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EXPERIMENTAL STUDY OF INCREMENTAL FORMING OF SHEET METAL PRODUCTS

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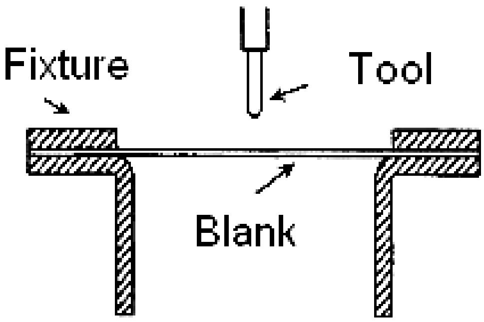
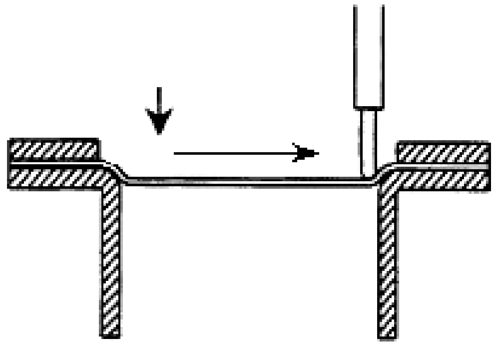
Abstract: *In recent few years, new sheet metal forming technique, incremental forming, has been introduced. There are some different variants of incremental forming, two of which are compared in current study. There are some limitations of using incremental forming processes. For example, it is very difficult to achieve vertical walls, and the thickness of final product depends directly on the wall angle. There are also some problems caused by residual stresses after forming. In this paper authors study the effect of residual stresses on the geometry of the final part. The experimental study has been performed using standard CNC milling machine and tools designed by the authors specially for the study of incremental forming processes.*
Key words: *Incremental Forming, Dieless Forming, Sheet Metal Forming, Experimental Study*

1. INTRODUCTION

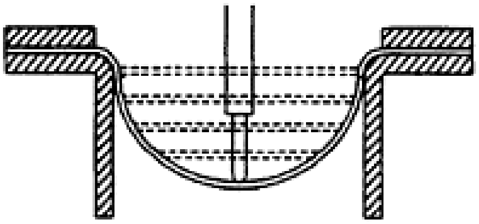
It is a general trend that product development cycle is becoming shorter, but on the other hand, more different variants of products have to be offered. In addition, the design of products is becoming increasingly more complex, higher quality level has to be achieved.
In engineering design, parts made of sheet metal are widely used. For manufacturing of 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.
In recent few years, new sheet metal forming technique, incremental forming, has been introduced. It is based on using of simple spherical tool, which is moved along CNC controlled tool path. The part is produced by deforming the sheet locally. The principle is explained on the Fig. 1 (a) to (c). The instrument draws a contour on horizontal plane, then makes step downwards and draws next contour and so on until operation is completed. For the process universal 3 or more axis CNC machining centre can be used. For preparation of NC – code general purpose Computer Automated Manufacturing (CAM) software can be used.



(a)



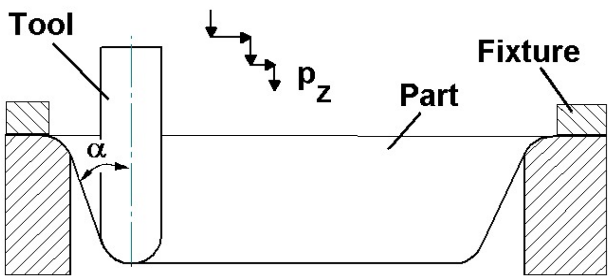
(b)



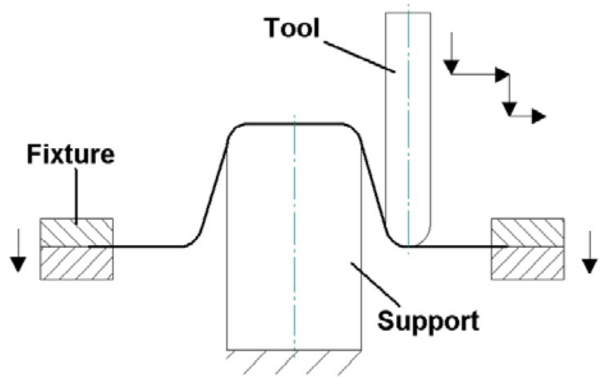
(c)

Fig. 1. Schematic diagram of the incremental sheet metal forming process (Kim & Yang, 2000).

