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Modelling and optimal design of the incremental forming process

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Abstract. Recently, a new sheet metal forming technique, incremental forming, has been introduced. It is based on the use of a universal spherical tool, which is moved along the CNC controlled tool path. For optimal design of the incremental forming process, application of non-linear mathematical programming is suggested. To estimate the limitations and main parameters of the process, a complex model for process design has been developed. Incremental forming processes are investigated using experiments and finite element analysis.

Key words: incremental sheet metal forming, finite element analysis, optimal design, non-linear programming.

1. INTRODUCTION

In engineering design, parts made of sheet metal are widely used. For manufacturing parts with conventional sheet metal forming techniques (for example, deep drawing), dedicated tools are needed. They are highly specialized, expensive and time-consuming to produce.

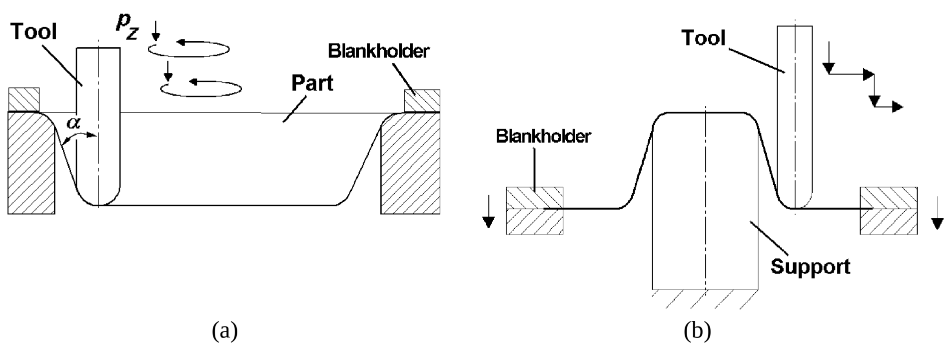
Recently, a new sheet metal forming technique, incremental forming, has been introduced. Incremental forming is especially suitable for the production of prototypes and for small series production. It is based on the use of a universal spherical forming tool, which is moved along the CNC controlled tool path. The part is produced by deforming the sheet locally. The instrument draws a contour on a horizontal plane, then makes a step downwards and draws the next contour and so on until the operation is completed. For the process a special machine tool or a universal 3- or multiple-axis CNC machining centre can be used. For preparation of the NC code, the general purpose Computer Automated Manufacturing (CAM) software is used. Using the technology described above, sheet metal parts with complicated geometry can be manufactured with simple and relatively inexpensive tooling.

There are two versions of the incremental forming process: forming without or with the support (Fig. 1, a and b, p_z is the vertical step and α is the wall draft angle). The authors have studied both versions.

In recent years, several papers have been devoted to the modelling of the incremental forming processes. An approximate deformation analysis for the incremental bulging of the sheet metal, using a ball, has been developed by Iseki [1]. The incremental bulging method has been applied for manufacturing non-symmetric shallow shells. In [1] the plane strain deformation model has been used. This model assumes that the sheet metal in contact with the ball stretches uniformly. The friction at the interface between the tool and the sheet, 2D anisotropy and Bauschinger effect of the sheet material are neglected. The closed-form expressions for uniform strains $\varepsilon_x, \varepsilon_y$ and ε_t of the deformed shell are derived. The tensile force is determined from the condition that the undeformed part is rigidly moved by the stiffness of the shell. The results, obtained with the approximate deformation analysis, FEM calculations and experiments, are in good agreement. Vertical wall forming of a rectangular shell, using multistage incremental forming, has been studied in [2]. A method of calculating the approximate distribution of the thickness strain and of the maximum bulging height has been proposed using the plane strain deformation model with constant strain gradient. In [3], a relationship between the blank and the formed specimen under the condition of even strain has been obtained.

A simplified calculation model was developed in [4] assuming that only shear deformation takes place. The intermediate shape of the part was determined from the predicted thickness strain, assuming uniform distribution of the deformation.

