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복잡한 형상제품의 인크리멘탈 성형과 FEM을 이용한 공정 최적화

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Incremental Sheet Forming of Complex Geometry Shape and Its Optimization Using FEM Analysis

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Abstract

In order to optimize the press formability of incremental sheet forming for complex shape (e.g human face), a combination of both CAM and FEM simulation, is implemented and evaluated from the histories of stress and strain value by means of finite element analysis. Here, the results, using ABAQUS/Explicit finite element code, are compared with fracture limit curve (FLC) in order to predict and optimize the press formability by changing parameters of tool radius and tool down-step according to the orthogonal array of Taguchi's method. Firstly, The CAM simulation is used to create cutter location data (CL data). This data are then calculated, modified and exported to the input file format required by ABAQUS through using MATLAB programming. The FEM results are implemented for negative incremental sheet forming and then investigate by experiment.

Key Words: Incremental forming; Sheet metal, Formability, FEM, FLC, Taguchi

1. Introduction

Incremental sheet forming (ISF) is an innovative process to manufacture sheet metal products by the CNC controlled movement of a simple forming tool which plastically deforms the blank according to the desired shape. To get the tool path for complex shape, a CAD file of the completed formed part must be designed, imported to CAM software, and simulated. Depending on the complexity of the part, the process can include a basic geometry supporting die or no dies at all. Although it is a slow process, makes it a very suitable process for low series production due to the cost reduction linked to the fact that punches or dies are avoided, in comparison with the traditional stamping or drawing processes. Several studies have been performed with emphasis on assessing and improving the formability in this forming method. Iseki and Kumon (Ref. 1) have carried out a forming limit for the incremental sheet metal forming process. They had shown that the forming limit curve (FLC) is located much higher than those based on theories of plastic instability. Kim and Yang (Ref. 2) proposed the double-forming technique to improve formability, assuming that only shear deformation occurs in the material. In order to investigate the influence of the main material parameters of the sheet material, process parameters on formability and improve the formability of (ISF) several researches had been proposed (Ref. 3-4).

To predict and investigate the effect of parameters on formability of incremental sheet metal forming, the use of FEM simulation is shown to be a realistic and cost-effective method. Shim and Park (Ref. 5) performed a numerical simulation of the single layer in the forming of truncated pyramid to find the deformation characters along the tool path. Iseki (Ref. 6) modeled the

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incremental forming of a shell of the frustum of a quadrangular pyramid based on the shell elements without considering material anisotropy and Baushinger effects of shell material, and the formed height of the part was just 5 mm. Ambrogio et al (Ref. 7) showed that the single point incremental sheet forming process mainly depended on geometrical and process conditions. Recently, Park and Kim (Ref. 8) studied and showed the strong points in incremental forming of Magnesium alloy sheet with rotating forming tool. Particularly, the accuracy of the final geometry was mainly influenced by the tool down step. However, almost researches used simple geometry model like as rectangular, circular geometries or the combination of them in simulation model.

In this study, the incremental forming process of complex geometry shape is simulated using ABAQUS/Explicit finite element code. The input file was obtained by the combination of CAM and CAE simulation through using MATLAB programming. The FE simulation results for a test sample are presented in Fig. 1. The effect of tool radius and tool down-step are then investigated to determine their influence on the press formability by comparing with forming limit curve. Finally, the optimum geometry is presented according to Taguchi's experimental technique to achieve the optimum conditions for tool radius and tool down-step.

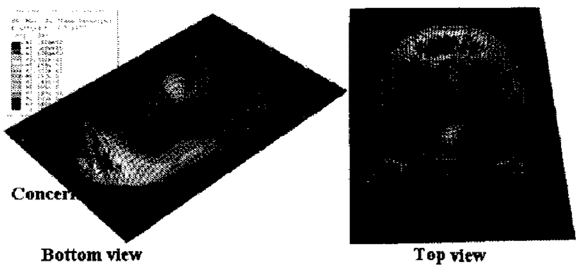

Fig. 1 - Deformed shape in finite element simulation of test sample which shows $\varepsilon_{max} = 1.395$; $\varepsilon_{min} = 0.055$

2. Finite-Element Simulation

This study used the commercial software ABAQUS version 6.5 to simulate the forming process. This software can provide elastic-plastic and rigid-plastic simulations of metal forming in the case of a large deformation, thereby significantly reducing the cost and time involved in tool and die design.

