THE FLC, ENHANCED FORMABILITY, AND INCREMENTAL SHEET FORMING

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ABSTRACT

The FLC is a well known concept in the sheet metal forming world. It is used to map the material's formability and the make-ability of a product. The FLC is valid only within certain restrictions. These restrictions are: A: a straight strain path; B: absence of bending; C: absence of through-thickness shear; D: a condition of plane stress.

The formability of a material can be increased significantly if one is allowed to violate any of these restrictions, meaning either: use a complex strain path, incorporate bending, incorporate through-thickness shear, or apply a contact stress. Both shear and contact stress change the stress state, and both lower the yield stress in tension and raise the necking limit up to a certain level. Bending creates a non-uniform stress distribution over the thickness of the sheet, resulting in a reduction of the yield force in tension, and it creates a range of stable elongation depending on the sheet thickness at each passage of the punch. The effect of a complex strain path depends on the particular situation; in incremental sheet forming it is based on non-isotropic hardening.

In general it will not be possible to create such conditions in the entire product at once. However it is possible to do this intentionally in a small, restricted zone by creating special situations there. By moving this zone over the entire product the whole part can be made with increased formability. This technique of incremental forming is explained briefly. The special conditions around the punch indeed violate the FLC restrictions mentioned above. The enhanced formability obtained in incremental sheet forming is illustrated with many examples.

Keywords: Formability; FLC; Incremental Sheet Forming; Shear; Bending; Complex Strain Path.

1. INTRODUCTION

The Forming Limit Curve (FLC) is a well known concept in the sheet metal forming world. It is both used to map the material's formability and to map the make-ability of a product. The concept was originally defined by Goodwin and Keeler in the 60's (hence the old term: Goodwin-Keeler diagram), and much research has been carried out within the IDDRG in the 70's. However, occasionally situations were encountered where the FLC seemed wrong: material fractured well below the FLC, or did not fracture at strains well above the FLC. An example is presented in figure1 showing an actual automotive component where at location 1 the measured strain was 80% (plane strain). This is far more than expected from the material properties, even when corrected for the local curvature of the part.

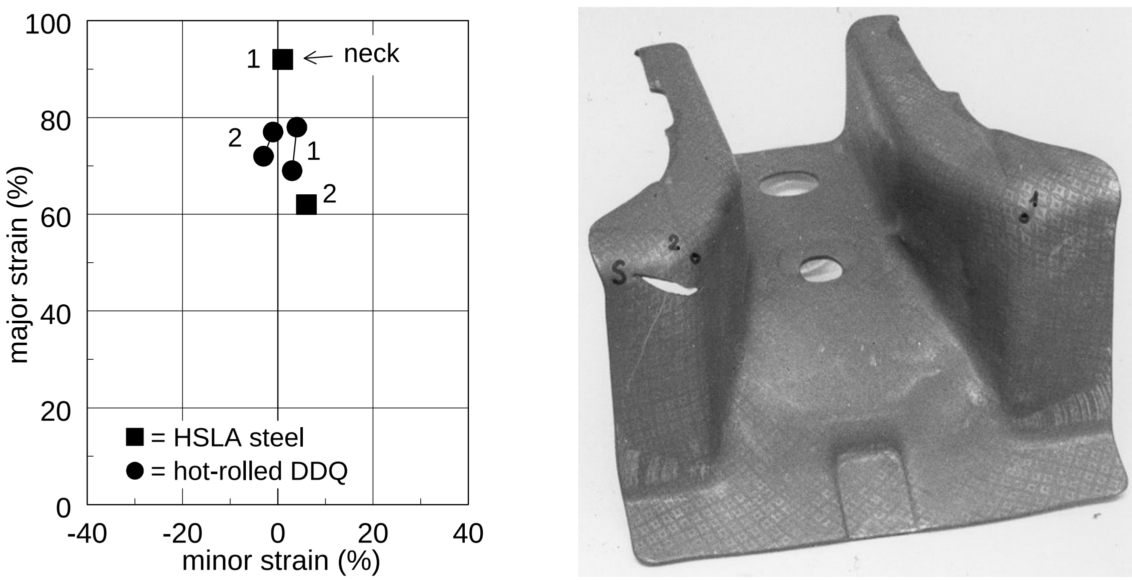

Figure 1*. A commercial automotive part (1984) made from two grades of 2 mm steel showing exceptionally high local strains. Left: measured strains, right: picture of the part (HSLA steel). Numbers 1 and 2 denote measuring position. (no fracture occurred at S when using DDQ steel)*

Researchers became aware that the FLC is only valid under certain conditions, notably:

- absence of bending
- a straight strain path

These limitations may look severe, but in many actual automotive parts the situation is close enough to these conditions to allow successful application of the FLC.