The formability of the sheet metal in incremental forming has been studied in [5–7]. A unique forming limit curve was obtained. It was pointed out that the forming limit curve is quite different from that in conventional forming. It appears to be a straight line with a negative slope in the positive region of the minor strain in the forming limit diagram. It was also observed that the cracks



(a) (b)

Fig. 1. Different incremental forming processes: (a) forming without support; (b) forming with support.

occur mostly at the corners (due to greater deformations). In [6], the effect of the process parameters (tool size, feed rate, plane anisotropy) on the formability have been studied.

Compared with the general sheet metal forming processes, the incremental forming process has a simple deformation mechanism, but the deformation path of its moving tool is much longer. To design the incremental forming process, complex mathematical models are needed to estimate the main parameters of the process as the decrease of the wall thickness of the manufactured part, accuracy and surface quality of the part, residual stresses after forming, etc. The decrease of the wall thickness is the most serious limitation of the process. Because of the forming principle, all deformations are prevalently shear deformations [4]. Thus for the calculation of the thickness, the following simplified equation (also known as sine law) can be used [8]:

$$t_2 = t_1 \sin\alpha, \tag{1.1}$$

where t_1 and t_2 denote wall thickness of the part before and after processing, respectively. Because of the springback, high accuracy is hard to achieve. In addition, if high surface quality has to be achieved, the step p_z must be small.

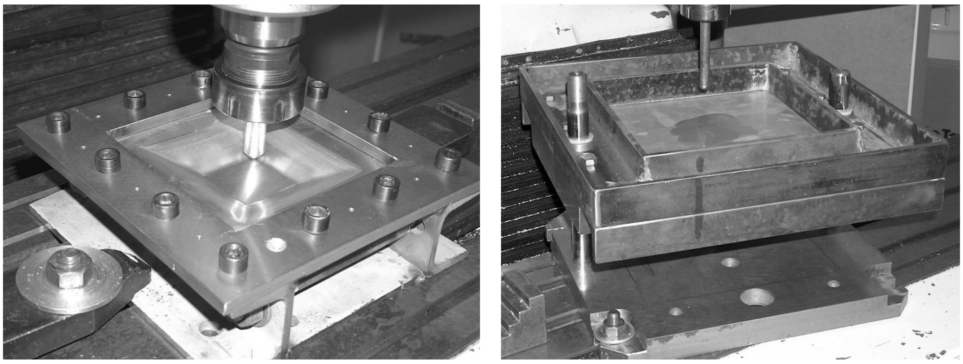
The main objective of this research is to develop techniques for estimating the optimal parameters of the incremental forming process, based on computer simulation of the process using FEM tools and models developed on the basis of experimental analysis.

2. EXPERIMENTAL STUDY OF INCREMENTAL FORMING

Although the deformation mechanisms of incremental forming with and without support are relatively similar (in both cases shear deformations prevail), some important differences exist. Use of the support introduces an additional parameter – the stretching force. This force is applied to the blankholder; thus the process is somewhat similar to stretch forming. It has been observed that increasing this force helps to achieve higher accuracy of the geometry.

For experiments, a special tooling was designed (Fig. 2). Experiments were performed using a standard CNC milling machine. In order to investigate the effect of the control parameters to the output parameters, a series of experiments was made using the theory of design of experiments.

Because of the need of preparing the support, incremental forming with support is more complicated and more time-consuming as compared to forming without support. At this stage only few series of experiments of incremental forming with support have been made in order to be able to compare the form deviations from original computer model with results of both types of incremental forming. The results of the experiments have also been used to validate the simulation model [9]. A more extensive experimental study has been carried out on incremental forming without support [10].



(a) (b)

Fig. 2. Tooling for experimental study of incremental forming: (a) without support; (b) with support.