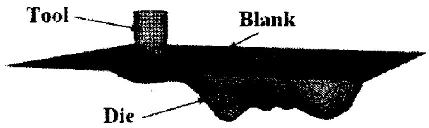

Fig. 2-Finite element model for simulation

2.1. Geometry and models

Figure 2 shows the finite-element model of ABAQUS version 6.5 for the incremental forming test process. Here, the tool and die model were made from the shape of the product using CATIA software, the blank modeled using shell elements S4R, and the punch and die modeled using rigid surface-elements R3D4 with three integration points. Throughout this study, the average element size of the uniform mesh was about 1mm in width, and 1mm in length; the average element size of the uniform mesh of rigid surface-elements was about 2mm in width, and 2mm in length.

2.2. Materials

A cold rolled steel with the thickness of 1.0mm. The parameters characterizing the uniaxial-stress-plastic-strain response of the material used in the FE simulations are also given in the table 1 in terms of the parameters in Krukowsky's work-hardening law, using the following expression:

$$\bar{\sigma} = K(\varepsilon_0 + \bar{\varepsilon}_P)^n \qquad (1)$$

Where K is the plastic coefficient, n is the work-hardening exponent, and $\bar{\sigma}, \bar{\varepsilon}_P, \varepsilon_0$ are the equivalent stress, equivalent strain, and yield strain, respectively.

Table I. Mechanical properties of tested material

Material	Cold Rolled Steel
Density (ρ)	7.8e-06
Young's modulus (E)	210
Possion's ratio	0.3
Tensile strength (MPa)	140
ε	0.0009
K (MPa)	534.1
n-value	0.274
Lankford value R_m	1.679

2.3. Boundary conditions, loading, and interactions

The die was fixed in all directions. The tool was allowed to move following the tool-path which obtained from CAM simulation. The friction behavior was modeled using the Coulomb friction law. The friction coefficients between the blank and the punch/die were

$\mu_1=\mu_2=0.1$.

3. Obtained CAE input file procedures

3.1. Tool path generation

In order to obtain cutter location (CL) data for human surface, firstly, 3D scanner is used to create a point cloud of geometric samples on the surface of the subject. These points can then be used to extrapolate the shape of the subject. Nomally, the point clouds produced by 3D scanners are usually not used directly, although for simple visualization and measurement in the architecture and construction world, points may suffice. Most applications instead use polygonal 3D models, NURBS surface models, or editable feature-based CAD models. The process of converting a point cloud into a usable 3D model in any of the forms described above is called '*reconstruction* or "modeling"'. Here, the reconstruction and modification is performed by utilizing CATIA software to creat NURBS surface model from point cloud and scale down as 65% in order to fit with small experimental machine. Fig. 3 shows the method to obtain CAD model. This model then save to IGES file and import to CAM software, namely CIMATRON E 6.0, that are used to generate CL data and also define the motion of the machines in processing. In this software, a Z-level milling operation is sellected with spiral tool path strategy and out-in downward movement of the tool (Fig. 4). After simulation, the CL file, which includes the position of tool center point followed linear and circular interpolation, is generated and used to modify CAE input file.

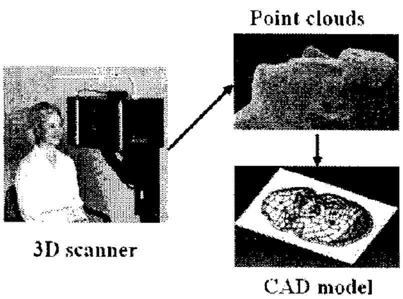

Fig. 3 - The method to obtain CAD model

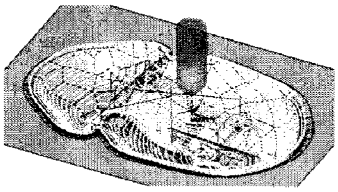

Fig. 4 -Tool path strategy

3.2. CAE input file modifications

As above mention, CL file includes linear and circular interpolations of the position of tool center point. Linear interpolations are easy to assign the movement to the deforming tool of ABAQUS. But in circular interpolations, tool center point must be rotated around other center points generated by CAM sofware, it seems impossible to assign the movement to the tool. So that in this study, a procedure, which scans the circular interpolations and divides them into linear segments satisfied allowable error, has been completed.

