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Reduction of Explicit Incremental Forming Simulation Time by Mass Scaling Parameters Adjusting and Symmetrical Setting

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Abstract: For the sake of reducing the extremely long time-cost in the incremental sheet forming simulation process, a new simulation method combining symmetry setting and mass scaling setting is introduced in this work. In this paper, a CNC milling machine was used to shape a 40° pyramid in the material of AA3003-H18 Al alloy sheet at room temperature. Simulations were designed based on the experiment. Mass scaling in different factors 100, 500, 900 for 1/2, 1/4 and whole part symmetrical settings were investigated to reduce the simulation time. Furthermore, mises stress, equivalent strain, thickness, and profile of the part were compared. The results indicate that the 1/4 parts explicit dynamic simulation in mass scaling factor 900 keeps a good consistency with whole part simulation and also greatly reduces simulation time by 94%, which can be used for quick simulation of ISF. Compared with frequently-used methods (like explicit replacing implicit code), the method in this work achieves higher efficiency without losing accuracy. The proposed method provides a new idea to shorten the simulation verification time for researchers, which can greatly shorten the research cycle of ISF.

Keywords: *Incremental sheet forming, finite element simulation, simulation efficiency, symmetrical setting, mess scaling*

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I. INTRODUCTION

Computer use is a major turning point in the history of sheet forming, and it is widely used in Incremental Sheet Forming (ISF) [1]. Nowadays, the frequency of the replacement of all kinds of daily necessities and work products becomes faster. The demand for small and medium volume and customized products is increasing, and ISF is exactly suitable for making this kind of product. In addition, the great demand for customized parts in the fields of medical equipment, automotive parts, solar cookers, cranial plates and so on [2], also promotes incremental forming and makes great efforts in these fields. ISF

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*Correspondence concerning this article should be addressed to Dongwon Jung, Department of Mechanical Engineering, Jeju National University, Jeju Island, South Korea, E-mail: jdwcheju@jejunu.ac.kr is generally divided into two forms according to different process methods: Single Point Incremental Forming (SPIF) and Two Points Incremental Forming (TPIF) [3]. Although it can improve the forming accuracy, TPIF requires two punches to move up and down, which has high requirements for equipment. Due to simple equipment requirements and process design, SPIT was investigated by a number of researchers and was also adopted in the present work [4].

During the incremental sheet forming process, a metal sheet is fixed on the operating platform [5, 6, 7]. By using the Computer Numerical Control (CNC), the simple punch moves in a specified tool path over the sheet surface and then the local plastic deforming is caused [8]. That means different from conventional metal forming, the specialized die is not required. Hence the ISF technology can save the die designing time and reduce the production cost significantly [9]. Whats more, due to the small increment of punching force and shear force exerted by the tool head on the sheet, ISF greatly improves the forming ability of the sheet compared with the traditional stamping process [10]. However, forming problems like sheet thinning and spring back always happen after sheet forming. In order to reduce the material waste caused by failed sheets, it is particularly important to predict the ISF process and results of sheets in advance by using the technology of finite element simulation.

In recent years, computer technology has developed rapidly. Numerical simulation technology has been widely used in all kinds of fields. Lots of scholars take the ISF to numerical simulation [11, 12]. However, ISF simulation is a high nonlinear problem because of the combination of nonlinear material properties, variable contact conditions and continuous spatial position change of the punch [13, 14]. Hence, the numerical simulation of ISF is destined to be a long process. Smith, Jacob and Malhotra, Rajiv and Liu, WK and Cao, Jian [15] carried out a full-size simulation of sheet metal using an 8-node entity unit and completed the whole simulation process in about 30 days based on 56 processors. Ren et al. [16] simplified the size of the model, but it took more than 4 months to complete all the simulations. Based on the above studies, it is significantly important for us to develop a way to short simulation time without reducing the simulation accuracy as well.