There are two more conditions for the FLC that however are of less relevance for practical sheet metal forming operations and are of more fundamental interest. These are:

- absence of through-thickness shear
- a situation of plane stress

Violation of these four conditions does not always reduce the formability of the material. On the contrary: the formability of the material can be improved significantly if one is allowed to violate any of these conditions. This will be shown in the following. However using this to improve the formability of a material in general is far from simple. It requires the creation of special forming conditions that in general can only be done very locally. This is the underlying secret in Incremental Sheet Forming (ISF).

2. MECHANISMS

The mechanisms presented here are discussed in detail in [1] and the reader is referred to that for further information and an overview of literature. The discussions here will be brief.

2.1 Through-thickness shear and contact stress

Contact stress is defined as a compressive stress normal to the sheet surface ($\sigma_3<0$), and through-thickness shear is shear where the two surfaces of the sheet are shifted one relative to the other.

Both phenomena have a similar effect. Both affect the stress state of the material in such a way that a lower stress in tension is required for plastic deformation. This stems for example directly from the well-known von Mises yield criterion which for the general case is:

$$2\cdot\sigma_f^{\,2}=(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6\cdot\left(\tau_{12}^{\,2}+\tau_{23}^{\,2}+\tau_{31}^{\,2}\right) \qquad (1)$$

where σ_f is the flow stress, and τ_{ij} the shear stresses. The effects of additional normal stress σ_{33} or additional shear stress τ_{ij} on the yield locus are graphically presented in figure 2.

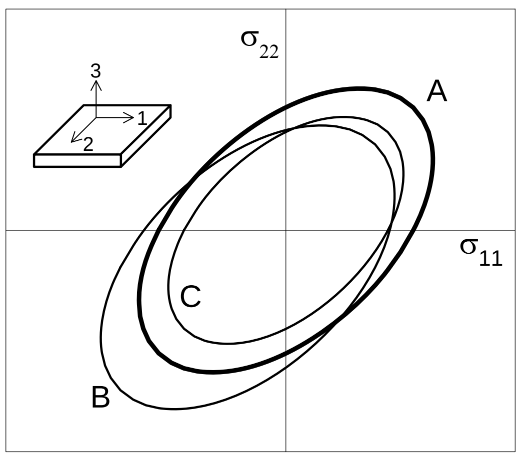

Figure 2*. Effects on the von Mises yield locus, σ_{11} and σ_{22} are orthogonal stresses parallel to the sheet surface. A = standard locus as used in traditional sheet metal forming (σ_{33} = 0, τ = 0); B = effect of contact stress (σ_{33} < 0, τ = 0); C = effect of shear (σ_{33} = 0, $\tau \neq 0$).*

A lesser known effect is that both also increase the formability, meaning that necking takes place at higher length strains than in situations without these effects. In general this is more difficult to analyze, and only under certain conditions like plane-strain a simple analytical model can be used. Therefore this situation is often analysed using a Marciniak-Kuczynski method.

The effect of shear on formability has been investigated only recently. Some results of theoretical work are presented in figure 3 that have been derived with a simple analytical model. Based on this principle Allwood has proposed a new class of forming processes named 'paddle-forming', and has demonstrated with a repetitive linear paddle test that uniform strains of 300% can be obtained on annealed Al 1050 [2].

Contact stress occurs at every place of contact between workpiece and tool. However one should distinguish between single sided contacts and double side contacts. Double sided contacts only occur when the material is actually being clamped in the tool, and only then a proper through-thickness compressive stress can be generated. At single sided contacts the normal stress varies over the thickness, the mean value is lower than the value at the actual contact surface. The effect of through-thickness contact stress on formability has been investigated theoretically by several researchers and some results are presented in figure 4, all showing an increase of the necking limit.

The effects of both phenomena on the FLC have been investigated theoretically recently by Allwood, and he has proposed a Generalised Forming Limit Diagram (GFLD) that incorporates both effects [2].

