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# Manufacturability and limitations in incremental sheet forming

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**Abstract.** In the actual incremental sheet forming process two kinds of risks can be outlined: material failure and tool failure. From the point of view of safe manufacturing, both risks should be minimized. The aim of the current study is to predict material and tool failure. An experimental, numerical and theoretical study is performed in order to determine the material formability and the forming load components. Incremental sheet forming strategies for determining the forming limit diagram are pointed out.

**Key words:** sheet metal forming, forming limit diagram, incremental forming, finite element analysis.

## 1. INTRODUCTION

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

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

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

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 exists for determining the forming limit curve in the ISF process. Both experimental and theoretical studies in this area are in development. Some general ideas for test design are presented in [2,4]. In [4], tool paths, corresponding to uniaxial and biaxial stretching conditions, are given. In [2], an empirical formula is used for the approximation of the forming limit diagram (FLD).

Two important limiting factors, studied in the current paper, are the forming forces and the material formability. Forming forces dictate what machine tools can be used, what is the material of the forming tools and what is the material type and thickness that can be used for the designed parts. Material formability determines whether it is possible to produce the designed part from the selected material.

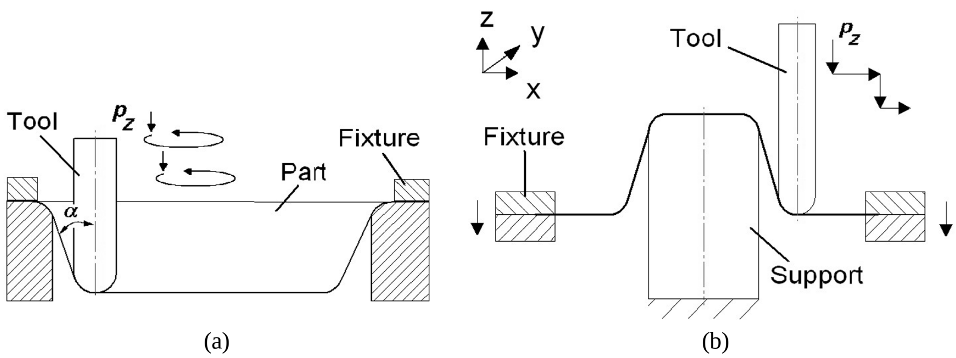


**Fig. 1.** Forming principle of ISF: (a) negative forming; (b) positive forming.

In this study, the problems concerning forming forces have been investigated experimentally and numerically. An approximate theoretical solution has been proposed. Formability analysis has also been carried out and some general technological problems of the ISF process have been treated.

## 2. THE FORMING FORCES

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

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

The square pyramid shaped box was formed on the NC milling machine and the force components were measured in $x$, $y$ and $z$ directions (Fig. 3).

