |
| Process time  | 150sec        | 150sec        | 150sec        | 150sec        |
| CPU time (2.4GHz, 112 cores) | 36hr 05min     | 05hr 17min     | 4hr 56min     | 03hr 06min    |

4. Conclusions
The FE simulation conditions were optimized for the incremental sheet forming simulations as following:

- The analytical rigid tool with smooth surface description is required to have more stable reaction forces and moments.
- Using the fixed boundary conditions are preferred over modeling the blank clamping process to save the computational time. The effect of the initial blank size is minimal, but at least a radius of 100mm is required to show the converged results regarding the reaction force of the die.
- The full integration 8-node hexahedral solid element, C3D8, is chosen as the optimum element type. This element has less numerical problems such as the hourglass mode and the locking problem.
- As for the contact algorithm, the computationally more efficient penalty method is recommended because its simulation results show similarity with the ones from the kinematic method.

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