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Review

An overview of stabilizing deformation mechanisms in incremental sheet forming

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ABSTRACT

In incremental sheet forming (ISF) strains can be obtained well above the forming limit curve (FLC) that is applicable to common sheet forming operations like deep drawing and stretching. This paper presents an overview of mechanisms that have been suggested to explain the enhanced formability. The difference between fracture limit and necking limit in sheet metal forming is discussed. The necking limit represents a localized geometrical instability. Localized deformation is an essential characteristic of ISF and proposed mechanisms should stabilize the localization before it leads to fracture. In literature six mechanisms are mentioned in relation to ISF: contact stress; bending-under-tension; shear; cyclic straining; geometrical inability to grow and hydrostatic stress. The first three are able to localize deformation and all but the last, are found to be able to postpone unstable growth of a neck. Hydrostatic pressure may influence the final failure, but cannot explain stability above the FLC.

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1. Introduction and scope

The last decade has shown an increasing interest in a new class of forming processes known as incremental sheet forming (ISF). The name incremental forming is used for a variety of processes, all characterized by the fact that at any time only a small part of the product is actually being formed, and that area of local deformation is moving over the entire product. This definition covers many processes, including spinning but also for example rolling. The paper will however focus on incremental sheet forming that is generally carried out by having a small steel punch drawing consecutive overlapping contours over the sheet with increasing depth, thus creating a part of some depth. These processes have originated in Japan in the early 1990's (see Iseki et al., 1993) and are discussed extensively in the overview paper by Jeswiet et al. (2005).

It was noticed from the beginning that ISF allows sheet metal to be stretched much further than in conventional stamping operations, well beyond the common forming limit curve (FLC), see for example Iseki et al., 1993. This is widely recognized and accepted, but only few publications try to explain this behaviour. Often, the enhanced formability is simply attributed to the localized character of the deformation but without an explanation.

Basically two questions arise:

- A: Why is the deformation localized to a small zone in ISF operations?
- B: Why is the operation not limited by the instabilities that limit common stamping operations?

This paper gives an overview of deformation mechanisms found in literature that are suggested to explain the enhanced formability in relation to the localization of the deformation. For every mechanism, it is discussed how, and under which conditions it may avoid the limits of ordinary sheet forming. If available, experimental evidence for a mechanism is presented and the relevance for ISF is assessed. Also the mechanisms will be discussed in the view of localization of the deformation. The word 'mechanism' in this respect is used in a very wide sense.

In dealing with formability in ISF it can be asked: what mechanism finally limits the process? This aspect of deformation mechanisms is fundamentally different from the ones mentioned above, but in practice they are hard to separate. If the mechanism that lifts the formability above the FLC fails to operate by whatever reason, the material is likely to fail as well as it is already stretched beyond the stability limit. Nevertheless, failure mechanisms in general, and thus the final formability limit are not addressed in this paper.

ISF has still several variants: negative or positive, single point incremental forming (SPIF) or two point incremental forming (TPIF), etc. In this paper a distinction between these variants will generally not be made, with only one exception. It may be assumed that in a practical ISF operation several mechanisms are at work at the same time, but the relative contribution of each will not be discussed.

The paper follows the terminology that is conventional in sheet metal forming: σ_{33} is the normal stress perpendicular to the sheet surface, and σ_{11} and σ_{22} are normal stresses parallel to the surface. Note however that σ_{11}, σ_{22} and σ_{33} are not necessarily principal stresses in the material. In some sections reference is made to the von Mises yield function, which for the general situation is

$$2\sigma_f^2 = (\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2 + 6(\tau_{12}^2+\tau_{23}^2+\tau_{31}^2) \quad (1)$$