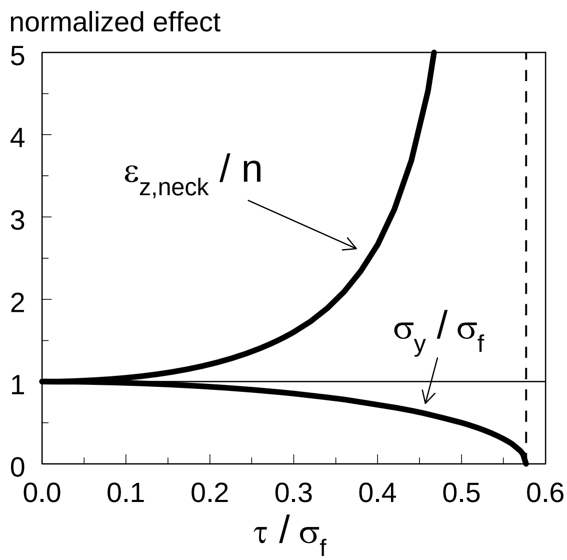

***Figure 3**. Effects of additional shear stress on formability [1]. Bottom line: normalized yield stress in tension σ_y; upper line: normalized length strain at onset of necking ε_z. σ_f = flow stress, τ = shear stress, n = hardening coefficient.*

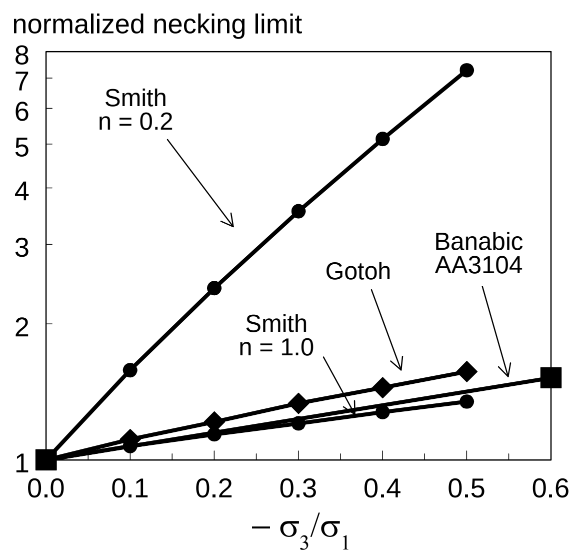

***Figure 4**. Effect of contact stress on formability by three models [1]. σ_3 = contact stress, σ_1 = conventional major stress. n = conventional hardening coefficient.*

2.2 Bending.

The effect of bending is different. Bending does not change the stress state, it is in fact a simple tension operation where however the strain varies over the thickness of the material. This situation is known as Bending-Under-Tension (BUT) and is in fact a combination of pure bending and stretching. A special situation occurs when the bending is so severe that at one side the material is actual in compression. This phenomenon is well known from the literature, and if bending and stretching are done simultaneously the following effects occur:

- the material can be bent with a lower moment than in a situation without stretching
- the material can be stretched (elongated) by a lower force than in a situation without bending

The latter effect is presented in figure 5, that also shows another important effect: in a situation where the bending radius remains constant, as often encountered in practice, the force increases with elongation, creating a zone of stable deformation that is proportional to the thickness of the sheet. Based on this effect a Continuous-Bending-Test (CBT) has been developed that is described in detail in [3], and by which uniform elongations of up to 430 % have been obtained. Note that the effect of BUT differs principally from that of shear and contact stress. Shear and contact stress raise the formability to a certain, absolute level, but BUT creates a zone of stable deformation at every bending operation. BUT works when the material is being bent, not when it has been bent.

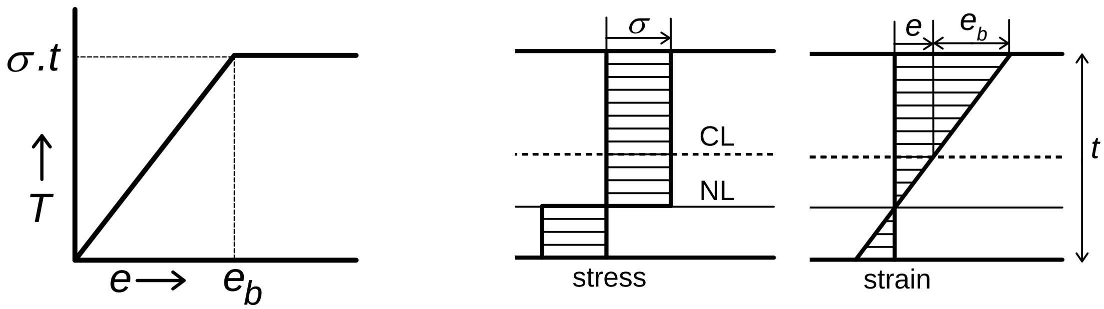

Figure 5. *Basic effect of BUT [1]. Left: Graphic presentation of the relation between tension force per unit width T and elongation e, under conditions of constant bending radius.* $e_b = t/2R$*, t = sheet thickness, R = bending radius,* σ *= material flow stress. Right: example of distribution of stress and strain for the case* $e=e_b/2$*. CL is the sheet centre line, NL is the neutral line that is shifted downwards.*

2.3 Non-straight strain path.

The effect of a non-straight strain path (non-proportional loading) on formability is complex. Early work was done by Gronostajski [4] who measured the FLC of pre-strained material, and observed that a complex strain path can both enhance and reduce the formability, see figure 6. Recent analytical work by Yoshida et al. showed the same effect [5]. A general discussion is beyond the concept of this paper as the effects are simply too much dependent on the actual strain path.