For the sake of reducing the long simulation time, a lot of methods were tried. The selective reduction integral solid-shell element was developed in prior research and applied to the simulation of sheet metal to improve the efficiency of ISF numerical simulation. From the work of Q Qin, and E S Masuku, and Alan N Bramley, and A R Mileham, and G W Owen. [17], the punch was given rigid and solid elements respectively to solve the time and the simulation results of the two elements were completely consistent. While the simulation time of the punch of the rigid element was reduced from 2h to 24 min. Eyckens, Philip and Van Bael, Albert and Aerens, R and Duflou, Joost and Van Houtte, Paul [18] analyzed the contact forces in the incremental sheet forming process of cone bench parts by using the finite element sub modeling and compared the contact forces in all directions with the experimental values. The results showed that the sub-cycle simulation improved the efficiency and simulation accuracy due to the optimization of mesh quality [19, 20, 21].

In this paper, a new method is proposed by setting the symmetry and improving the mass scaling. In order to improve explicit simulation efficiency, mass scaling in different factors 100, 500, 900 for 1/2, 1/4 and whole part symmetrical settings were investigated respectively. To check the simulation results, the mises stress distributions, equivalent strain distributions, geometries, thickness distributions and simulation time were compared in nine comparative simulation experiments. Finally, the ratios between kinetic energy and internal energy of 900 mass scaling and 1/4 parts symmetrical setting were identified to ensure whether the simulation result was influenced by mass scaling.

II. METHODOLOGY

Mass scaling is a common method people use to short explicit dynamic simulation time. When mass scaling is used, factors like mass, rotary inertia in shells and so on are affected. An equation can be employed to express the explicit dynamics procedure stability limit [22]:

$$\Delta t = \left(\frac{L^e}{C_d}\right) \tag{1}$$

While L^e is the smallest characteristic element length, C_d is the material dilatation wave speed.

Meanwhile, the dilatation wave speed in a linear elastic material (with Poissons ratio equal to zero) is:

$$C_d = \sqrt{\frac{E}{\rho}} \tag{2}$$

While E is elastic modulus, is material density. That means if we increase the material density f, the wave speed C_d will decrease. Consequently, the stability limit Δt will increase $\sqrt{f}$.

Because of the amplification of mess density, the error will occur by the subsequent amplification of inertia.

Up to now, a widely accepted criterion for judging the inertial effect is that the ratio of kinetic energy and internal energy should be less than 5% [23].

III. EXPERIMENT

The 3D model was designed with the modelling part of commercial software Fusion 360, and then the model was imported to the CAM manufacturing part to generate NC code for machine-reading. Next, a three-axis CNC machine refitted for ISF Fig. 1(a) was used to shape a 40° pyramid according to the instructions of the NC code in the material of AA3003-H18 Al alloy sheet at room temperature. Table 1 shows the material properties of AA3003-H18. During the manufacturing process, oil and grease lubricants were mixed and adopted to reduce friction between the punch and sheet. The square area and forming depth of the target geometry are $60 \times 60\ mm^2$ and 20 *mm*, which can be seen in Fig. 1(b).

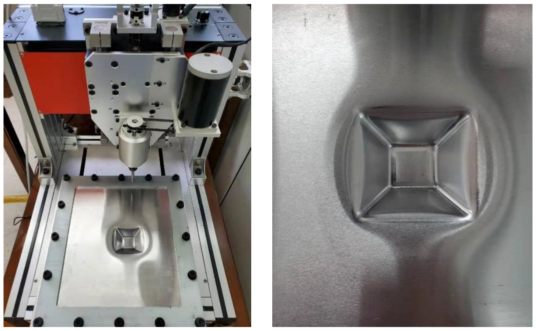


Fig. 1. Three-axis CNC milling machine and target geometry of the part

TABLE 1
MATERIAL PROPERTIES OF AA3003-H18.

