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DEVELOPMENT OF STEP-WISE COMBINED IMPLICIT-EXPLICIT FINITE ELEMENT METHOD

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ABSTRACT

A combined implicit-explicit scheme for the analysis of sheet forming problems has been proposed in this work. In the finite-element simulation of sheet metal forming processes, the robustness and stability of computation are important requirements, since the computation time and convergency become major points of consideration in addition to the solution accuracy, due to the complexity of the geometry and boundary conditions. The implicit scheme employs a more reliable and rigorous scheme in considering the equilibrium at each step of deformation, whilst in the explicit scheme the problem of convergency is eliminated at the cost of solution accuracy. The explicit approach and the implicit approach have both merits and demerits. In order to combine the merits of these two methods, a step-wise combined implicit-explicit scheme has been developed. Computations are carried out for the deep drawing of an oil pan by implicit, explicit and combined implicit-explicit schemes. From the comparison between the methods the advantages and disadvantages of the methods are identified and discussed.

Key Words : implicit, explicit, sheet forming, finite-element simulation, robustness, stability, computation time, convergency, deep drawing

1. INTRODUCTION

Complicated sheet metal parts are now subjected to simulation in order to design the process properly to avoid redundant trial-and-error steps in the design and manufacture of processes and tools. A reliable method of simulation is then required to solve difficult problems involving geometric and material non-linearity, as well as variable contact and frictional interface conditions.

The finite-element method has long been used as a means of reliable computation to analyze various sheet forming processes, analyses have been carried out by the implicit method based on the direct solver as well as by the explicit method based on the dynamic solution1-5). For two-dimensional analyses of simple sheet metal forming processes, the implicit method of analysis seems to be much more efficient than the explicit method based on dynamics, which requires relatively large amount of computer time due to the limitation in time increment imposed by the stability conditions. As a consequence, much of the effort for development in the following years has been concentrated on implicit

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method. The successful use of two-dimensional finite-element analyses has led to a natural extension of implicit method to three-dimensional problems brings about a number of unexpected difficulties. In particular, the variable contact conditions caused a number of problems. This has led to a renewed interest in the application of explicit method based on dynamics to the essentially quasi-static sheet forming problems. In the explicit method, the size of time increment must be determined by the limitation in stability but it is not affected significantly by the increased number of contact points.

A general sheet metal forming process can be characterized as non-linear to a high degree. This is not only due to geometric and material non-linearity, but also due to complex variation in the contact conditions. Traditional instabilities occurring in the typical deep-drawing process, the formation of wrinkles and necking, also give rise to additional non-linear effects. Due to these strongly non-linear effects, the implicit method often fails to converge, whereas the explicit integration technique does not involve a convergency problem. The explicit dynamic algorithm has several significant advantages over the conventional implicit static algorithm for sheet metal forming problems. In the explicit method, there is no direct, banded, linear equation solver. Consequently, the computational cost of a solution does not grow quadratically with the problem size. In general, the computational cost is linearly procedure. Large deformation, and contact constraints, are relatively easy to implement in the explicit procedure. The kinematic contact constraints can be enforced explicitly by the direct trial-and-error method and, since there is no equation solver, change of contact conditions does not require the consideration of bandwidth optimization. The major disadvantage of the explicit dynamic procedure comes from the fact that it is a time and rate dependent dynamic procedure, sometimes losing static stability of a solution.

In finite-element simulation of sheet metal forming processes, the robustness and stability of computation time and convergency become major points of consideration due to the complexity of geometry and boundary conditions. The implicit scheme employs a more reliable and rigorous scheme in considering the equilibrium at each step of deformation, whilst in the explicit scheme the problem of convergency is eliminated at the cost of solution accuracy. The explicit and implicit approach have both merits and demerits, respectively. In order to obtain the merits of both methods simultaneously, a step-wise combined implicit-explicit scheme is developed.

2. STEP-WISE COMBINED IMPLICIT-EXPLICIT SCHEME

The implicit approach has been used widely in the analysis of metal forming processes because of its excellent accuracy and reliability. However, the implicit approach often encounters convergence difficulties in the forming of complex shape and the computing time increases quadratically according to the number of equation. The explicit finite-element method is known to be more efficient than the implicit approach for forming a complex shape that requires a huge number of equation, because it has no problem of convergence. However, the accuracy and reliability of solution are not as accurate as those of the implicit approach. In order to combine the merits of the two methods, the step-wise combined implicit-explicit scheme is developed and then the possibility and usefulness of the method are checked.