An even more complex situation arises in situations of cyclic straining where the strain path changes repeatedly. Such a situation occurs in Incremental Sheet Forming as will be shown below in section 3.2. Eyckens has studied this particular situation in detail [6]. He has derived a cyclic strain path from FEM simulations of an ISF process and carried out a Marciniak-Kuczynski type analysis. This revealed that indeed the necking instability is shifted to higher strains. Noteworthy is that enhanced formability was only obtained when using a non-isotropic hardening relation. This

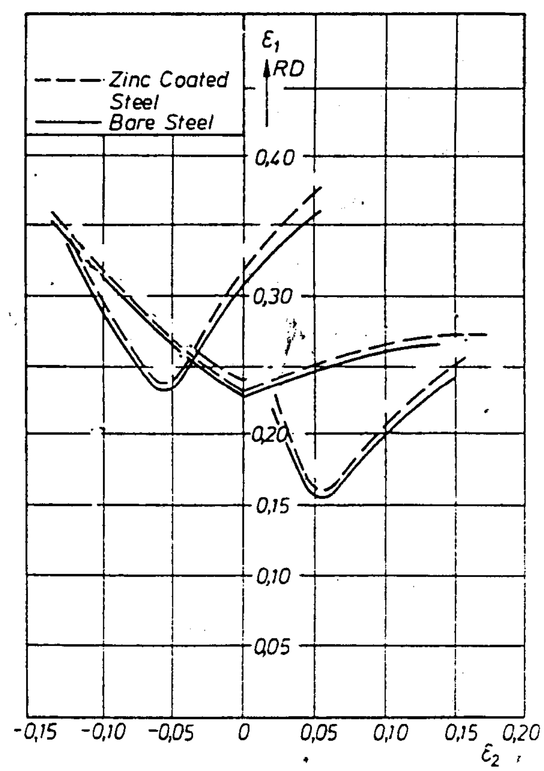

Figure 6. *Effects of strain path on the FLC as measured by Gronostajski [4].*

suggests that the effect of a non-straight strain path strongly depends on non-isotropic hardening behavior. A very simple example of the latter is the well-known Bauschinger effect occurring at full strain reversal.

2.4 Summary of mechanisms

The former has illustrated some effects that can occur when the elementary conditions underlying the FLC are violated.

Both the presence of shear and contact stress increase the formability (strain in tension at the onset of necking) to an absolute level depending on the level of shear or contact stress.

Bending-under-tension on the other hand is a dynamic effect. It only occurs when the material is being bent and stretched at the same time. The formability is not increased to an absolute level, but a zone of stable deformation is created at every operation governed by geometric parameters only, independent of the straining history of the material.

All three mechanisms have one thing in common: they all lower the (mean) stress in tension needed for plastic deformation; this is a relevant phenomena in ISF as will be discussed below.

The effect of non-straight strain path is very complex and can only be determined for a specific situation. Furthermore it requires sophisticated material models that for example incorporate the Bauschinger effect.

2.5 Practical application of mechanisms

So it is clear that the formability of a material can be enhanced significantly if one is not restricted by the limitations that underlie the FLC. However it will also be clear that this is very difficult to achieve in production. For example, one cannot take an arbitrary product like an auto body part and change the process so that much more shear occurs, and by that improve the formability. So the question is how this knowledge does help us. Application of the mechanism discussed in this section requires the creation of special forming conditions. Such conditions cannot be created globally, but it is possible to do it very locally, in such a way that a small localized forming zone is being created where these (or some) special conditions prevail. By moving that zone over the work piece these conditions can be made to rule over the entire part. This is done in Incremental Sheet Forming.

3. INCREMENTAL SHEET FORMING

3.1 General description

The name incremental forming describes a wide family of forming processes all characterized by the fact that at any time only a small part of the product is actually formed, and the forming zone travels over the entire part by some means. This description includes classic operations like hammering and spinning. The 'modern' variant Incremental Sheet Forming has been developed in Japan in the late 80's but can be traced back to original work by Mason (Univ. Nottingham, UK) in 1978. In this process a steel punch or similar describes consecutive closed contours over the sheet with increasing depth. The most simple form is pictured in figure 7. A punch with a hemispherical end draws a contour A over the surface pushing the material slightly downwards (1) creating a shallow recess. The punch only follows the perimeter of the recess, the bottom remains undeformed. After that the punch is moved inwards and downwards (1 → 2) and draws a second contour (2), and another (3) etc, creating a product of increasing depth. Note that the clamp is for positioning the blank only. It is not a blankholder as, due to the localized character of the deformation, there is no tendency that material will be pulled inwards.