A simple rectangular cup has been used as the specimen. The control (input) parameters of the process and their minimum and maximum values were selected as follows:

– tool radius R, $R_{\min} = 3$ mm, $R_{\max} = 10$ mm;

– vertical step of the tool p_z, $p_{z\min} = 0.1$ mm, $p_{z\max} = 1$ mm;

– draft angle of the wall α, $\alpha_{\min} = 30°$, $\alpha_{\max} = 60°$.

The output parameters considered (representing the main technological features of the process) were as follows:

– resulting wall thickness t;

– flatness deviation of non-horizontal walls FD;

– surface roughness on the walls Ra;

– total form deviation FMD.

Statistical analysis of the experiments has shown that in a selected area of variables the linear model is not accurate enough and interactions of the variables are important.

An example of the complex model for estimating the main process parameters that are based on experimental analysis of the forming without support is as follows:

$$t = 0.163 + 0.638\alpha, \qquad (2.1)$$

$$FD = 0.259 - 0.00284R + 0.16p_z + 0.157\alpha - 0.024R\alpha - 0.204p_z\alpha, \qquad (2.2)$$

$$Ra = 1.2 + 0.0932R - 0.478p_z - 0.319\alpha - 0.17Rp_z - 0.145R\alpha + 4.15p_z\alpha, \qquad (2.3)$$

$$FMD = 6.47 - 0.0466R + 3.25p_z - 1.47\alpha - 3.72p_z\alpha, \qquad (2.4)$$

where α is in radians.

3. SIMULATION OF THE PROCESS USING FEM ANALYSIS

For simulation of the incremental forming process, the FEM system ANSYS was used. Both 2D and 3D analyses were performed. Because of the nature of the process, there are several non-linearities involved in the simulation of incremental forming. In addition, usually a large number of elements has to be used and the tool moves along a relatively long trajectory. This all makes the finite element analysis complicated and time-consuming.

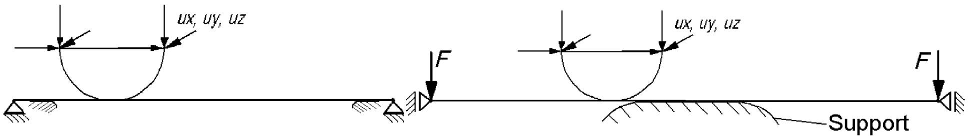
In order to validate the model, the same parameters and material properties have been used in simulation and in experimental study [9,10]. In simple cases the coordinates for tool paths can be calculated with a spreadsheet program, but in the current study the CAM software was used. In Fig. 3 basic calculation schemes are illustrated. In Fig. 3, F is stretching force, u_x, u_y and u_z are displacements in x, y and z directions, respectively. In general, contact calculation is inevitable. Replacing contact by multipoint constraints or modelling it in some other way to shorten computation time was not found feasible.

By modelling incremental forming with support, the workpiece–support interface was also modelled using contact calculation (Fig. 1, b). The pretension of the bolts that fix the sheet to the blankholders (Fig. 2, a) was ignored in calculations. By simulation of the process, the effects of acceleration were assumed to be insignificant; thus static analysis was made. The tool movement was controlled using predefined displacement constraints in several load steps.

In the simulation, the multilinear isotropic strain hardening rule and anisotropic plastic material model were used. The tool and the support were modelled using a simple linear elastic material model. For all 3D simulations, two types of 3D shell elements, with 4 and 8 nodes, were used. Both of them have non-linear capabilities and they account for the thickness change.

As mentioned above, the simulation of the incremental forming process may be very time-consuming. In order to perform simulation, a high approximation level has to be used. There are two main parameters which influence the solving time most: the number of nodes/elements (element size) in the model and the number of tool path segments (the number of load steps). All simulations were performed on Windows XP PC with a single 1.6 GHz CPU.

In preliminary analysis the size of the models was reduced to shorten the simulation time (sheet size 50×50 mm, thickness 1 mm). The tool radius was 5 mm and the support had a rectangular shape 15×15 mm with corner radiuses



(a) (b)

Fig. 3. Calculation schemes of incremental forming processes: (a) forming without support; (b) forming with support.