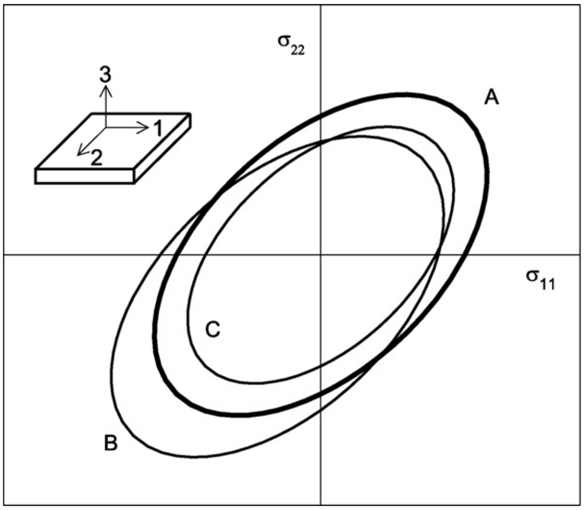

Fig. 1. Effects on the von Mises yield locus, σ_{11} and σ_{22} are orthogonal stresses parallel to the sheet surface. A = standard locus as used in traditional sheet metal forming ($\sigma_{33} = 0$, $\tau = 0$); B = effect of contact stress ($\sigma_{33} < 0$, $\tau = 0$); C = effect of shear ($\sigma_{33} = 0$, $\tau \neq 0$). The insert defines the directions 1, 2 and 3.

where σ_f is the flow stress, and τ_{ij} the shear stresses (see Fig. 1). This equation serves as an illustrative example, but the arguments in the following sections are by no means limited to the von Mises yield function.

2. Plastic instabilities

2.1. Forming limits in conventional stamping

Any metal that is continuously being deformed will finally fail. The continuous deformation creates more and more dislocations that move through the material, interact with each other and create voids that finally result in a crack. The limit strain before failure is called the fracture limit and depends on the stress state: a high level of hydrostatic compressive stress squeezes the voids and slows down damage development. This is the reason why forming processes that are largely compressive of nature like rolling and wire drawing can create large levels of strain in the material without causing damage. This is contrary to processes that operate largely in tension. Forming processes operating largely in tension like conventional stamping can also be limited by another phenomenon: instabilities. Instabilities do create a situation that the deformation gets concentrated into a small region (the neck) with the result that the remainder of the product does not deform any further. This limits the amount of deformation that can be generated in a practical forming operation, the limit is conveniently called the necking limit. Because of the small size of the neck, even small extra displacements will generate large additional strains and the material will soon reach the fracture limit and fail. The large deformations in the neck are not practically relevant because they cannot be controlled and, because of the small size of the neck, they do not contribute to the shape of a product.

The best known example of a necking limit is the conventional forming limit curve. Fig. 2 schematically presents the relative position of the FLC and also of the fracture limit as for example measured for steel and aluminium. An actual example are the curves measured by Embury and Leroy for Al 5154 that are presented both by Atkins (1996) in his study on fracture in forming, and by Hosford and Duncan (1999) in their review article on sheet metal forming. Fig. 2 illustrates the experience that for most ductile metals, the necking limit is much lower than the fracture limit. This leads to

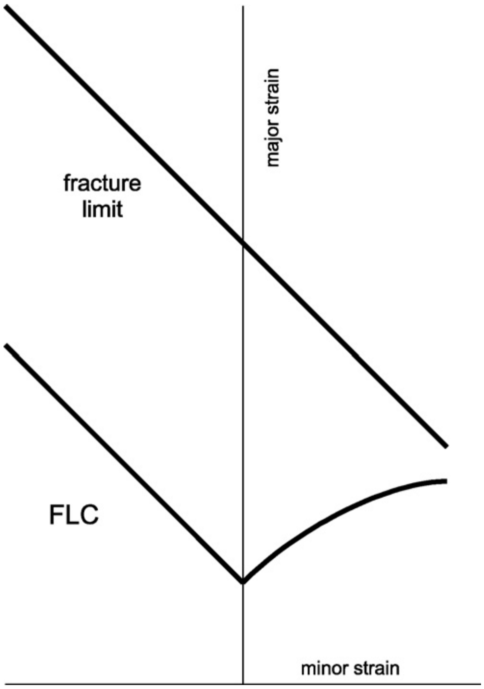

Fig. 2. Schematic presentation of the necking limit (FLC) and the fracture limit.

an important conclusion: the formability of a material in a forming operation can be increased significantly if one is able to get rid of the instabilities.

It is known that the FLC is only valid under certain restrictions. These are

(1) the strain path should be straight (proportional loading),
(2) the deformation is dominantly caused by membrane forces (absence of bending),
(3) through-thickness shear is negligible, and
(4) a situation of plane stress exists ($\sigma_{33} = 0$).

These conditions look severe, but many practical forming operations operate closely enough to these conditions to justify practical use of the FLC. In ISF, however, all four conditions are violated as will be shown in the following sections.

2.2. Stabilization of necking in ISF

In ductile metals, much 'deformation potential' is available if the necking instability can be avoided or postponed or the growth rate of a neck is reduced. Apparently, at least one of these causes is active in ISF. This means that in the material special situations have to be created.