As a result of using the technology described above, sheet metal parts with complicated geometry can be manufactured with simple and relatively inexpensive tool. As expensive and highly dedicated tools are not needed, incremental forming is especially suitable for production of prototypes and for small series production.
There are two variants of incremental forming process. Firstly, forming without support (Fig. 1 and Fig. 2 (a)). Secondly, forming with support (Fig 2 (b)). Generally, last one allows achieving better results but is more complex. Both variants have been studied by the authors.



(a)



(b)
Fig. 2. Different incremental forming processes.

An approximate deformation analysis for the incremental bulging of sheet metal using a ball has been developed by Iseki (Iseki, 2001). The incremental bulging method has been applied for non-symmetric shallow shells. In (Iseki, 2001) the plane-strain deformation model has been proposed. This model makes an approximation that the sheet metal in contact with the ball stretches uniformly. The friction at the interface between tool and sheet, the plane anisotropy and Bausinger effects of the sheet material are neglected. The tensile force is determined from the condition that the un-deformed part is rigidly moved by the stiffness of the shell. The results, obtained by the approximate deformation analysis, FEM analysis and experiments are in good agreement. However, the complete incremental bulging operation has been not modeled in (Iseki, 2001). Vertical wall surface forming of rectangular shell using multistage incremental forming is studied in (Iseki & Naganawa, 2002). The formability in incremental forming of sheet metal is studied in (Shim & Park, 2001; Kim & Park, 2002; Kim & Park, 2003). In (Shim & Park, 2001) a forming tool containing a freely rotating ball was developed. The results observed in the tests were examined by grid measurement and finite element analysis. 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 occur mostly at the corners (due to greater deformation at the corners). In (Kim & Park, 2002) the effects of process parameters (tool size, feed rate, plane-anisotropy) on formability are studied. The formability of an aluminium sheet under various forming conditions is considered in (Kim & Park, 2003). Complex shapes (octagonal cones, stepped shape, etc) were produced with the proposed technique.
Different die technologies and dieless technologies for trial and small lot production are compared in (Naganawa, 2000). The principles and features of the recently developed incremental forming processes are overviewed in (Strano, 2003), where a special attention is paid to cone metal spinning and flow-forming.
Incremental forming has several limitations. First, with incremental forming it is hard to produce parts that have steep walls. Because of the principle of the forming, all deformations occur prevalently by shear deformation (Kim & Yang, 2000), so for calculation of thickness the following equation (also known as sine law) can be used (ASM, 1988):

$$t_2 = t_1 \sin\alpha, \qquad (1)$$

where t_2 – thickness after processing;
t_1 – thickness before processing and
α – draft angle of the wall (see Fig. 2 (a)).
The decrease of wall thickness is the most serious limitation of the process.

Second, because of the spring-back, high accuracy is hard to achieve. Third, if high surface quality has to be achieved, small z-step size has to be used. It causes that the process is very time consuming.
Third, problems caused by residual stresses after forming.
The experimental study in current paper has been performed using standard CNC milling machine and tools designed by the authors especially for the study of incremental forming processes.
With current study, the authors study the possibilities to overcome the basic limitations of incremental forming process, to make it more attractive to engineers in order to shorten the time to market for new products.

2. COMPARISON OF FORMING WITH AND WITHOUT SUPPORT

Although, the deformation mechanism in incremental forming with and without support is relatively similar, that is, shear deformations are prevailing, there are some important differences. Using support introduces one extra parameter – stretching force. The stretching force is force applied to sheet fixture for pulling the sheet onto the support, so the process is somewhat similar to stretch forming (Siegert et al, 1997). It has been noticed that increasing this force helps to achieve higher accuracy of geometry. Questions concerning these issues are addressed in section 3 below.
The experiments, both, incremental forming with support, and without support, that were made during current study, are described in the following sections. In both cases material of the blank was 1 mm thick annealed 99.6 % pure aluminium sheet.

2.1 Experimental study of incremental forming without support

For experimental study special tooling was designed (Fig. 3). To investigate the effects of input parameters to output parameters series of experiments were made using theory of design of experiments (DOE).


Fig. 3. Tooling for experimental study of incremental forming without support.

Simple rectangular cup has been used as model in the study.
Input parameters considered were as follows:

- Tool radius (R);
- Tool vertical step size (p_z);
- Draft angle of the wall (α).

Minimum and maximum values were selected as follows:

- R_{min} = 3 mm; R_{max} = 10 mm;
- $p_{z\,min}$ = 0,1 mm; $p_{z\,max}$ = 1 mm;
- α_{min} = 30°; α_{max} = 60°.

Output parameters considered were as follows:

- Resulting wall thickness;

- Flatness deviation of non-horizontal walls;
- Surface roughness on the walls;
- Total form deviation;
- Micro hardness of wall section.

