MANUFACTURABILITY ISSUES IN INCREMENTAL SHEET FORMING
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Abstract: In the current research paper, incremental sheet forming (ISF) process modelling is studied. Main attention is paid to limitation analysis. In actual ISF process two kinds of risks can be considered: material failure and tool failure. From point of view of safe manufacturing both risks should be minimized. Aim of the current study is to predict material and tool failure. Experimental, numerical and theoretical study is performed in order to determine material formability and the forming load components. Incremental sheet forming strategies for determining forming limit diagram (FLD) are pointed out. The obtained experimental results have been found to be in a good agreement with theoretical considerations.

Keywords: Sheet Metal Forming, Forming Limit Diagram, Incremental Forming, Finite Element Analysis.

1. INTRODUCTION

ISF is a novel technology for sheet metal forming. Incremental forming technique has been developed during last decade (see [1,2] and [3]). ISF is a very flexible process – the set-up of production of the new part is a matter of hours rather than days, like in some traditional forming methods. The process uses accurate CAD data that represents the part produced. No considerable manual work is required, and thus the repeatability of the process is very good. The drawback of the process is relatively long forming time. For that reason, ISF is feasible in prototype and small series production.

The process of ISF is based on layered manufacturing principles, where the model is divided into horizontal slices. The numerically controlled (NC) toolpath is prepared using contours of these slices. In the process, universal spherical forming tool is moved along NC controlled toolpath as follows (see Fig. 1): tool moves downwards, contacts the sheet, then draws a contour on the horizontal plane, and then makes a step downwards, draws next contour, next step downwards, and next contour and so on. The process can be performed on universal NC milling machine. The edges of the sheet blank remain usually fixed in horizontal plane by special blank holder throughout the operation. There are two approaches, negative forming (Fig. 1 a)) and positive forming (Fig. 1 b)). The latter is used more as it allows to achieve better accuracy.

Fig. 1. Forming principle of ISF.
In industrial implementations of ISF, it is very important to know the limiting factors of the process. The limiting factors may be due to:

- Special features of ISF process (hard to form accurately shallow surfaces with large radius of curvature and vertical surfaces);
- The machine tool used (productivity, sheet material thickness to be formed, part size, etc);
- The forming tool and the fixture (minimal curvature radius of surfaces, required surface roughness, material to be formed, etc);
- The material used (formability, spring-back, etc) and other.

It is well-known that in the case of ISF 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 on the forming limit diagram. However, no standard test procedure has been defined for determining the forming limit curve in ISF process. Both, experimental and theoretical studies in this area are in development. Some general considerations for test design are proposed in [2] and [4]. In [2], tool paths, corresponding to uni-axial and bi-axial stretching conditions, are given. In [4], the empirical formula is used for FLD approximation.

Two important limiting factors studied in the current paper are forming forces and material formability. Forming forces dictate what machine tools can be used, what is the material of forming tools, what is the material type and thickness that can be used for designed parts. Material formability deals with questions like, is it possible to produce designed parts made of specified material.

In the current study, issues concerning forming forces have been investigated experimentally, numerically and some simplified theoretical solutions have been used. In addition, formability analysis issues in incremental sheet forming and some general technological issues of ISF have been addressed.

2. FORMING FORCE ISSUES

It is always important to know the forces required for successful operation in forming processes, mainly for appropriate equipment selection.

In order to predict and avoid forming tool failure the force required for incremental forming should be determined. In the literature some techniques for prevention of tool overload may be found. In [5], a special tool holder was described that was able to compensate for too high loads. It is especially important if rigid metal support is used, and the gap between tool and support is kept small.

To analyse the forming forces, experimental study was performed. The force measuring set-up is shown in Fig. 2. It consists of ISF fixture that is mounted on top of the piezoelectric load cell. The measuring system also includes charge amplifiers, data acquisition cards and a PC. The sampling rate in force measurement was 50 Hz.

![Fig. 2. Set-up for force measurement in ISF on a NC machining centre.](image)

The square pyramid shaped box was formed on CNC milling machine, and the force components were measured in x, y and z directions. In Fig. 3 the force components measured in the experiment are shown.
As can be seen on Fig. 3, the force patterns in the $x$ and $y$ directions are not similar. This is due to sheet anisotropy and nonsymmetric deformation mode. The results are in agreement with the results given in $[6]$. For a more detailed study, numerical analysis has been performed earlier $[7,8]$. Now calculation models have been refined and better accuracy of simulations has been achieved. To validate the finite element analysis (FEA) results, reaction force data from calculation was compared with measured values. The force diagram from FEA is shown in Fig. 4. As can be seen from comparison of Fig. 3 and Fig. 4, the force values are generally in agreement, except for high peak values in experimental study. These peaks occur in the corners of the pyramid as the tools’ moving direction changes rapidly. Note that the time in Fig. 3 and Fig. 4 is not in scale, i.e. the comparison can be made considering the patterns of load curves –
generally peaks occur when the tool is in the corner of the pyramid, higher peaks occur when the tool is making the vertical step downwards.
The fact that the FEA model could not predict the force peaks may be due to too large time step used in the calculation, data output or too large elements used in the model. Avoiding this means longer duration of calculations and bigger result data files (the total size of result files is even in current case >1 GB).
The ISF process is modelled using FEA software LS-DYNA. Anisotropic yield criteria (Hill, Barlat) and multi-linear stress-strain approach are employed [9]. The material parameters (Lankford coefficients, yield stresses and stress-strain curve data) are determined experimentally. The calculated force components are stored in text file and corresponding diagrams are composed in post-processing phase.
Simplified theoretical model for estimating force components in ISF process is proposed by [2]. The latter model is completed by the authors of the current study in order to consider plastic anisotropy.