The observation that at any moment the deformation is localized is by itself no explanation for the enhanced formability in ISF. On the contrary, in classical sheet forming localization is synonymous with necking and instability. This is due to the fact that the necking zone requires the lowest force to elongate. Once a neck is originated it will remain the weakest point.

Another aspect of ISF is that the zone of localized deformation moves with the tool over the sheet. One might argue that high deformations in ISF are obtained because the neck cannot grow into a crack, since the tool is already in another place before the fracture limit is reached. This explanation is not completely satisfying, because it does not explain why a neck once generated will not keep growing, if it is still under tension.

ISF as a practical sheet metal forming process works if the deformation is localized into a small zone, *and* if in that zone a special situation exists that suppresses or retards necking. At the same time, outside that zone the situation must be such that if a neck is generated inside the zone it will not grow. This effect of stabilization can be achieved in two ways: the stress at the location of the neck is reduced to below the level that is required for further growth, or the situation at the originated neck is changed such that the stress needed to develop the neck any further is raised above the level of local stress. The latter phenomenon requires that the effect of the mechanism that causes localized deformation must be reversible.

In literature, a number of mechanisms have been suggested to explain the enhanced formability in ISF, notably the combination of stretching with shear forces, normal forces or bending forces, cyclic or non-proportional deformation paths, too small deformation zones and hydrostatic compressive stresses. Apart from the last two, all suggested explanations indeed violate the conditions for which the standard FLC is supposed to give a valid forming limit.

In the following sections, the suggested mechanisms will be discussed in view of the localization and stabilization considerations. It will be assumed that if a sheet is deformed in tension mainly, a local reduction of the yield force will also localize the deformation.

For all mechanisms their theoretical ability to avoid or postpone necking or reduce the growth rate and their relation with ISF will be assessed. If available, experimental evidence of the stabilizing effect will be presented.

3. Effects of shear

This section reviews shear as a stabilizing mechanism. It starts with an explanation of the principle of the mechanism, followed by the relation to ISF and a review of testing.

3.1. Principle

In terms of stability, simple shear would completely avoid necking, because no tensile force is applied in the plane of the sheet. However of more relevance is shear superposed on stretching of the sheet.

An additional shear stress will lower the yield stress in tension. This follows directly for example from the von Mises yield criterion presented above, and the effect is graphically presented in Fig. 1. If a sheet is stretched to a level just below the flow stress, even a relatively small additional shear stress may be sufficient to start plastic deformation. This shows that an additional shear stress is capable to localize deformation. If the shear stress is caused by a tangential displacement, e.g. by tool movement, the shear stress cannot be sustained if a neck starts to grow. Without a shear stress, the in-plane yield stress increases again and the deformation mechanism is stable until the in-plane stress is high enough to deform the sheet plastically even without additional shear stress.

The result of this stabilizing effect is that it raises the necking limit; the latter defined as the length strain at the onset of necking. This has been shown by Tekkaya in an elaborate analysis, and some results are presented in Fig. 3 (Tekkaya and Allwood, 2006). This figure shows how the yield stress in tension (bottom line) and the necking limit (upper line) are affected by an additional shear stress, the latter expressed as the ratio between shear stress and the material's flow stress.

Eyckens has investigated the effect of through-thickness-shear on the FLC by carrying out an MK-type analysis and found that the presence of shear can raise the FLC significantly, but depending on the orientation of the shear (Eyckens et al., 2008b).

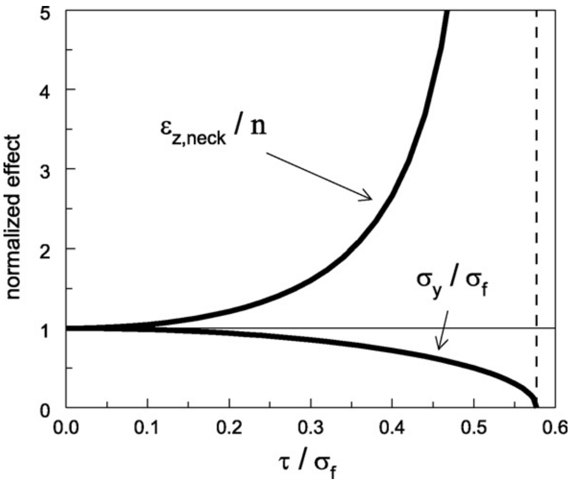

Fig. 3. Effects of additional shear stress on formability. Bottom line: normalized yield stress in tension σ_y; upper line: normalized length strain at onset of necking ε_z. σ_f = flow stress, τ = shear stress, n = hardening coefficient. Graph constructed using results presented by Tekkaya and Allwood (2006).