By using ABAQUS, the movement of tool is defined thought step module. It means that once the movement is correlative with the step of step module. Unluckily, there are more than thousand steps need be used to simulate for incremental forming process. If we operate the position of tool center point manually, it will waste a lot of time and may get some mistake during operation. So in this study, MATLAB software has been used as a programming tool to modify the CL data and also CAE input file.

Because the procedures for other steps are the same excepted values of position coordinate of tool center point. So firstly, the CAE input file is exported for first and second steps to get initial CAE input file. Then the text file of CL data is modified to obtain all position coordinate of tool center point as a standard CL data file through a subroutine of MALAB. Finally, in order to obtain final CAE input file, another MATLAB's subroutine had been written to add all next steps and assign values of tool center point from the standard CL data file to initial CAE input file for the correlative steps.

4. Taguchi Orthogonal Array

As above mention, many processing parameters contribute to enhancing the formability of incremental sheet forming process. If parameters is not suitably selected a crack will appear at the concerned area. In this study, only tool radius (R) and tool down step (H) parameters is considered to verify and optimize the influence on press formability. This failure was subjected to serious strain during the incremental forming process and found to be prone to internal or superficial micro-defects due to excessive tensile stress. This initial damage and its growth then cause quality problems, such as necking and fractures, due to ductile tearing of the sheet. The reason is that the small difference between the major strains (ε_1) and the FLC values at the same point for the minor strains (ε_2) at the concerned area; ($\Delta\varepsilon = \varepsilon_{FLC} - \varepsilon_1$) (Fig. 5). The forming limit curve (FLC) in incremental forming was determined based on the straight groove test (Ref. 6). When changing the selected parameters, it was found that the magnitude of the difference in the major strain ($\Delta\varepsilon$) also changed. Thus, it was concluded that the geometry of the concerned area of the blank could be optimized.

The quality design first proposed by Taguchi in the 1960s is now widely applied due to its proven success in improving industrial product quality (Ref. 9). Therefore, this study used the Taguchi method to optimize the shape of the concerned area of the blank.

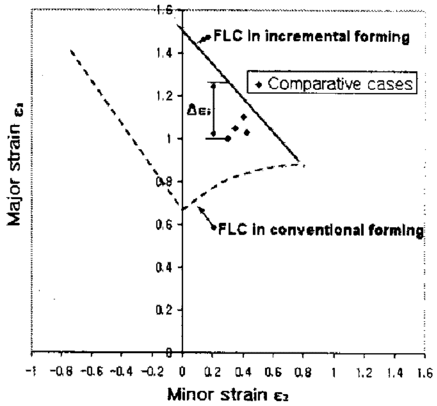

Fig. 5 - Definition of the difference of major strain (Δε)

In the preliminary study, the difference in the major strain ($\Delta\varepsilon$) were set as the objective functions of the Incremental forming process, while the two parameters – the tool radius (R), and tool down step (H).

When using this quality characteristic, the problem becomes a larger-the-better type problem in the case of the difference in the major strain ($\Delta\varepsilon$). Thus, according to the Taguchi method, the larger the difference in the major strain ($\Delta\varepsilon$), the better the press formability.

The signal-to-noise ratio (*S/N* ratio) defined according to the Taguchi method is:

$$\eta_i^b = -10\log_{10}(\Delta\varepsilon_1^{-2}) \qquad \text{(Eq 2)}$$

Where η denotes the observed value (unit: dB). Since the maximizing procedure for the S/N ratio minimizes the press formability, the best conditions can be obtained by maximizing (η_i)

Figure 6 presents the definition of the two parameters, while their selected levels are listed in Table 2.