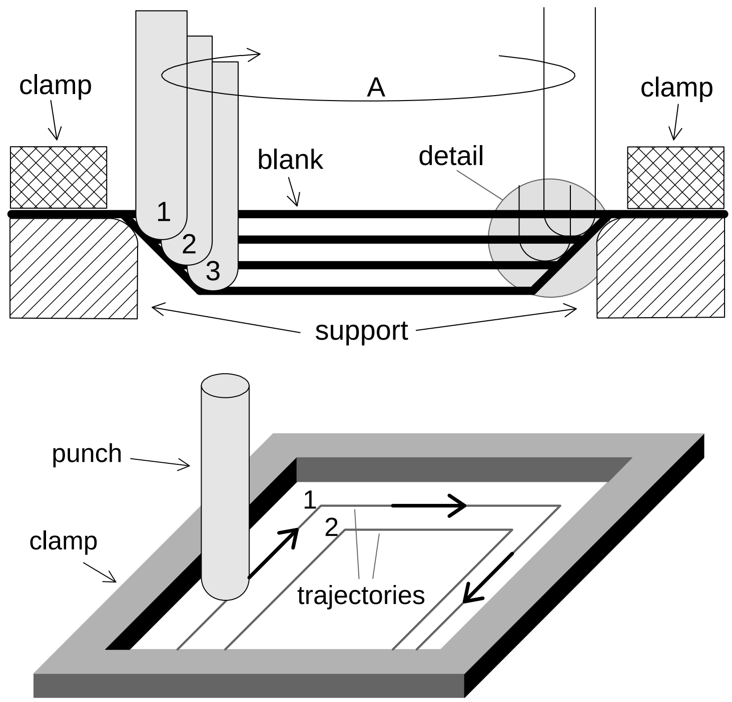

Figure 7. *Schematic presentation of the ISF process. The detail is shown in figure 9.*

The procedure pictured in figure 7 is called SPIF (Single Point Incremental Forming). The punch moves from the outer side inwards, the blank remains fixed and the center moves downwards. A more or less inverted procedure is called TPIF (Two-Point Incremental Forming). Here the punch moves from the inner side outwards, the blank moves down, and the centre of the product remains fixed by some support placed under the product. There are more advanced methods as well that use two moving punches simultaneously, one at each side of the sheet.

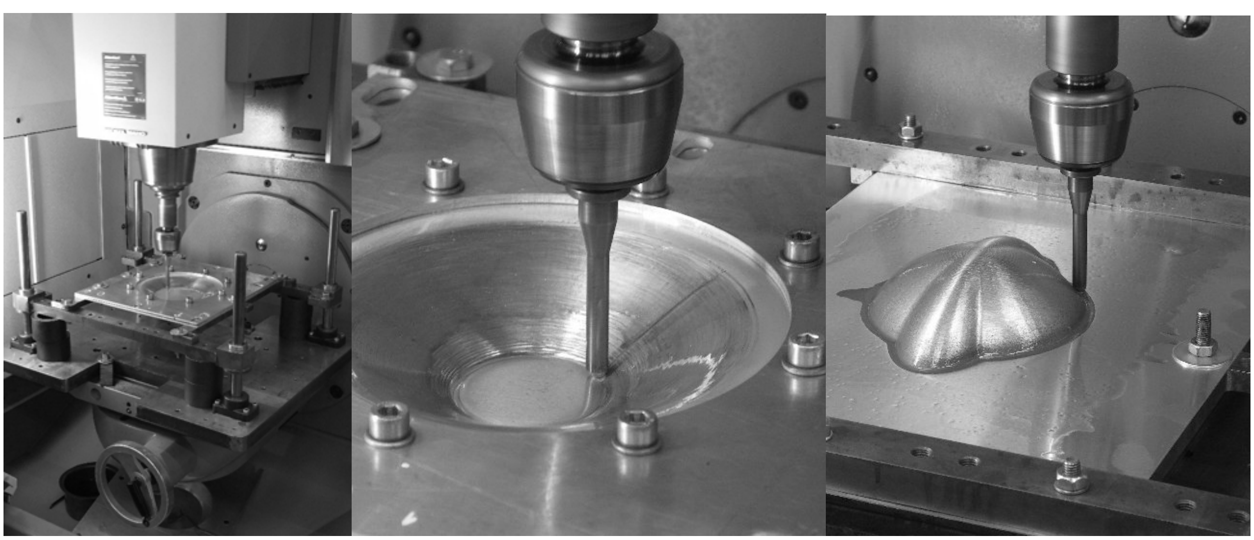

Figure 8. *ISF set-up. Left: overview of set-up in a conventional CNC milling machine. Center: SPIF detail. Right: TPIF detail.*

Figure 8 shows some photographs of an actual set-up (IUL, Univ. Dortmund). In this case a conventional CNC milling machine is used, although commercial ISF machines are on the market as well. Furthermore, ISF can be also be performed using a heavy industrial robot [7].