It has been found that in selected area of variables in addition to linear dependencies also interactions of variables have important role.

However, the results of these experiments are not in the focus of current paper.

2.2 Experimental study of incremental forming with support

Tooling designed for experimental study of forming with support is shown on Fig. 4. It consists of base plate with two columns, support and sheet fixture.

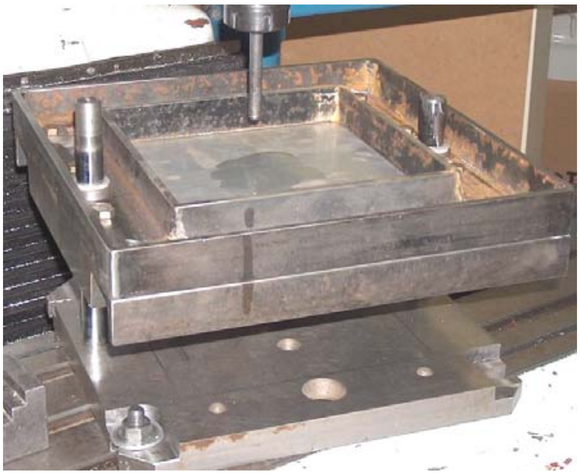


Fig. 4. Tooling for experimental study of incremental forming with support.

Because of the need for support preparation incremental forming with support is much more complicated and time consuming compared to forming without support. So, at this stage not all experiment series like in section 2.1 were performed, but only few to be able to compare form deviations from original computer model in both cases. For comparison zero – level model was chosen (R = 5 mm, p_z = 0.55 mm and α = 45°).

In forming with support, the geometry of support is very important. For producing simple parts, for example pyramids, cones etc, where accuracy is not critical, simple supports can be used that support only upper part of the geometry. In cases where geometry is complicated and accuracy is more important, full support is needed. As forces acting to the support are relatively low and if batch size is small, then support may be made of soft materials.

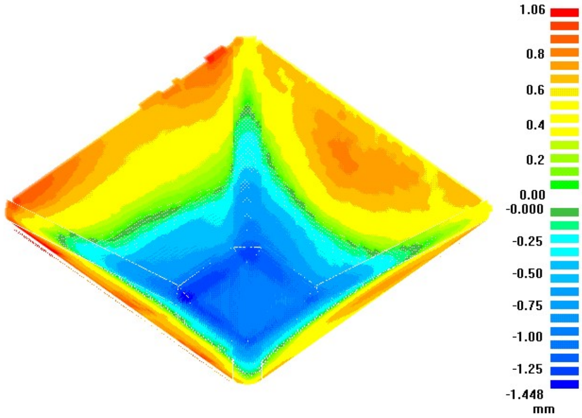
In our case, support was made of model building plastic. Only 15 mm of upper part of the support was prepared, so the rest of the forming was performed "on the air". The support was machined on the same machine tool and fixed in the same incremental forming tooling used later for forming, to avoid set-up errors.

The results of experimental study has also been used for validation purposes of simulation model in (Pohlak et al, 2004).

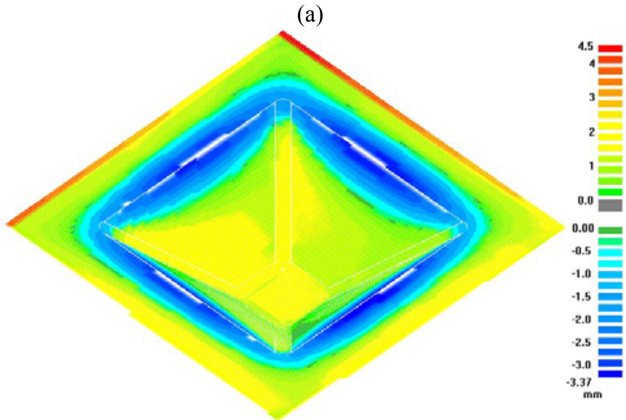
2.3 Comparison of results

Because of the differences in the principle of forming, the same CAD model can not be used without complementary work in both cases. In the process of incremental forming without support, tool is forming the sheet on the "negative" or cavity side and minimum radius of the geometry depends directly on the tool radius. On the other hand, in the process of incremental forming with support, tool is forming the sheet on the "positive" or core side, so small radiuses can be achieved more easily. Because of all this, to make results comparable, some extra rounds were added to the model before preparing of the toolpaths for the forming with support.

After forming in both cases, the geometry of the part was scanned and compared with original CAD model. The deviations of the geometry were calculated and plotted using special reverse engineering software. The deviation plots are shown on Fig. 5.