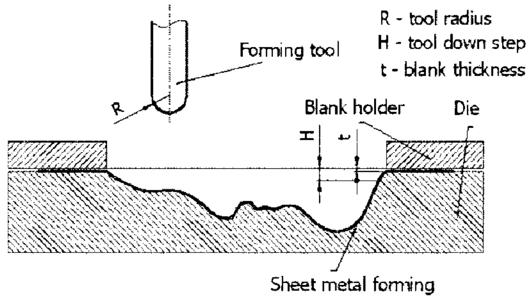

Fig. 6 - Definition of considering parameters

Table II. Factors and their levels in FEM simulation

Factors (mm)	Level 1	Level 2
A (R)	6	4
B (H)	1.0	0.7
C(t)	1.0	1.0

Table III. Taguchi's L_4 orthogonal array for simulations

Case	A (R) mm	B (H) mm	C (t) mm
1	1(6)	1(1.0)	1(1.0)
2	1(6)	2(0.7)	2(1.0)
3	2(4)	1(1.0)	2(1.0)
4	2(4)	2(0.7)	1(1.0)

As the FE simulation using the two factors with two levels gave four degrees of freedom, a minimum of four tests were required to investigate the effect on the FE simulation. Table 3 shows the L_4 orthogonal array chosen from Taguchi's standard-orthogonal-array table.

5. FE analysis to obtain FLC

In this study, we utilized numerical analyses to obtain the forming limit curve of the sheet. This method had been investigated and indicated in good agreement with experimental results of Kim and Park (Ref. 3). Here, the simulation has been carried out on square blanks with a side of 100mm; the straight groove tests for a length of 70mm, with parameters chosen from Taguchi's L_4 orthogonal array, have been performed (Fig. 7). In order to determine the limitation of fractures, we assumed the values of maximum and minimum strain supplied by FE code will be failure if the elements' thicknesses are bellow 0.25mm.

By adopting a linear model to formulate a forming limit curve (FLC) for steel sheets (see Fig. 8) with parameters in Table 3, it has followed that the same is expressible as (Eq. 3):

$$\varepsilon_1 + \varepsilon_2 = 1.52 \qquad \text{(Eq 3)}$$

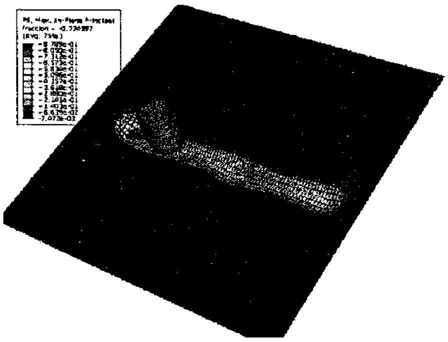

Fig. 7 – Simulation of straight groove test

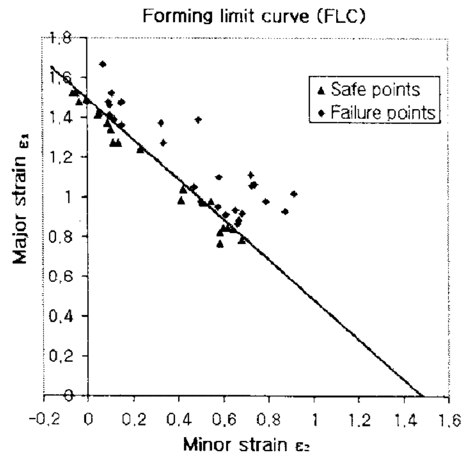

Fig. 8 – Forming limit curve obtained by FEM

6. Results and Discussion

According to the Taguchi method, an analysis of the mean (ANOM) and analysis of variance (ANOVA) were used to represent the relationship between the geometry factors for the concerned area and the observed values for the difference in the major strain $(\Delta\varepsilon)$. In this experiment, the observed values were found to be related to the two parameters (Table 4). The optimization of the observed values was then determined through a comparison with the Taguchi signal-to-noise (*S/N*) ratio. The ANOVA values calculated for the two factors and their corresponding three levels (tabulated in Table 2) were obtained using an L_4 orthogonal array.

The increase in the factor effect was measured using the *S/N* ratio of the factors. Moreover, the analysis of the mean (ANOM) and analysis of variance (ANOVA) for the quality characteristics provided a better understanding of the individual effect of each factor.

Table 5 shows a summary of the calculated results. The formulation used to calculate the sum of the squares was as follows:

$$2(m_{j1} - m)^2 + 2(m_{j2} - m)^2 \qquad \text{(Eq 4)}$$

Where m is the overall mean of the η_{i}, value for the four experiments, and m_i is the average of η_j related to level *i (i=1, 2)* of factor *j* given by $m_{ji} = 1/2\sum_{i=1}(\eta_j)_i$.