5 mm. The tool was moved along a rectangular path, the downward step was 0.5 mm and the total downward moving distance was 2.5 mm.

In the first simulation, the element edge length on the tool and support was 1 mm and on the sheet 2.5 mm. The elements with 8 nodes were used. It took 14 h to solve the model, but stress distribution in some areas indicates the need for smaller elements. In the second simulation, the elements on the sheet blank were refined. Now the edge length of 1 mm was used. Other parameters remained the same. This model took 120 h for calculations.

In more detailed simulation of incremental forming without support, the sheet edge was fully constrained. A tool radius 5 mm was used and the sheet dimensions were 100 × 100 mm with thickness 1 mm. The element edge length used on the tool was 1 mm and on the sheet 2.5 mm. On the sheet, shell elements with 4 nodes and on the tool, shell elements with 8 nodes were used. The tool was moved along a rectangular toolpath, with downward step of 1 mm. The total downward moving distance was 20 mm. The model took 72 h to solve. In order to find out how well the model is able to represent the reality, comparison with experimental study was made. When the part was complete, its geometry was measured and compared with the simulation results. The maximum positive normal deviation of the form was 0.439 mm and maximum negative normal deviation 1.295 mm.

It can be concluded that the FE model needs further refinement; blankholder needs to be modelled more precisely. The main restriction for using the FEM simulation for the optimization of the process was the long calculation time.

4. OPTIMAL DESIGN OF INCREMENTAL FORMING OPERATIONS

In the preliminary phase of the design of the operation, the main geometrical parameters of the operation as length of the tool path L, draft angle of the wall α, the number of technological passes (intermediate operations) and the wall thickness after processing t must be determined considering the geometry of the machined part. Using the models (2.1)–(2.4), a non-linear optimization problem can be formulated for the design of the incremental forming operation. In the current study the optimization problem was solved using the Mathcad software system. The problem was formulated as follows:

for a given geometry of the part find the control parameters of the operation p_z, R and α that give the minimum machining time (maximum productivity)

$$T = T(L, p_z, R, f, \alpha) \rightarrow \min, \tag{4.1}$$

and satisfy the following constraints:

$$FD\,(R, p_z, \alpha) \le [FD],\ \ Ra(R, p_z, \alpha) \le [Ra],\ \ FMD(R, p_z, \alpha) \le [FMD],$$

$$\alpha_{\min} \le \alpha \le \alpha_{\max},\ \ R_{\min} \le R \le R_{\max},\ \ p_{z\min} \le p_z \le p_{z\max},\ \ t(\alpha) \ge [t],\quad f \le [f], \tag{4.2}$$

where f is the feed rate of the tool and parameters in brackets present maximum allowable values of corresponding parameters. After optimization, an additional approximate or FEM deformation analysis must be made (post-processing phase).

In order to validate the plastic instability condition [11,12]

$$\frac{\partial \sigma_y}{\partial \bar{\varepsilon}^P} = \frac{\sigma_y}{Z}, \tag{4.3}$$

in FEM analysis, the post-processing variable ψ "risk of necking" is introduced as

$$\psi = \begin{cases} e^{\overline{\psi}} - 1 & for \quad \overline{\psi} < 0, \\ 1 - e^{-\overline{\psi}} & for \quad \overline{\psi} \ge 0, \end{cases} \tag{4.4}$$

where

$$\overline{\psi} = \frac{1}{Z} - \frac{\partial \sigma_y}{\partial \bar{\varepsilon}^P}\frac{1}{\sigma_y}, \tag{4.5}$$

and σ_y is the yield limit

$$\sigma_y = K\bar{\varepsilon}^n. \tag{4.6}$$

Here $\bar{\varepsilon}^P$ is the effective plastic strain increment,

$$\bar{\varepsilon} = \frac{(1+r)}{(1+2r)}\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \frac{2r}{(1+r)}\varepsilon_1\varepsilon_2}, \tag{4.7}$$

where ε_1 is major strain and ε_2 is minor strain; r is the average Lankford coefficient: $r = (r_0 + 2r_{45} + r_{90})/4$ (i.e., normal anisotropy is assumed). Lankford coefficients r_0, r_{45} and r_{90}, measured along the rolling, diagonal and transverse directions of the sheet, are defined as width-to-thickness strain increment ratios

$$r_\beta = \frac{\varepsilon_{\text{width}}}{\varepsilon_{\text{thickness}}}, \quad \beta \in \{0,45,90\}. \tag{4.8}$$