As shown in Fig. 1, when the implicit analysis fails to converge in a particular deformation step,

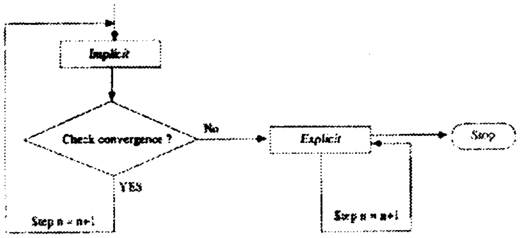
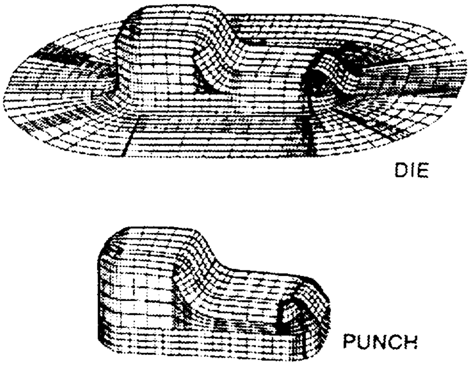


Fig. 1. Flow chart for the step-wise combined implicit-explicit scheme.

the analysis is continued by employing the explicit approach for the next deformation step. The suggested method is a compromise between the explicit scheme and the implicit scheme to combine the merits of both methods in terms of computation time and accuracy. The number of iterations in the current deformation step is used as a switching criterion in the present work. If the number of iterations exceeds the assigned limit, then the solution scheme is changed automatically to the explicit approach. When changing the solution scheme, the converged displacement of the previous deformation step is considered to be the displacement of the explicit scheme.

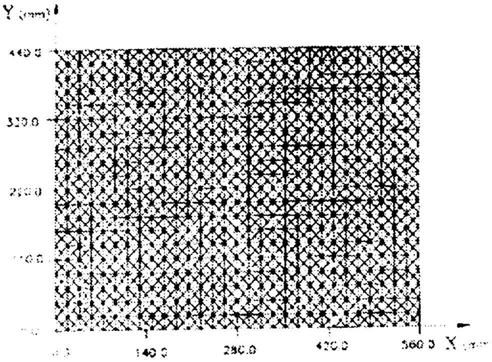
3. APPLICATIONS : DEEP DRAWING OF AN OILPAN

The deep drawing of an oilpan involves complicated three-dimensional deformation during the sheet forming process. Due to the complex geometry, some sliding and redistribution of material takes place from region to region. Since the draw depth is quite deep in comparison with the original size of the sheet blank, the oilpan (part of an automobile engine) is difficult to form and the flatness of the flange is very important. Until recently, finite-element simulation for deep drawing of a rectangular box with stepped geometry was mainly carried out using explicit commercial packages based on elastic-plastic shell elements. Vreede et al.[6] analyzed the forming processes for the head-light bracket of a truck and Liu and Karima[7] predicted the initial blank shape of an oil pan by using a one-step finite-element approach based on the upper-bound theorem from the viewpoint of design concept. The rigid tool was modelled by the CATIA CAD/CAM system that is widely used in the automobile industry. Fig. 2 shows a schematic view of the tool



	surfaces	patches
punch	55	97
die	80	174
Σ	135	271

Fig. 2. Schematic view of the parametric tool surfaces for oilpan deep drawing.



NODES	1,251
ELEMENTS	2,400

Fig. 3. Finite-element mesh used in the analysis of the deep drawing of an oilpan.

surfaces in which 135 composite surfaces (271 parametric patches[8]) are used to describe the punch and the die. Three-node BEAM elements are used in the implicit analysis and three-node Damping Energy Augmented BEAM elements[8], which are considered for controlling in-plane rotational deformation, are used in the explicit analysis. Fig. 3 shows that the finite-element mesh used for the analysis has 1251 nodes and 2400 triangular elements. The blank has an originally rectangular shape of 560 mm by 440 mm. The material and process variables used in the analysis are as follows.

initial sheet thickness : 1.2 mm

stress-strain curve :

$$\bar{\sigma}=451.8(\bar{\varepsilon}+0.008)^{0.306}\ \text{MPa}$$

Lankford value for normal anisotropy :

$$r = 1.984$$

Coulomb coefficient of friction : μ = 0.1

blank-holding force : 860 kN

The explicit analysis was carried out with a constant punch velocity of 15 m/s, which punch velocity does not affect the solution reliability and is able to provide economic analysis, being chosen from numerical tests for various punch speeds. In the combined implicit-explicit scheme, the implicit analysis is performed until a punch stroke of 82 mm, at which point a convergence difficulty is encountered. The analysis is then converted to the explicit scheme and performed until the end of computation. Fig. 4 shows the comparison of thickness-strain dis-tribution at the punch stroke of 130 mm, the overall distribution of thickness strain being in agreement. The combined scheme renders almost the same results as for the implicit case. However, as shown in Fig. 4, the deformed pattern for the region (indicated by the arrow) computed by the implicit analysis is different from that for the explicit analysis, as explained in the following.