3.2 Forming conditions

An essential aspect of ISF is that the material is deformed only in a small zone around the contact between punch and workpiece. As a consequence in that zone special conditions can be generated that normally do not occur in conventional stamping. The situation around the punch contact is shown in figure 9.

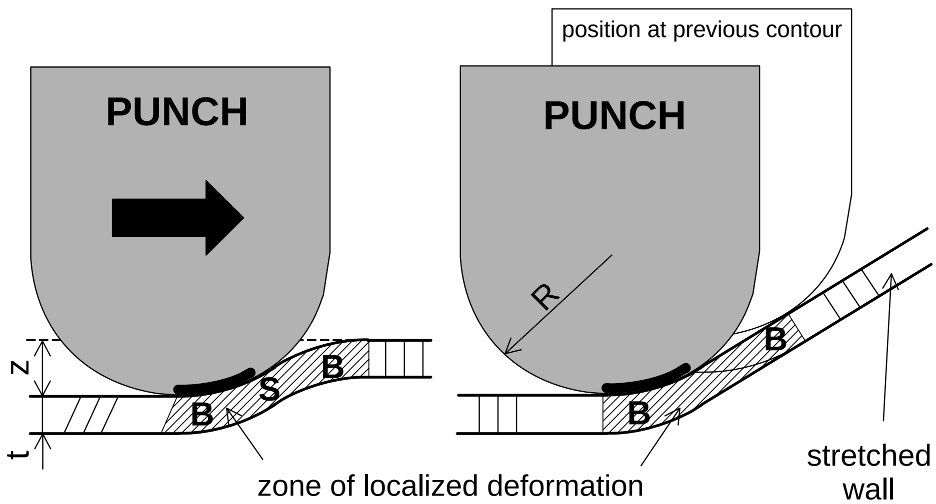

Figure 9*. Situation around the punch contact (detail from figure 7, top). Left: cross-section in the direction of punch movement denoted by the arrow. Right: cross-section across the direction of punch movement as in figure 7. The thick line denotes the area of high contact stress, B denotes bending, S denotes shear, the triple cross section lines indicate stretch or shear.*

The thick lines indicate locations of high contact stress. Due to the small radius of the punch (typical 5-10 mm) these stresses can be very high, in the order of the yield stress of the sheet material [8].

The cross section in the direction of punch movement (left) shows that the material is being bent and unbent. In that zone also (some) shear takes place, the occurrence of that has been established experimentally [9]. Shear is caused by the high shear forces that the punch exerts on the sheet surface due to the high contact stress. There is no stretch in that direction.

The cross section perpendicular to the movement of the punch (right) shows that the material is also bent in that direction, obviously as otherwise no angled wall can be created. Basically there are both a bending and unbending operation. The finished wall shows simple stretch in the perpendicular direction with little or no shear [9]. The strain state as measured on the surface is basically plane strain, except in areas of high curvature like corners where it shifts to biaxial.

The picture is exaggerated, the vertical step increment z is normally (much) lower than the sheet thickness t, typical 0.1 - 0.2 mm. This means that in fact the punch passes a certain location several times, up to a few dozen. This further implies that the material is subjected to cyclic straining, notably repetitive bending and unbending. Figure 10 presents an example of strain history that was obtained by an FEM simulation of the process.

So in ISF all four conditions that underlie the FLC are violated.