3.2. Relation with ISF

In literature the effect of shear on formability in ISF has been described in different ways. Contrary to deep-drawing, in ISF a product is made without the flow of new material from a blankholder area. This means that the product is made by 'stretching' (in a wider sense) and that the material is elongated in at least one direction and thinned. In the early days it has been suggested that this 'stretching' is done mainly by out-of-plane shear (see Fig. 4 for definition). This suggestion was not based on experimental evidence, but intuitively by drawing a parallel with shear-spinning. However recent detailed experimental investigation has showed that this suggestion is false, see for example Jackson and Allwood (2009).

An early mentioning of through-thickness shear in the direction of punch movement (see Fig. 4 for definition) was done by Sawada as a conclusion of FEM simulations. In fact this study was one of the first to investigate in detail the forming of the sheet around the punch contact (Sawada et al., 2001).

Bambach has also noticed the occurrence of shear in his simulation of ISF, and observed that the level of shear depends both on the punch head diameter and the vertical pitch (Bambach et al., 2003).

Jackson has detected the presence of through-thickness shear in the direction of punch movement experimentally by measuring the relative displacement of both surfaces of a sandwich panel in SPIF (Jackson et al., 2007), and by a rigorous measurement of a cross section of a 3 mm thick copper plate in both SPIF and TPIF (Jackson and Allwood, 2009). Some shear was also detected across the direction of punch movement. Eyckens has detected the presence of shear by drilling small holes in the sheet and measuring their orientation after forming. He also observed shear in the direction of punch movement, but little or none in the perpendicular direction (Eyckens et al., 2008b).

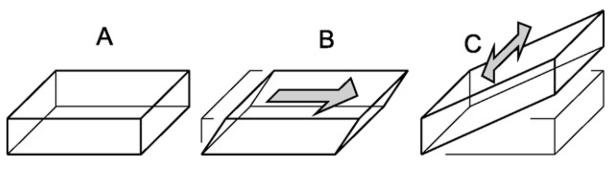

Fig. 4. Definitions of shear as occurring in ISF. (A) Undeformed part of the sheet. (B) Through-thickness shear as observed in the direction of punch movement. (C) Out-of-plane shear as originally proposed to occur in ISF. The arrows indicate the direction of punch movement.

Allwood has explained the observed enhanced formability in ISF as due to the presence of through-thickness shear (Allwood et al., 2007).

Besides the shear that can be detected in the finished product, it must be taken into account that shear can also take place during the process in an intermediate stage, without showing up in the finished product.

3.3. Testing

No tests are known to investigate the stabilizing effect of this mechanism quantitatively, but Allwood has proposed a new class of forming processes based on this called 'paddle forming', and has achieved high levels of uniform straining (Allwood and Shouler, 2007).

4. Effects of contact stress

This section reviews contact stress as a stabilizing mechanism following the same structure as Section 3. It starts with an explanation of the principle of the mechanism, followed by the relation to ISF and a review of testing.

4.1. Principle

Contact stress refers to a compressive stress normal to the surface of the sheet caused by the contact with the tool. This happens in all situations where the sheet makes contact with a tool, but it is often more severe if the radius of the tool is small. A distinction must be made between single-sided and double-sided contacts. In a single-sided contact (as on the die radius in deep-drawing) the contact stress varies over the thickness of the sheet. At the actual contact it has a maximum, but on the other side of the sheet it is zero. Only in a two-sided contact where the material is actually clamped a proper through-thickness stress can arise. No analysis has been found that deals with single-sided contacts.

An additional contact stress will lower the yield stress in tension. This follows directly for example from the von Mises yield criterion presented above, and the effect is also graphically presented in Fig. 1. The effect on localization and stabilization is equivalent to the effect of additional shear stress. At the point of contact the in-plane flow stress is slightly reduced, causing localized deformation and if the incipient neck would grow too much, contact will be lost or at least reduced, increasing the in-plane flow stress and avoiding unstable growth.