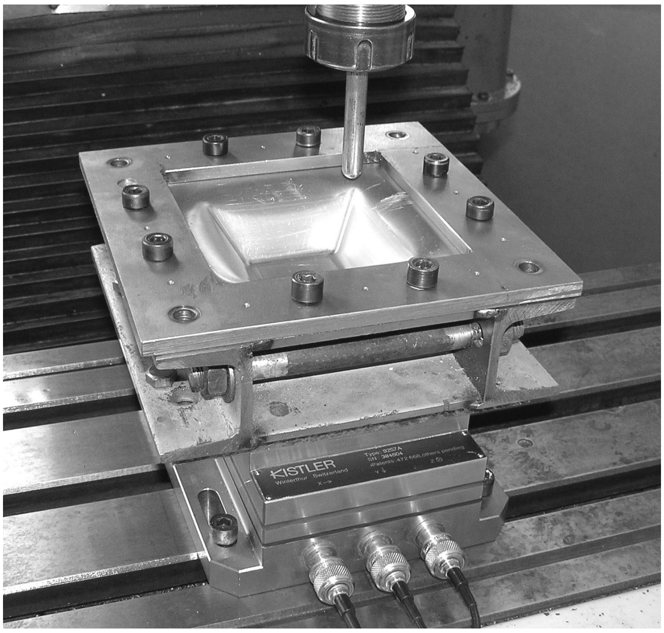


**Fig. 2.** Set-up for force measurement in ISF on a NC machining centre.

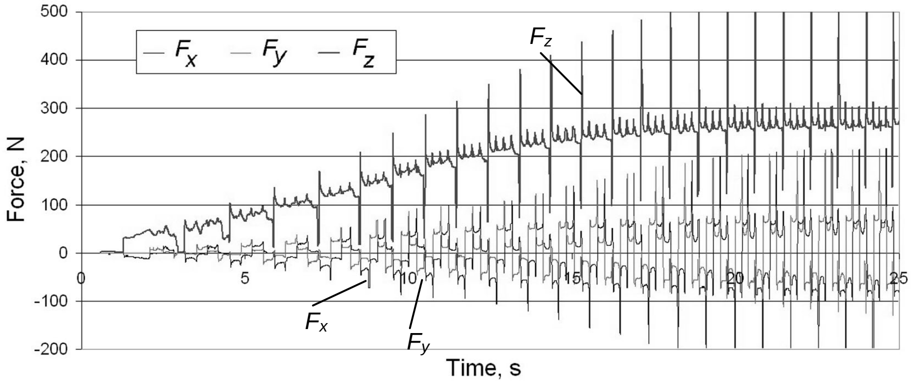


**Fig. 3.** Force components, measured in experimental study of incremental forming of a pyramid-like shape.

As can be seen in Fig. 3, the force patterns in the $x$ and $y$ directions are not similar. This is due to sheet anisotropy and non-symmetric deformation mode. The obtained results are in agreement with the results given in [6].

Numerical procedure, described in [7–9], has been refined and a better accuracy of simulations has been achieved. The calculated contact forces are shown in Fig. 4.

The ISF process is modelled using FEA software LS-DYNA. In [9], a similar simulation was carried out for an isotropic material. In the current study, anisotropic yield criteria and the exponential hardening rule are used [10,11]. The material parameters (Lankford coefficients, yield stresses and stress–strain relationship) were determined experimentally.

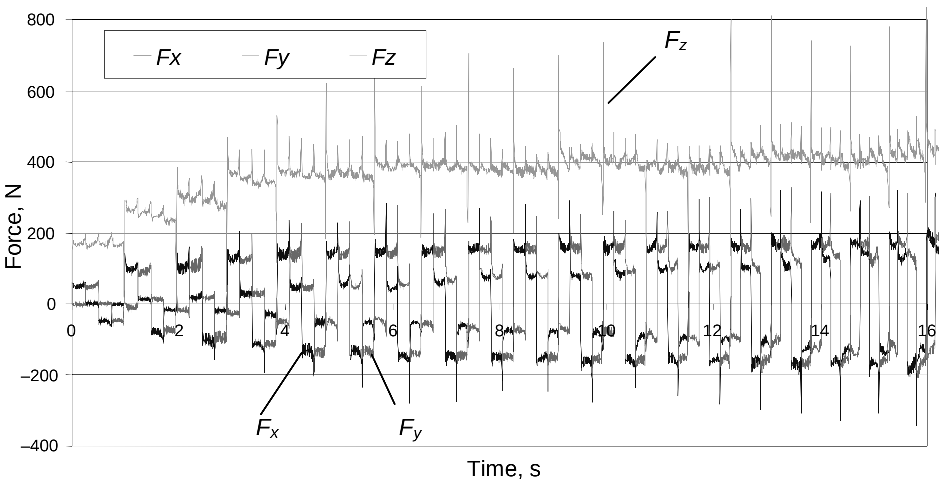


**Fig. 4.** Force components obtained by FEA.

Comparison of Figs. 3 and 4 shows that the force patterns are in agreement. However, the calculated forces are higher than those measured experimentally. This fact may be caused by the approximation used for describing the strain-hardening behaviour in the FEA model. Similarly, higher calculated forming limits in comparison to those obtained experimentally have been observed also in [12], when simple exponential (Hollomon) strain-hardening relationship was adopted. In [12], the Voce approximation was suggested for copper and aluminium alloys. The current FEA model will be improved by describing the strain-hardening behaviour of the material with multi-linear approximation.