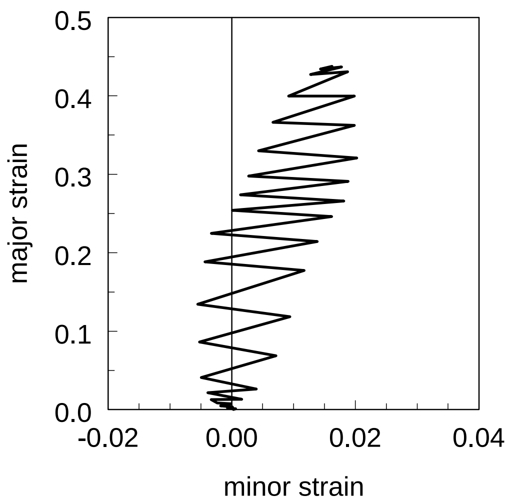

Figure 10. *Example of cyclic strain history occurring in ISF (schematic) [1].*

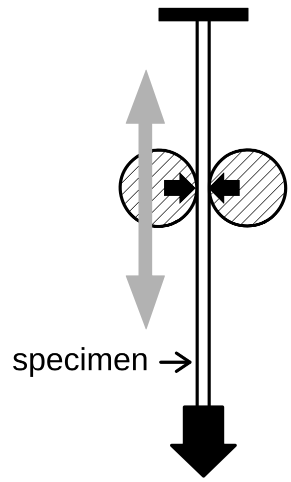

Figure 11. *The Taraldsen test, see text for description.*

3.3 The incremental character

Special emphasis should be placed on the incremental character of the process. At any time only a small zone is actually deformed. The fact that the deformation is concentrated into a small zone is caused by simple geometrical considerations, and the observation that three of the four mechanisms discussed above actuality reduce the yield stress/force in tension. A material subjected to tension will yield in the weakest spot, and if some mechanism reduces the force required for plastic yield locally, it will concentrate the deformation in that spot.

By moving the punch the zone of localized deformation moves over the workpiece, and at any location the material is subjected to small strain increments, one at each passage of the punch. If these increments are small enough the material, speaking in a popular way, may simply have not enough time to develop a neck. This incremental character is particularly noticeable in the so-called Taraldsen test [1]. In this test a large specimen is subjected to a conventional tensile test, but at the same time a pair of rolls clamping the specimen with a modest force is moving continuously up and down (figure 11). The main effect of the rolls is that they concentrate the deformation into a small zone at the roll contact, the increase of formability there is negligible. Nevertheless with this test uniform strains of up to 600% have been obtained with copper [10]. This increase of strain must be contributed largely to the incremental character. Similar repetitive tests have been carried out with a three-roll bending set [3], or a paddle creating shear [2], all creating final levels of uniform straining well above what can be obtained in a single pass.

3.4 Formability

Figure 12 presents a typical pyramidal product made from mild steel DC06 with walls that have a slope of 60^0. The flange and flat top are not deformed. Only the walls are deformed and the strain state is plane strain. That means that the material in the walls has elongated 100%, and the thickness is accordingly reduced. This level of deformation is common in ISF. The maximum obtainable wall angle <u>in a single operation</u> is often used as a parameter to characterize the formability of a material in ISF and values of 60^0 - 70^0 are quite common, occasionally even more. This implies that the limit strain under conditions of plane-strain is in the range of 0.7 - 1.2. As a rule of thumb, the formability increases when decreasing the vertical step increment z, decreasing the tool radius R, or increasing the sheet thickness t. Higher wall angles, up to 90^0 or more can be obtained by multiple operations, but it is still an open question if this also leads to higher levels of strain.

The forming limit in ISF has often been found as being a straight line of negative slope as shown in figure 13. For many materials the slope is ≈ -1, but steeper lines of slope up to -2 have been reported as well. Most data has been obtained for the right-hand side of the diagram (biaxial state). Little data is available for the left-hand part, so that part is still uncertain.

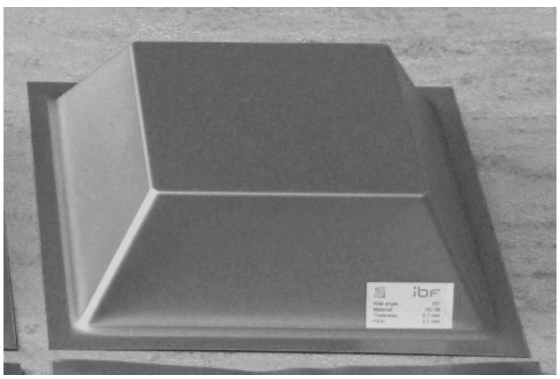

***Figure 12**. A sound pyramidal product with walls of 60^0 slope.*

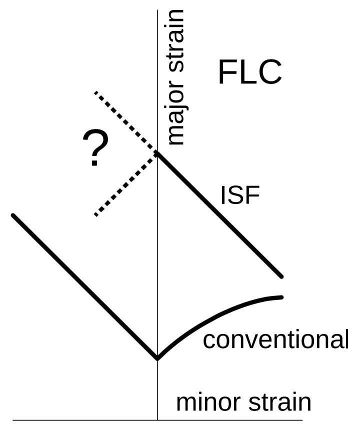

***Figure 13**. Schematic presentation of a typical FLC for ISF, compared to a conventional FLC.*

3.5 Process Characteristics

The previous sections have discussed some fundamental formability aspects of Incremental Sheet Forming in detail. As some readers may not be too well familiar with that process, the basic characteristic are summarised here.