Parameters		Units
Density	2730	Kg m^{-3}
Modulus of Elasticity	69.581	Gpa
Poissons ratio	0.33	
Yield Stress	164.088	Mpa
Ultimate tensile stress	192.878	Mpa
Total elongation	4.948	

IV. NUMERICAL SIMULATION

The simulation geometry is composed of punch, sheet, holder and die, which can be seen in Fig. 2 The property parameters of the sheet material Al A3003 H18were imported into simulation software. Youngs modulus is 69581, Poissons ratio 0.33, and the plastic data were imported into the software. Shell element was used and the thickness was set as 0.55 *mm* as the actual sheet thickness. To synchronize the mixed lubricant adopted in the experiment, the friction coefficient between the punch tool and sheet was set as 0.05. The holder, sheet and die are tied together at the contact part to simulate the state that the sheet fixed on the machine platform. For the load part, the tool trajectory code same as the tool moves on the machine was input into the software. Because of the characteristics of easy convergence and high accuracy, the linear reduced integration element S4R was employed for the meshing sheet. The punch, holder and die were set as rigid bodies to reduce simulation time and the sheet was meshed with the geometry 1 *mm*.

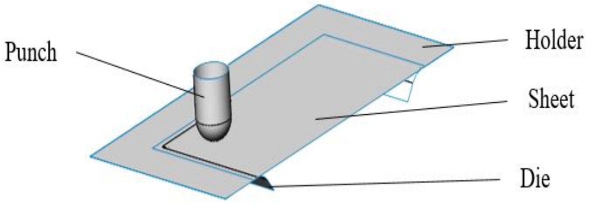


Fig. 2. Assembly geometry (half) for simulation.

V. RESULTS

To verify the accuracy with mass scaling increase and Symmetry setting, mises stress and equivalent strain were obtained to make a comparison, As Fig. 3, 4. As shown in the figure, the stress and strain distribution areas are roughly the same, and the maximum values are almost the same (Some partitions occur in the 1/4 and 1/2 parts, which will be discussed in the discussion part). Spring back is a tricky problem that always occurs in ISF [24, 25], hence, predicting the spring back is also an important work in a simulation job. Fig. 5 shows the deformed profile geometry of the sheet, the profile is the shape of the sheets natural surface. It is worth noting that thinning is a very tough question to investigate, which always results in sheet fracture directly. According to Reagans work [26, 27], the thinning in ISF obeys the sine law:

$$t_f = t_i \sin\alpha \tag{3}$$

Where t_f is the final thickness, t_i is the initial thickness of the sheet, and is the angle between forming slope and horizontal plane.

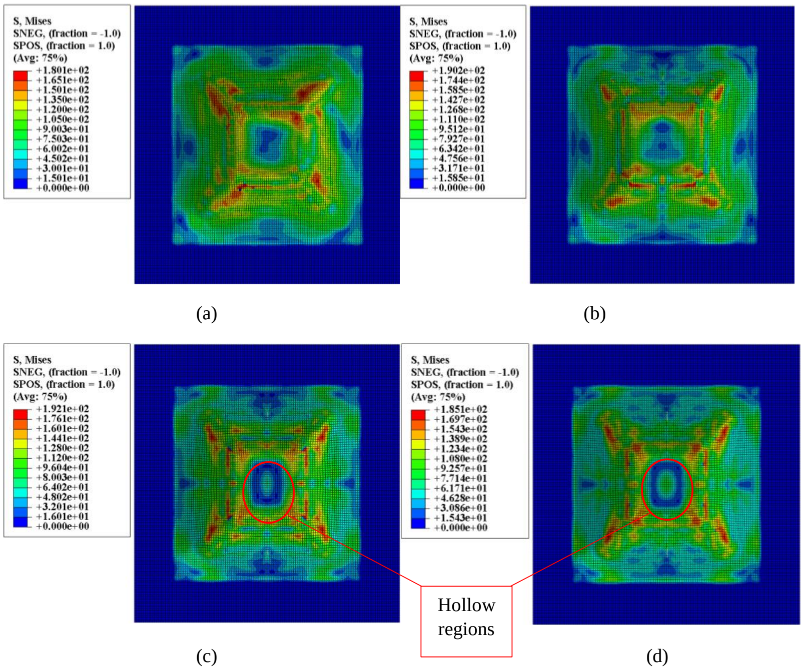


Fig. 3. Mises stress distribution of deformed part (whole part/mass scaling 100 (a), 1/2 parts/mass scaling 100 (b), 1/4 parts/mass scaling 100 (c), 1/4 parts/mass scaling 900 (d)).