The common FLC is measured at the condition of plane stress (absence of contact stress), but the effect of contact stress on the FLC has been the subject of several investigations. Smith has developed an analytical model that predicts the effect of contact stress on the position and shape of the FLC (Smith et al., 2005). In his paper, he compares his result to those obtained by Gotoh et al. (1995) and has found a significant discrepancy in the magnitude of the effect. Some results of both models are presented in Fig. 5 that shows the effect on the strain at onset of necking at plane strain conditions, note that the Smith model depends on the material's hardening coefficient n. Whichever may be correct, both models predict that the presence of contact stress will raise the FLC and consequently the formability of the material. Banabic has carried out a detailed MK-type analysis on the effect of contact stress and also observed a raise of the FLC (Banabic and Soare, 2008). Result of an analysis of Aluminium 3014-H19 are presented in Fig. 5 as well, but the data

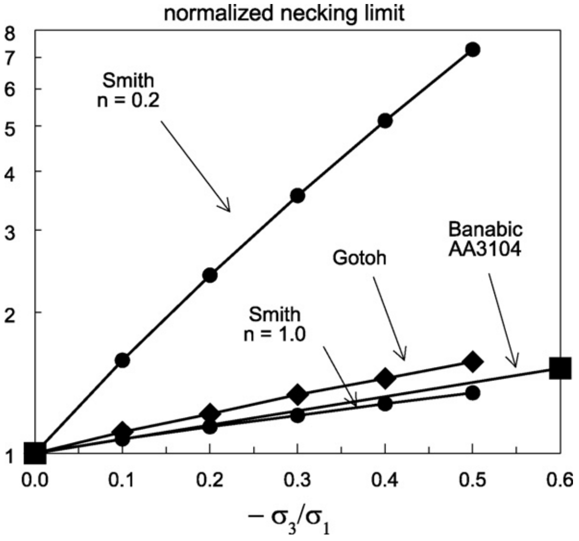

Fig. 5. Effect of contact stress on formability by three models. σ_3 = contact tress, σ_1 = conventional major stress, n = conventional hardening coefficient. Graph constructed using results presented by Smith et al. (2005), and by Banabic and Soare (2008).

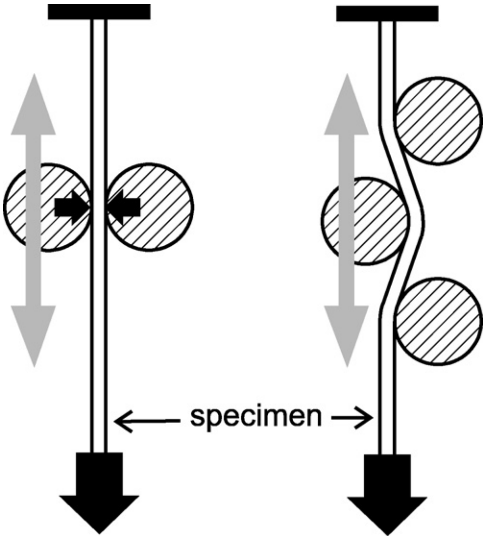

Fig. 6. Two adapted tensile tests for obtaining high levels of uniform straining. Left: Taraldsen test, right: CBT test.

have been converted here and should be regarded as estimates. There is a reasonable good agreement with the Gotoh model.

4.2. Relation with ISF

In ISF mostly single-sided contacts are encountered. Double sided contacts can only arise in TPIF with a full die, or in so-called 6-axis ISF with a movable counter-punch, of course depending on the experimental conditions.

Bambach has observed high levels of contact stress in his simulations and concluded that it may be of influence on the occurrence of hydrostatic stress in ISF (Bambach et al., 2003). Eyckens has carried out ISF simulations that also show high levels of contact stress but does not draw conclusions from that (Eyckens et al., 2008a).

Recently only Huang made a direct relation between the enhanced formability in ISF and the presence of contact stress, based on the aforementioned work by Smith (Huang et al., 2008).

Silva has presented an elaborate analysis of the ISF process based on membranes. This analysis cannot distinguish between a single-sided and two-sided contact but assumes through-thickness stress (Silva et al., 2008). The contact stress is introduced in this model by stretching of the sheet over the punch radius. Examination of Silva's formulae reveals that the yield stress in tension is reduced by the contact stress, see the Eqs. (10), (11) and (14).

If indeed the contact stress in ISF is caused by the bending of the sheet around the punch, it may be assumed that the stress increases with increasing sheet thickness and decreasing punch radius. Assuming this mechanism to operate this would mean that the formability also increases by that, and this is in agreement with general observations. An extension of the analysis of Silva by Martins predicts the same (Martins et al., 2008).