Note that the time scales in Figs. 3 and 4 are different, i.e. the comparison can be made considering the load curves; generally, peaks occur when the tool is at the corner of the pyramid and higher peaks occur when the tool is making the vertical step downwards.

A simplified theoretical model for estimating force components in the ISF process is proposed in [2]. Uniform stretching of the sheet metal under plane strain condition is assumed. The bending stress and the friction force are neglected. In the present paper the latter model is improved in order to take into account plastic anisotropy. The Hill's second and higher order yield criteria are employed for describing anisotropy. The following estimation for the tensile membrane force $T$ has been obtained:

$$T = 2R_B K \left\{ \frac{[2(1+R)]^{\frac{1}{m}}}{2} \left[ 1 + \frac{1}{(1+2R)^{\frac{1}{m-1}}} \right]^{\frac{m-1}{m}} \right\}^n \left( \frac{(1+R)}{(1+2R)} \right)^{\frac{1}{m}}$$

$$\times \left( \frac{(1+2R)^{\frac{1}{m-1}} + 1}{2} \right)^{\frac{m-1}{m}} t_0 e^{-\varepsilon_x} \varepsilon_x^n, \tag{2.1}$$

where $R$ is the normal anisotropy coefficient, $m$ is Hill's yield criteria exponent, $K$ is the strength coefficient, $n$ is the strain hardening exponent, $t_0$ is the initial thickness of the sheet and $R_B$ is the radius of the tool. The strain component $\varepsilon_x$ is determined by forming geometry. Formulas for computing $\varepsilon_x$ are given in [2].

In [2], the forming force components $F_z$ (vertical direction) and $F_x$ (tool moving direction) are given as

$$F_x = T\sin\theta, \qquad F_z = T(1-\cos\theta), \tag{2.2}$$

where $T$ and $\theta$ are the tensile force and contact angle, respectively. The geometrical relations for evaluating the contact angle $\theta$ are given in [2].

The forming force components, obtained from theoretical analysis (Fig. 5), are given as functions of the bulging height (forming geometry), but their corresponding experimental (and numerical) results describe their dependence on the forming time.

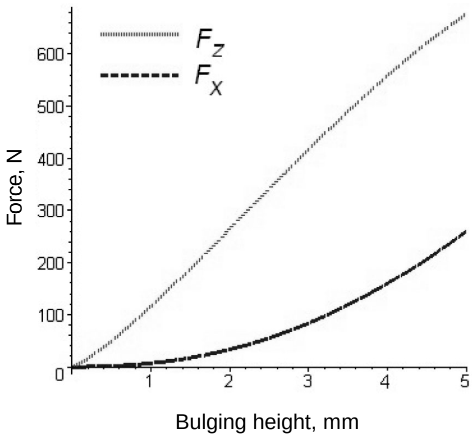


**Fig. 5.** Forming force components.

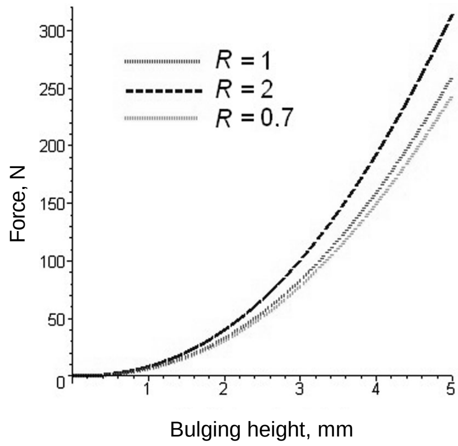


**Fig. 6.** Influence of the plastic anisotropy on the forming force $F_x$.

In Fig. 6 the forming force components $F_x$ for different values of the plastic anisotropy parameter $R$ are plotted. In the case of $R = 1$ the theoretical results coincide with those obtained with the Iseki's models.