As a result of this, the sheet thickness of the simulation was got to test the accuracy. As can be seen in Fig. 6, the thinnest locations occur in the same place on the sheet profile. The 1/4 parts thinning value is lower than the whole part and 1/2 parts, but the difference value is 0.025, which is acceptable. Moreover, some small peaks appear at the trough with the minimum thickness in 1/4 parts and 1/2 parts symmetric setting simulations.

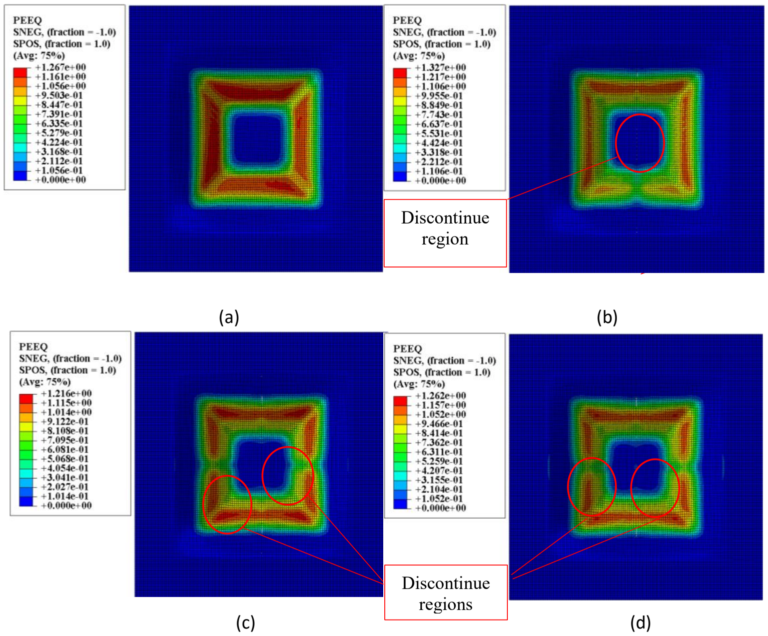


Fig. 4. Equivalent strain distribution of deformed part (whole part/mass scaling 100 (a), 1/2 parts/mass scaling 100 (b), 1/4 parts/mass scaling 100 (c), 1/4 parts/mass scaling 900 (d)).

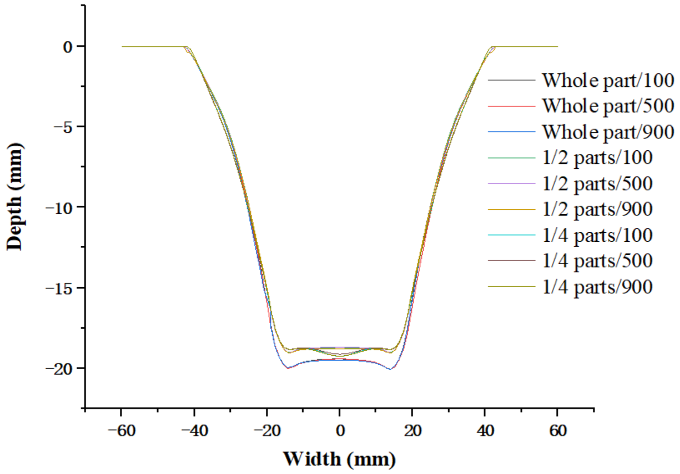


Fig. 5. Deformed profile geometry of the sheet (natural surface).