4.3. Testing

The effect of contact stress on formability can be tested effectively by adapted tensile tests as originally proposed by Taraldsen (1964). Taraldsen has developed this test with the sole purpose to overcome the instability that normally limits the tensile test. The test method is basically a normal tensile test with a set of two rolls that continuously move up and down along the specimen and is presented schematically in Fig. 6, note that this is a proper example of a two-sided contact. The level of contact stress at the roll contact is typical 1–10% of the material's flow stress. Taraldsen used octagonal and square rods and has obtained uniform strains of up to 600% with OFHC copper, but the test method can be used on strip as well as has been shown by Rijken (1965). Olejnik has used this test to obtain high levels of uniform straining in his research on damage development and obtained strains of 590% with mild steel (Rosochowski and Olejnik, 1988).

5. Bending-under-tension

This section reviews bending-under-tension (BUT) as a stabilizing mechanism following the same structure as Sections 3 and 4. It starts with an explanation of the principle of the mechanism, followed by the relation to ISF and a review of testing.

5.1. Principle

Bending-under-tension refers to the simultaneous bending and stretching of a sheet. This situation is well known in stamping as it occurs for example when in deep-drawing the sheet is pulled over a draw-bead; the mechanism is treated in text books extensively, see for example Marciniak et al. (2002).

BUT as a mechanism is principally different from shear and contact stress. Shear and contact-stress do change the stress state of the material, but in BUT the stress state is not changed. The integrated stress over the thickness (the tension force per unit width) is reduced as some part of the thickness is compressed, in a pure bending operation half of the thickness. There is another fundamental difference. Shear and contact-stress are basically static situations. BUT however is based on the fact that the zone of deformation moves, or in other words: the moving punch causes the strip to be bent and unbent continuously. BUT does not work because the sheet has been bent, it works only when the sheet is being bent.

BUT means simultaneous bending and stretching so the stress is not uniform over the thickness of the sheet. The tensile force depends both on the stretching strain e (strain of the centre fibre), and the bending strain e_b (strain of the outer fibre in pure bending), the latter defined as $e_b = t/2R$, where t is the sheet thickness, and R the bending radius of the sheet centre. The effect of stretching on the tension force is presented in Fig. 7; this figure has been derived

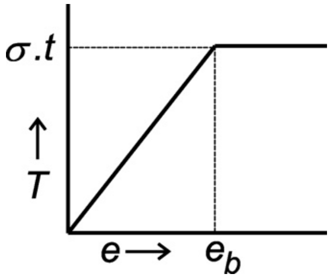

Fig. 7. Basic effect of BUT. The graph shows the relation between tension per unit width T and elongation e, under conditions of constant bending radius. $e_b = t/2R$, t = sheet thickness, R = bending radius, σ = material flow stress.

for an idealized condition, but the conclusions do not change in a more practical situation. The figure presents the relation between tension force per unit width T and the elongation e, for a situation of constant bending radius R. The figure shows that for small elongations ($e < e_b$) the tension force is reduced, which means that the mechanism can trigger localized deformation. Furthermore, for small elongations the tension force increases with elongation, creating a situation of stable elongation. The length of this stable regime is equal to $e_b = t/2R$, linking the formability created by this effect directly to the sheet thickness.

This reveals a third fundamental difference. Both shear and contact-stress just raise the formability to a certain level depending on the level of shear stress or contact stress. However BUT creates a small regime of stable deformation at *every* pass of the tool. As long as the strain increment e stays within that regime the deformation remains stable and can be repeated on and on.

5.2. Relation with ISF

Sawada has proposed BUT as a mechanism to operate in ISF based on his simulations (Sawada et al., 2001). The first author of this paper has also proposed this mechanism to operate in ISF based on can shaping experiments carried out at Hoogovens R&D in the late 1990's, inspired by the observed proportionality between formability and sheet thickness (Emmens, 2006).

BUT is a true dynamic phenomenon, it only occurs when the material is actually moving around the punch. As such its occurrence in an actual ISF operation is difficult to establish directly. However it is obvious that in ISF the material is being bent near the tool and being stretched (at least in some directions) so it is save to assume that BUT will occur to some extent. The mechanism predicts an additional stabilizing effect proportional to t/R, meaning that enhanced formability created by BUT will increase with increasing sheet thickness and decreasing punch radius. This is in agreement with general observations.