(a)



(b)

Fig 5. Form deviation plot: (a) deviation of geometry formed with support from initial CAD geometry; (b) deviation of geometry formed without support from initial CAD geometry.

The results of the comparison are in table 1. It can be seen, that in case of forming with support, the total form deviation is lower.

Table 1. Results of comparison of test parts.

Model	Maximum positive normal deviation, mm	Maximum negative normal deviation, mm
Forming without support	1,557	-3,373
Forming with support	1,055	-1,448

3. EFFECT OF STRETCHING FORCE

Generally, it has been noticed that stretching force applied to the sheet holder in case of forming with support helps to achieve more accurate results. On the other hand, too high stretching force may cause necking and bending-back on already processed surfaces.

In current study stretching force was applied using extra weight attached to the sheet fixture.

On Fig. 6 form deviation and stretching force relationship is presented. Stretching force includes fixture weight.

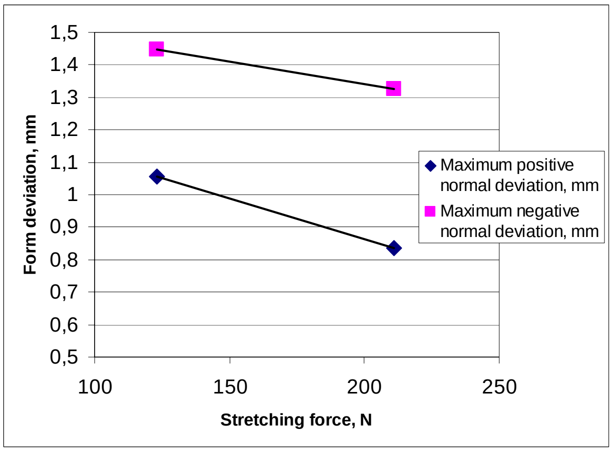


Fig. 6. Form deviation and stretching force relationship.

In table 2 are shown measured form deviation values for both cases, for fixture without extra weight and for fixture with extra weight.

Table 2. Deviation and stretching force relationship.

Stretching force, N	Maximum positive normal deviation, mm	Maximum negative normal deviation, mm
123	1,055	-1,448
211	0,835	-1,326

4. EFFECTS OF RESIDUAL STRESSES AFTER FORMING

One limiting factor of incremental forming is residual stress issue. In case of incremental forming the part has always a planar flange from where it was held in place during forming. Majority of applications do not allow parts to have those flanges, so they have to be removed. In addition, real parts need some areas to be cut out, holes to be drilled or some features welded onto them. All this affects the stress balance of the part and causes additional geometric deviations. To study this, rectangular cup test part was produced. It was produced with forming without support. After forming, the flanges were removed by cutting with wire EDM. The resulting geometry was then measured and analyzed. As it can be seen from Fig. 7, the geometry changed after flange cut-off considerably. Fig. 7 shows deviation plot of geometry before and after cutting.

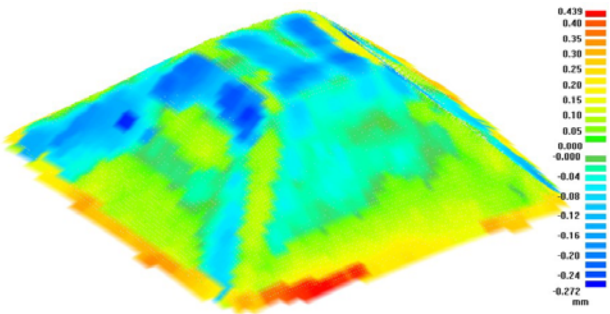


Fig. 7. Deviation plot of geometry before and after cutting.

Based on aforementioned observations, it can be concluded that in some cases where form accuracy is the issue, annealing after forming for the stress relieve is needed before cut-out operations.

5. CONCLUSION

There are two main variants of incremental forming, forming with support and forming without support. In both cases deformation mechanism is relatively similar, shear deformations dominate. However, as it has been shown in current paper, forming with support allows achieving more accurate geometry, but it also adds some extra cost because of the need for preparing supports.

The form accuracy in forming with support is affected by stretching force. It has been found that increasing stretching force helps to achieve more accurate form. On the other hand, if stretching force is too high, it will cause additional problems due to sheet necking and increasing deviations of form. However, these aspects need further study.

As it was pointed out in current paper, the residual stresses caused by incremental forming can induce form deviations after cutting-out operations. So, heat treating, for example, annealing of the part after forming may be required.

Further developments of the work presented in the paper are concerned with overcoming the limitations of the incremental forming.

6. ACKNOWLEDGEMENTS

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