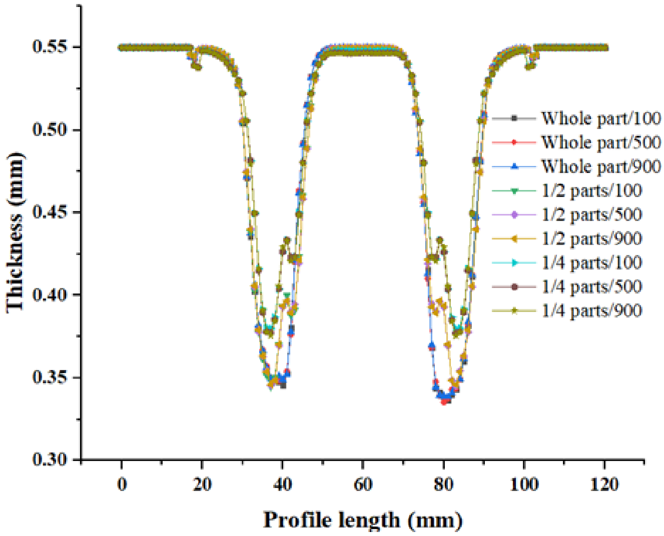
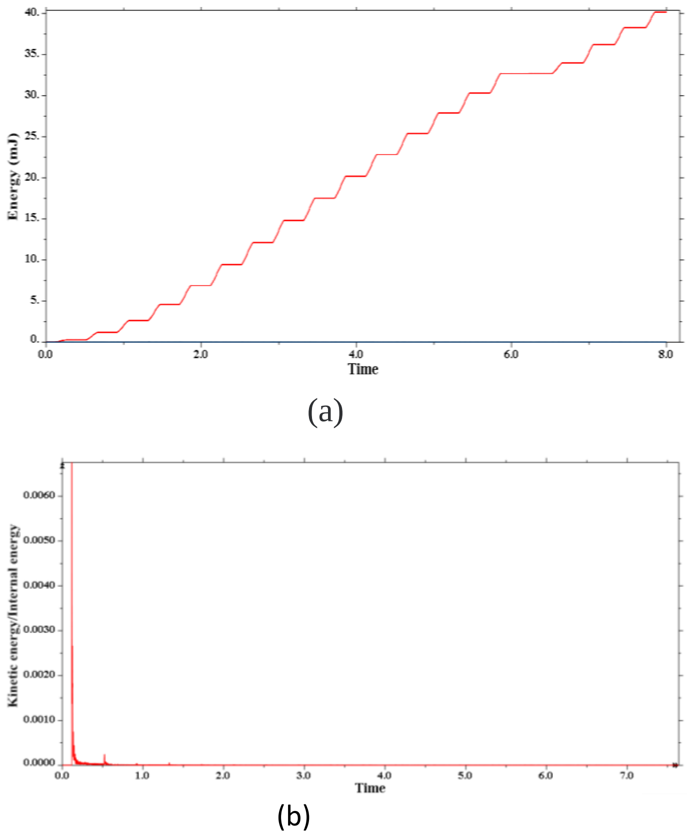


Fig. 6. Thickness distributions of the sheet simulation.

7-CPU cores were used to run all simulations. Table 2 shows the time cost in different mass scaling parameters 100, 500, and 900 for simulating in 1/4, 1/2, and whole parts, respectively. Both mass scaling and symmetric setting can decrease time greatly. Compared with mass scaling 100, mass scaling 900 reduced 66% the simulation time. Compared with the whole part, 1/4 parts reduced 83% the simulation time. To judge the influence of the inertia effect, the kinetic energy and internal energy and the ratio of them were obtained; see Fig. 7. It can be seen that the inertia effect produced by mass scaling parameter setting 900 is very small because the maximum kinetic and internal ratio of the sheet is 0.7%, far less than the standard 5%. That means mess scaling 900 is quite credible for simulation.