It is seen in Fig. 6 that the influence of the plastic anisotropy on material formability is significant. As it was to be expected, the forming force component $F_x$ increases with increasing value of the anisotropy parameter $R$.

## 3. FORMABILITY

The FLD is used as a tool for the estimation of the material formability in the 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 as compared to FLD of traditional forming processes (e.g. deep drawing) and the test methods in an ISO standard proposal for FLD-s [1–4,13–15]. Namely, the strain modes of incremental forming produce almost straight strain paths (except slight bending due to the tool radius). Generally, in ISF higher strains can be achieved, even over 300% (material: aluminium Al 3003-O) [15]. According to this, FLD, created for traditional forming processes, cannot be used effectively for the ISF process analysis. Thus a special FLD has to be created.

Although the formability is higher in 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 the material is pulled into the die while in ISF the deformation is local and the material is not pulled into the processing area. Thus, literally, some features of the part are built at the cost of the thickness of the part.

To create a FLD, a circular grid path of 3 mm diameter was printed on the sheet surface and the ISF process was performed up to the failure. The limit strains were determined from the circular grid near necks and fractures (Fig. 7).

The experimental results are fitted by a straight line in FLD. Deviations of the experimental limit strains from those obtained with linear approximation are not significant (Fig. 8).

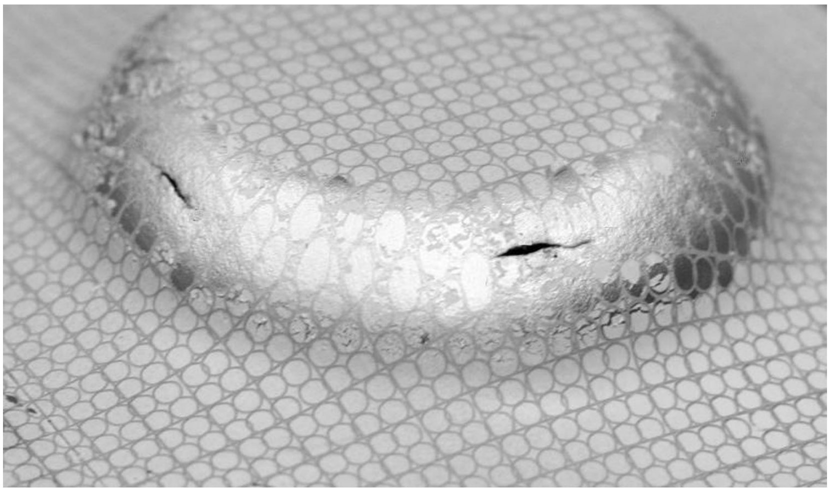

**Fig. 7.** Incremental formability test.

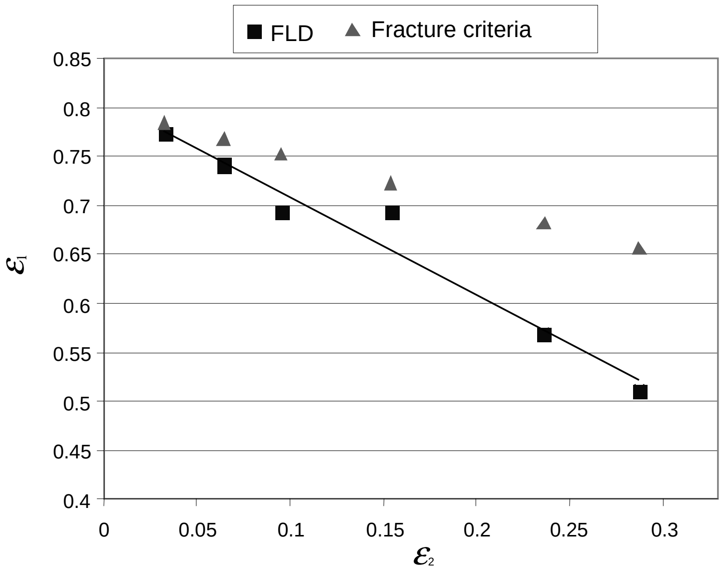


**Fig. 8.** Forming limit diagram for the ISF process.

Theoretical fracture strains are determined using the normalized Cockroft–Latham criterion [16]:

$$\int_0^{\varepsilon_{\mathrm{eq}}^{\mathrm{fr}}} \frac{\sigma_1}{\sigma_{\mathrm{eq}}} \mathrm{d}\varepsilon_{\mathrm{eq}} = C, \tag{3.1}$$

where $\sigma_1$ is the maximum principal stress, and $\sigma_{\mathrm{eq}}$ and $\varepsilon_{\mathrm{eq}}$ are the equivalent stress and strain, respectively. Equivalent fracture strain is denoted by $\varepsilon_{\mathrm{eq}}^{\mathrm{fr}}$. The calculated fracture strain and experimental limit strain, corresponding to the plane strain condition, are found to be close (Fig. 8). This result is in accordance with the empirical formula

$$\varepsilon_1 + \varepsilon_2 = \varepsilon_{\mathrm{fr}}, \tag{3.2}$$

proposed in [2]. In Eq. (3.2), $\varepsilon_1$ and $\varepsilon_2$ are the major and minor principal strains.

Based on the results, obtained above, we can conclude the following:

– it is reasonable to use general linear approach for limit strains

$$\varepsilon_1 + c_1\varepsilon_2 = c_2, \tag{3.3}$$

where $c_1$ and $c_2$ stand for material parameters;

– in plane strain condition the fracture strain, obtained by non-incremental forming, can be used to predict the limit strains for incremental forming;

– the proposed approximate theoretical model shows the best agreement with test results in case of bulging heights exceeding 2 mm.

## 4. SOME GENERAL TECHNOLOGICAL PROBLEMS

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 the elastic spring-back.

### 4.1. Problems with steep walls

In ISF, the final thickness of the wall depends directly on the wall draft angle (denoted with $\alpha$ in Fig. 1a). If $\alpha$ approaches $0°$, the strain state is above the forming limit curve (Fig. 6) and the material will break [7,17]. 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 excludes 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 an 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 millimeters or more. Thus thermal treatment for residual stress removal may be required before cut-out operations.

### 4.3. Problems with surfaces of a 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 a large radius of curvature as well. This is caused by the elastic spring-back, discussed in the previous section. In addition, smaller vertical tool steps should be used to avoid visible forming lines on the part surface. All that should be taken into account while planning production using the ISF processes.

### 4.4. The 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; if it is too small, the sheet is pressed between the tool and the support, causing the ironing effect (thinning occurs). As the 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 the range of several millimeters. A good starting point in gap selection is the initial sheet thickness [18].

## 5. CONCLUSIONS

The ISF process was modelled using FEM software LS-DYNA. The test procedures were designed for determining the FLD and forming force components in the ISF process. The obtained experimental and numerical results are found to be in a good agreement. An approximate theoretical model is found suitable for estimating force components in the case of bulging heights exceeding 2 mm. New incremental sheet forming strategies for determining FLD are pointed out. It is shown that in tests with uniaxial stretching conditions the influence of plastic anisotropy should be considered, but in tests with biaxial stretching conditions, the final geometry of the formed sheet can be chosen similar to traditional FLD tests (hemispherical punch test).

## ACKNOWLEDGEMENT

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# Lehtmaterjali sammvormimise tehnoloogilisus ja piirangud

Meelis Pohlak, Jüri Majak ja Rein Küttner

On uuritud lehtmaterjali sammvormimise protsessi ja selle modelleerimist. Põhitähelepanu on suunatud protsessi tehnoloogilistele piirangutele. Neist kaht – vormimiseks vajalikke jõude ning lehtmaterjali vormitavust – on uuritud eksperimentaalselt ja modelleeritud numbriliselt. Lisaks on loodud lihtsustatud teoreetilised mudelid vormitavuse ja jõukomponentide hindamiseks.