Table IV. L₉ orthogonal array and calculated observed values

Case	Column number and factor assignment			Difference in major strain $(\Delta\varepsilon)$	
	A (R)	B (H)	C (t)	$\Delta\varepsilon$	η_i^b (dB)
1	1(6)	1(1.0)	1(1.0)	0.115	-18.786
2	1(6)	2(0.7)	2(1.0)	0.266	-11.502
3	2(4)	1(1.0)	2(1.0)	0.222	-13.073
4	2(4)	2(0.7)	1(1.0)	0.343	-9.294

Larger-the-better type $\eta_i^b = -10\log_{10}(\Delta\varepsilon_i^{-2})$

Table VI. ANOM and ANOVA table for affect of difference in major strain $(\Delta\varepsilon)$

Factor		A(R)	C(H)	D(t)	Total
Average	1	-15.14	-15.93	-	
η by Level	2	-11.19*	-10.40*	-	
Sum of Squares		15.59	30.60		46.18
D.O.F		2	2		4
Sum of mean squares		7.795	15.30		23.10
Contribution		0.338	0.662		

* Indicates the optimum level

The results of the ANOM and ANOVA for the difference in the major strain $(\Delta\varepsilon)$ (Table 5) revealed that the tool down step (H), which reached 66.2%, made the major contribution to the overall performance. Meanwhile, the contribution percentages for the tool radius (R) were lower at 33.8%. Thus, it was concluded that the protrusion height (H) factor had the most significant affect on the difference in the major strain $(\Delta\varepsilon)$ in the concerned area.

In the Taguchi method, the higher the η value, the better the overall performance. Accordingly, the average for each experimental level was calculated using the highest η value for each factor to produce the response table (Table 5). As shown in the response table, the optimum conditions to maintain the difference in the major strain $(\Delta\varepsilon)$ successfully in the forming test were $A_2B_2C_1$, which means R = 4 mm, H = 0.7 mm, and t = 1 mm in Table 3.

Figure 10 depicts the FE simulation results of the optimum conditions ($A_2B_2C_1$) for the press formability. Here, the difference in the major strain $(\Delta\varepsilon)$ has the maximum value. Figure 11 shows the experiment results and supported die for optimum case, where no crack appeared in the concerned area.

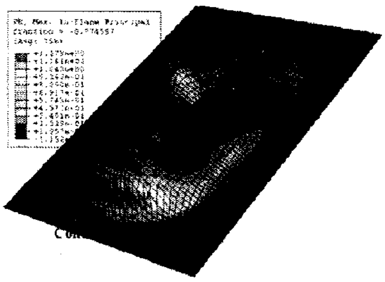

Fig. 10 - Deformed shape in FEM of optimum case $A_2B_2C_1$ with $\varepsilon_{max} = 1.170$ and $\varepsilon_{min} = 0.007$

From the above discussion, it was concluded that the use of Taguchi's experimental array for FE simulations allowed successful optimization of the selected parameters to improve the press formability. As a result, the selected parameters were optimized using a tool radius (R) of 4 mm, tool down step (H) of 0.7 mm, and blank thickness (t) of 1 mm.

Fig. 11 – Optimum case: D=4mm, H=0.7mm.

7. Conclusion

To simulate the incremental sheet forming process of complex geometry shape e.g human face, values of CL data, which was generated from CAM simulation, has been automatically added and assigned to the CEA input file through MATLAB's subroutine programming.

To verify and optimize the influence of parameters on the press formability, the tool radius and tool down step parameters was selected as main parameters by using the finite element simulations and then investigated by the experiments. Commercial software (ABAQUS version 6.5, explicit formulation) was used for the simulation according to the orthogonal array of Taguchi's method. As a result of the FE simulations based on the Taguchi orthogonal array, the tool down step (H) was identified as the important factors for improving the press formability of the incremental forming process. An optimized parameter, consisting of a tool radius (R) of 4 mm, a tool down step (H) of 0.7 mm, and blank thickness of (t) of 1 mm, was also predicted to show a better reliability compared to the original test sample.

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