3. FORMABILITY ISSUES

The FLD is used as the tool for estimation material formability in ISF process. The forming strategies are developed in order to cover the entire deformation mode corresponding to the positive minor strain region of the FLD.
Several studies of formability indicate that FLD in case of ISF is different compared to FLD of traditional forming processes, e.g. deep drawing [1-4, 10-12]. Generally, in ISF higher strains can be achieved, in some cases much higher – Jeswiet et al reported strains over 300% (Al 3003-O) [12].
According to this, FLD created for traditional forming processes cannot be used effectively for ISF process analysis, and special FLD has to be created.
Although, the formability is higher at ISF (forming limit curve is higher), there are more geometrical limitations when compared with traditional forming technologies, like deep drawing. This is caused by different process mechanics – in deep drawing material is pulled into the die, in ISF deformation is local, and material will not be pulled into processing area. Thus, literally, height of the part features is built at the cost of part thickness.
To create FLD circular grid path with 3 mm diameter has been printed on the sheet surface and ISF process was performed up to failure. The limit strains are determined from the circular grid near necks and fractures (Fig. 5).

Fig. 5. Incremental formability test.

The obtained experimental results are fitted by straight line in FLD. Deviations of the experimental limit strains from obtained linear approximation appears not significant (see Fig. 6).

Fig. 6. Forming Limit Diagram for ISF process.

The theoretical fracture strains are determined using normalized Cockcroft-Latham criteria [13]:

\[
\sigma_0 \frac{0.4}{0.45} \frac{0.5}{0.55} \frac{0.6}{0.65} \frac{0.7}{0.75} \frac{0.8}{0.85} \quad \varepsilon_2
\]

\[
0 \quad 0.05 \quad 0.1 \quad 0.15 \quad 0.2 \quad 0.25 \quad 0.3
\]

\[F LD \quad Fracture \ criteria\]
\[
\int_0^{\varepsilon_{eq}^{fr}} \frac{\sigma_i}{\sigma_{eq}} d\varepsilon_{eq} = C. \quad (3.1)
\]

In (3.1) \(\sigma_i\) is the maximal principal strain, \(\sigma_{eq}\) and \(\varepsilon_{eq}\) are equivalent stress and strain, respectively. Equivalent fracture strain is denoted by \(\varepsilon_{eq}^{fr}\). The calculated fracture strain and experimental limit strain corresponding to plane strain condition are found to be close (Fig. 6). This result is in accordance with empirical formula

\[
\varepsilon_1 + \varepsilon_2 = \varepsilon_{fr} \quad (3.2)
\]

proposed by [2].

In (3.2) \(\varepsilon_1\) and \(\varepsilon_2\) stand for major and minor principal strains, respectively. However, based on the results obtained in the current study, we can conclude that:

a) it is reasonable to use general linear approach for limit strains

\[
\varepsilon_1 + c_1 \varepsilon_2 = c_2. \quad (3.3)
\]

b) in plane strain condition fracture strain can be used as estimate for limit strain.

4. SOME GENERAL TECHNOLOGICAL ISSUES

Although ISF has some very useful features, it has some serious drawbacks as well. The main drawbacks are problems with making steep walls, and low accuracy induced by elastic spring-back. These topics are dealt with below.

4.1 Problems with steep walls

In ISF the final thickness of the wall depends directly on wall draft angle (denoted with \(\alpha\) in Fig. 1 a)). If \(\alpha\) is approaching 0°, the strain state is above forming limit curve (see Fig. 6) and material will break \([14]\). Generally, when using soft aluminium, walls with \(\alpha > 30°\) can be produced without material failures. Although some researchers have reported achieving \(\alpha = 0°\), it is still too hard to accomplish in everyday industrial practice. Thus, this is a serious limitation of ISF, which will exclude many possible applications.

4.2 Problems with elastic materials

Serious accuracy problems arise in case of processing elastic materials, e.g. stainless steel. Elastic spring-back effect may play important role especially if the gap between the tool and the support has been left large or forming without support is performed. This will appear after cut-out operations, when large relatively stiff edges are removed. In case of large parts, deviations will cumulate and may cause geometrical errors of several millimetres or more. Thus, thermal treatment for residual stress removal is required before cut-out operations.

4.3 Problems with surfaces with large radius of curvature

As has been said above, there are problems with steep walls, but it appears that there are some accuracy problems with shallow surfaces with large radius of curvature as well. This is caused by elastic spring-back, discussed in previous section. In addition, smaller vertical tool step should be used to avoid visible forming lines on the part surface. This all should be taken into account while planning production using ISF processes.

4.4 Gap between the tool and the support

One practical question is how large gap between the forming tool and the support should be left. If it is too large, the deviation will be too large as well, if it is too small, the sheet is pressed between the tool and the support, causing ironing effect (thinning occurs). As undeformed material is relatively stiff, the material pressed out from the tool-support contact area moves up and lifts the previously formed surfaces off the support. This, as the authors have discovered, may cause form deviations in range of several millimetres.
A good starting point in gap selection is the initial sheet thickness \[15\].

5. CONCLUSION

The ISF process is modelled using FEM software LS-DYNA. The test procedures are designed for determining FLD and forming force components in ISF process. The obtained experimental, numerical and theoretical results are found to be in a good agreement.

New incremental sheet forming strategies for determining FLD are pointed out. Some concepts used can be formulated as: in test design corresponding to uniaxial stretching conditions the influence of plastic anisotropy should be considered; in test design corresponding to biaxial stretching conditions, the final geometry of the formed sheet can be chosen similar to traditional FLD test (hemispherical punch test).

6. ACKNOWLEDGEMENTS

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7. REFERENCES