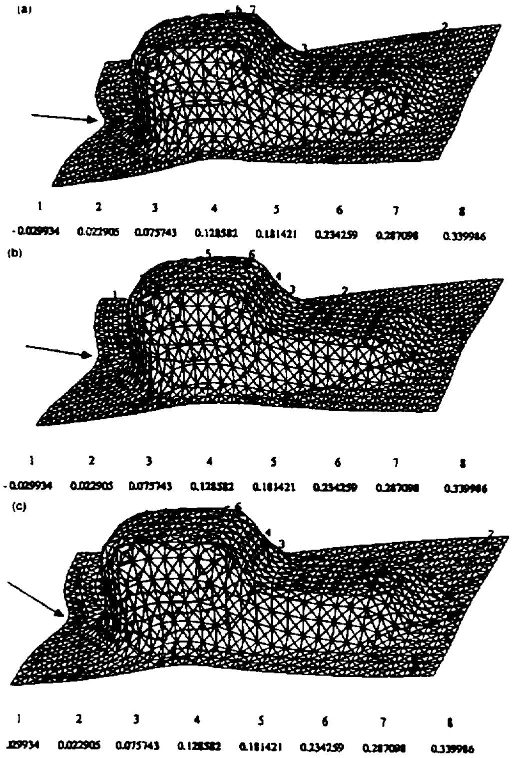


Fig. 4. Thickness strain distribution and deformed configuration of an oilpan predicted by : (a) implicit rigid-plastic analysis : (b) explicit rigid-plastic analysis : (c) combined implicit-explicit rigid-plastic analysis at a punch stroke of 130 mm.

In the explicit analysis, in order to save computing time, an increased punch velocity is taken without appreciably affecting the reliability of the solution. As the punch velocity increases, the inertial effect becomes larger and force cannot be sufficiently transmitted to the nodes located at the outer side of the blank. Accordingly, in the explicit analysis the punch velocity is increased in order to save computing time at the cost of solution accuracy. The combined analysis renders a realistic deformation pattern at the four corners of the sheet. The thickness-strain distribution at an arbitrary section is compared in Fig. 5. The overall tendency

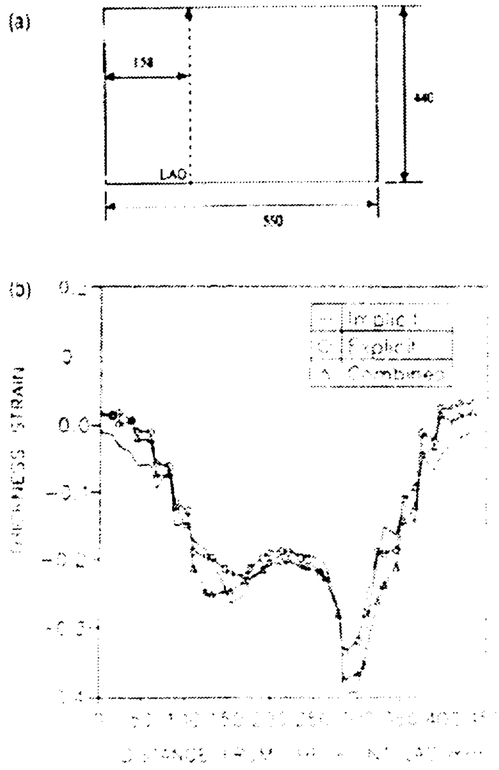


Fig. 5. Thickness-strain distribution for the deep drawing of an oilpan.

of the strain distribution is similar and the result by the combined scheme is somewhat closer to the implicit results than those for the explicit scheme. The combined scheme is supposed to improve the explicit scheme from the view point of accuracy. The whole computation of the explicit scheme took about 7 h in an Hp/730 workstation, for the combined implicit-explicit case it took about 11 h, and for the implicit case it took about 15 h with two restarts.

From the above results, the combined implicit-explicit method is proven to be robust and efficient for three-dimensional sheet metal forming simulation. The combined implicit-explicit method eliminates conver-gency problem with computational accuracy and effectiveness.

4. CONCLUSIONS

A dynamic explicit finite-element method based on rigid-plastic material modelling has been proposed and applied to the analyses of sheet metal forming processes. For analyses of more complex cases with larger and more refined meshes, the explicit method is more effective than the implicit method although the implicit method is used widely because of its excellent accuracy and reliability. In order to obtain the merits of the two methods simultaneously, a step-wise combined implicit-explicit scheme is proposed, the combined method being a compromise between explicit and implicit in computation time and accuracy. The step-wise combined implicit-explicit rigid-plastic finite-element method has been applied to the deep drawing of an oilpan, the results being compared with the computed results for implicit analysis and the dynamic explicit analysis. It has been shown thereby that the results of the above three methods are in good agreement, and that the developed combined implicit-explicit scheme can be applied effectively to the analysis of sheet metal forming processes.

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