In (4.6) n is a strain hardening exponent and K is a strength coefficient.

If Z is a function of the principal stress ratio $\rho = \sigma_2/\sigma_1$, where σ_1 is major stress and σ_2 is minor stress, then $Z = Z_{\text{Hill}}$ in the case of the negative strain increments ratio (localized necking) and $Z = Z_{\text{Swift}}$ otherwise (diffuse necking). The value of the variable ψ at an integration point indicates how far a point is from necking:

$$-1 < \psi < 0, \text{ elastic or stable plastic deformation,}$$

$$0 \le \psi < 1, \text{ unsafe flow.}$$

The explicit expression of the function Z depends on the particular yield criterion considered.

In the case of the Hill quadratic yield criterion and Hollomon strain hardening rule one obtains

$$\overline{\psi} = \frac{(1+\rho)}{(1+r)\sqrt{1+\rho^2 - \dfrac{2r}{(1+r)}\rho}} - \frac{n}{\overline{\varepsilon}}, \quad \text{if} \quad \frac{d\varepsilon_2}{d\varepsilon_1} < 0, \quad \text{(localized necking)} \qquad (4.9)$$

$$\overline{\psi} = \frac{\left[\sigma_1 - \dfrac{r}{(1+r)}\sigma_2\right]^2 \sigma_1 + \left[\sigma_2 - \dfrac{r}{(1+r)}\sigma_1\right]^2 \sigma_2}{\sigma_1^2 + \sigma_2^2 - \dfrac{2r}{(1+r)}\sigma_1\sigma_2} - \frac{n}{\overline{\varepsilon}}, \quad \text{if} \quad \frac{d\varepsilon_2}{d\varepsilon_1} > 0,$$

(diffuse necking) (4.10)

All these parameters are determined experimentally from tensile tests. Numerical validation of the plastic necking condition at an integration point is performed by using relations (4.4), (4.9) and (4.10).

5. CONCLUSIONS

In modern manufacturing industry, flexibility of production technologies is becoming more and more important. In recent years, a new sheet metal forming technique, incremental forming, has been introduced. Incremental forming is especially suitable for the production of prototypes and for small-series production. There is a need for optimal engineering design of the incremental forming process. For this purpose the non-linear mathematical programming has been proposed. The optimization can be carried out using complex mathematical models of the process that are based on experimental study and FEM simulations. For the design of an incremental forming process, the approach with three phases is proposed: 1) preliminary, geometrical phase, 2) optimization of the main control parameters and 3) post-processing phase to estimate the plastic instability condition.

In future studies, a generalization of the used techniques for calculating the forming force, deformation analysis of incremental forming process and integration of the optimal planning approach into an integrated CAD/CAM/CAE environment is planned.

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Sammvormimise protsessi modelleerimine ja optimaalne planeerimine

Meelis Pohlak, Rein Küttner ja Jüri Majak

Viimastel aastatel on lehtmaterjalist toodete vormimisel kasutusele võetud uus meetod, sammvormimine, mis baseerub lehtmaterjalist tooriku vormimisel sfäärilise otsaga tööriistaga universaalses arvjuhtimisega metallitöötlemiskeskuses. Protsessi parameetrite mõju uurimiseks teostati eksperimente ja viidi läbi arvutisimulatsioone lõplike elementide meetodit kasutades. Optimeerimisülesande lahendamiseks soovitatakse kasutada mittelineaarset planeerimist.