1. The process requires no die, or only a simple support that can be made of cheap materials, hence the alternative name 'die-less forming'; this makes the process ideal for prototyping and low-volume production.

2. The process is slow, the production time depends on the total contour length and the speed of the machine; the fastest machines available have a punch speed of 1 m/s, but still then the time for a single product may be in the order of hours.

3. The deformation is localized, meaning that no material is pulled in from a blankholder area and flat parts remain undeformed, but consequently there is considerable thinning of the sheet.

4. The levels of strain that can be obtained are much higher than in conventional stamping; this makes the process suitable for hard-to-form materials.

5. The deformation is asymmetrical causing a considerable spring-back in the product; as a result the dimensional accuracy is less than for conventional stamping, but procedures are being developed to reduce the inaccuracy to acceptable levels.

Figure 14 presents a collection of products that have been made by ISF, illustrating the versatility of the process. Realise that no material is pulled inwards from a blankholder area, and the products have been made in principle by local stretching only.

Figure 14. *A collection of parts (mostly automotive) made by Incremental Sheet Forming (courtesy Amino North America Corporation, www.aminonac.ca).*

4. FINAL DISCUSSION

Basically this paper deals with the enhanced formability encountered in Incremental Sheet Forming, that is considerably higher than normally encountered in stamping operations.

This enhanced formability is caused by the combination of two characteristics:

- at any time the deformation is restricted to a small zone;
- in that zone special conditions prevail that are normally not encountered in conventional stamping.

More in detail, these special conditions are known to be able to raise the formability of technical metals.

These conditions are essential. Due to the localized character of the deformation material is not being pulled into the forming zone from the surrounding area. Consequently any increase of surface area can only be obtained by stretching, and as the favourite strain state is plane strain we are facing the worst possible scenario. Would the material indeed be subjected to the conventional forming limits as expressed in the FLC, hardly any product could be made. But due to these special conditions with the aid of the incremental character itself it is possible to manufacture a variety of products. Even more, due to the localization of forming a freedom of shapes is obtained unprecedented in conventional stamping.

The process is slow compared to conventional stamping, but particularly suitable for prototyping as no expensive die is required. Assuming that the manufacturing of a single part takes 'just' a few hours, it should be possible to create a complete car body mock-up at full size from metal sheet using a fast ISF machine, directly from 3D CAD files, say, in a week.

5. REFERENCES

1. W.C. Emmens, A.H. van den Boogaard: "An overview of stabilizing deformation mechanisms in incremental sheet forming", J. of Material Processing Technology, in press, doi:10.1016/j.jmatprotec.2008.10.003.
2. J.M. Allwood, D.R. Shouler: "Generalised forming limit diagrams showing increased forming limits with non-planar stress states", Int. J. of Plasticity, in press, doi:10.1016/j.ijplas.2008.11.001.
3. W.C Emmens, A.H. van den Boogaard: "Extended tensile testing with simultaneous bending", Proc. IDDRG 2008 Int. Conf., Olofström, Sweden, June 16-18 2008, pp 219-229.
4. J. Z. Gronostajski: "The effect of zinc coating thickness on the formability and corrosion resistance of sheet steel", Proc. 16th IDDRG congress, Borlänge, Sweden, 1990.
5. K.Yoshida, T. Kuwabara, M. Kuroda: "Path-dependence of the forming limit stresses in a sheet metal", Int. J. of Plasticity 23 (2007) 361-384.

6 P. Eyckens, S. He, A. Van Bael, P. Van Houtte, J. Duflou: "Forming Limit Predictions for the Serrated Strain Paths in Single Point Incremental Forming", Proceedings Numiform 07, June 17-21, 2007, Portugal, AIP CP908, pp 141-146.

7 L. Vihtonen, J. Tulonen, J. Tuomi: "Incremental sheet forming with an industrial robot as a method for sheet forming prototyping and small series manufacturing"; Proc. IDDRG 2008 Int. Conf., Olofström, Sweden, jun 16-18 2008, pp 521-532.

8 P. Eyckens, A. Van Bael, R. Aerens, J. Duflou, P. Van Houtte: "Small-scale Finite Element Modelling of the Plastic Deformation Zone in the Incremental Forming Process"; Proceedings Esaform, Lyon, France, April 23-25 2008, paper 333.

9 K. Jackson, J. Allwood: "The mechanics of incremental sheet forming", J. of Material Processing Technology, 209 (2009) 1158-1174.

10 A. Taraldsen: "Stabilized tensile testing (i.e. without local necking)", Materialprűfung, vol 6 (1964), nr. 6, pp 189-195.