TABLE 2
SIMULATION TIME IN DIFFERENT MASS SCALING PARAMETERS AND SYMMETRIC (SEC)

	Mass Scaling 100	Mass Scaling 500	Mass Scaling 900
Whole part	71277	32228	24069
1/2 parts	27429	12926	9194
1/4 parts	12366	5519	4057



(a)

(b)

Fig. 7. Kinetic energy and internal energy during simulation process (a) and the ratio of kinetic energy and internal energy (b).

VI. DISCUSSION

It is worth noting that two hollow stress distribution areas in the middle of part bottoms and strain discontinuations were found in the 1/2 parts and 1/4 parts simulation. The reason for this phenomenon is the symmetric setting leads to the discontinuous stress distribution of the bottom material and strain distribution at the symmetric setting part edge during the simulation. However, because the stress is very small in the middle of the bottom (almost 0), it has little effect on the quality of the deformed part. In most cases, this area is not considered in the scope of stress analysis. Therefore, the impact of this range can be ignored. Whats more, the strain distribution of discontinuing areas can refer to the corresponding up and downside of the parts. Furthermore, some peaks in the thickness distribution are due to the reduction of stress near the symmetry plane. From the profile geometry result, with the change of symmetric setting, the profile changes (within acceptable ranges). From Fig. 7 we can see that mass scaling has little effect on the change of profile geometry.

From the mises stress and equivalent strain distributions, it can be seen that the main mises stress and equivalent strain are contrastively distributed in the areas that have direct contact with the punch. On the contrary, the areas with no punch contact keep very low stress and strain (even 0 in some areas). From all the mises stress distribution maps, the corners of the square have higher stress. This is caused by the concentration of stress distribution at the turning points. The opposite phenomenon appears in the equivalent distribution maps; it is because the material accumulates at the corner and flows less relative to the four sides. The maximum mises stress values are 180.1 Mpa, 190.2 Mpa, 192.1 Mpa, and 185.1 Mpa, respectively, in Fig. 3, which means mess scaling and symmetrical setting have little effect on the magnitude and distribution of stress. At the same time, the maximum equivalent strains in Fig. 4 are 1.267, 1.327, 1.126, and 1.262, respectively. This phenomenon further verifies the high accuracy of the above settings. Interestingly, the 1/4 parts and 900 mess scaling setting results are more similar to the setting with no mess scaling and no symmetry in the values. As a consequence, the combination of mass scaling setting and symmetric setting has enough ability to simulate and predict ISF with the advantage of greatly shortening the simulation time.

VII. CONCLUSION

ISF is a very flexible sheet forming technology; a spherical tool and a setup toolpath are just needed to manufacture the complex geometry parts. In recent years, numerical simulation has attracted more and more attention in the field of incremental forming, but a crucial weakness that has existed in the ISF simulation for a long time is that an extremely long time is needed to run the whole simulation. Different mass scaling factors and symmetric settings were adopted in this paper to simulate the forming process. The Mises stress, equivalent strain, profile geometry, and thickness distribution were compared and analyzed. Compared with the whole part simulation with the mass scaling factor of 100, the 1/4 parts with mass scaling 900 get 94 %time reduction without losing much accuracy. As a consequence, the efficiency of numerical simulation can be improved by properly increasing the mass scaling coefficient and symmetrical workpiece.

VIII. LIMITATIONS

Although the method presented in this work owns high accuracy in stress and strain values and reduces simulation time greatly, there is still some hollow area in mises stress distribution map and discontinuous areas in the equivalent strain distribution map.

IX. FURTHER RESEARCH DIRECTIONS

(1): Based on the limitations above, new ideas need to be put forward to solve hollow and discontinuous areas problems.

(2): Furthermore, the problem of long ISF simulation time can be solved from other perspectives. For example, optimize the punch trajectory, develop now mesh element which easy to convergence, and so on.

X. ACKNOWLEDGMENT

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