5.3. Testing

BUT can be tested in several ways. A well-known way is to perform a single 90° bend over a radius with back tension; this is often used in tribology research. A relation with ISF is better found in tests with repetitive bending as in the so-called 'Continuous Bending under Tension test', as originally developed by Benedyk et al. (1971). This test looks like the Taraldsen test, but instead of a pair of clamping rolls a set of three rolls is moving up and down the specimen, as in a three point bending test, see Fig. 6. This test has been used by the authors of this paper to study the mechanism extensively, and uniform elongations of up to 430% have been obtained with mild steel (Emmens and van den Boogaard, 2008). The test involves 2D bending, but it can be shown that in a 3D bending situation as in an actual ISF process the mechanism is also likely to occur, as the basic relation that is shown in Fig. 7 does not change significantly.

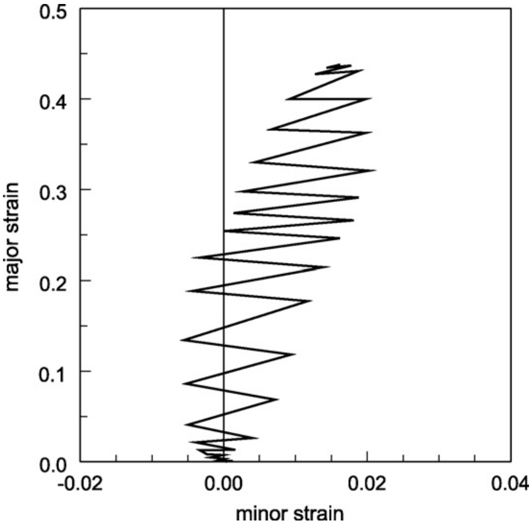

Fig. 8. Example of cyclic strain history (schematic); graph constructed using data obtained by Eyckens et al. (2007).

6. Cyclic effects

In a practical ISF operation the punch passes a certain material point several times, up to a few dozen. Each pass causes bending and unbending with possible strain reversal so the material is subjected to cyclic straining, see Fig. 8. Bambach has noticed this cyclic straining and the possible effect on material behaviour, and suggests that this "motivates further investigation of the process using a constitutive law that takes into account path-dependent damage" (Bambach et al., 2003). Eyckens has made the same observation and used the strain paths from his simulations to carry out a Marciniak–Kuczynski analysis. This indeed showed "a trend of high formability . . . when a physical-based hardening model is used that accounts for anisotropic hardening at strain path changes" (Eyckens et al., 2007). The conclusion is that cyclic effects indeed can enhance the formability, but a detailed investigation requires the development of sophisticated material models.

This mechanism should not be confused with the previously mentioned bending-under-tension. BUT involves repetitive bending but not necessarily cyclic, as the stress distribution over the thickness is fundamentally inhomogeneous. The stabilizing effect of cyclic loading, involves cyclic straining but not necessarily bending and the stress distribution over the thickness may be homogeneous. In a practical situation these mechanisms will be hard to separate, but their effects are fundamentally different.

7. Other mechanisms

This section presents some mechanisms that have been proposed in the literature but are not discussed there extensively.

7.1. Restriction of neck growth

Martins has examined fractured ISF products and noticed that there was no sign of an actual neck. He then proposed that the absence of a neck is due to the fact that necks do not have the ability to grow (Martins et al., 2008). The latter is based on careful examination of the geometry of the zone of localized deformation as used in the analysis presented by Silva and determining the place where a neck is likely to develop. However, the small zone of localized deformation is embedded in a surrounding area that experiences considerable lower stress and inhibits neck growth. This means that in short the zone of localized deformation is simply too small for a neck to develop.

7.2. Hydrostatic pressure

Hirt has proposed that the observed enhanced formability is caused by the occurrence of hydrostatic pressure, at least partially. Hydrostatic pressure is proposed to be the result of the localization of the deformation zone, notably the constraints created by the elastically deforming surrounding material (Hirt et al., 2002). Bambach has investigated this further and concludes that considerable back stresses are expected from the elastic surroundings. He further suggests that the observed hydrostatic pressure may also be caused by the high levels of contact stress (Bambach et al., 2003).

Also Martins has related the increased forming limits in SPIF as compared to conventional stamping to the reduced triaxiality ratio, the latter slowing down the rate of accumulated damage (Martins et al., 2008).

Indeed there is a relation between the origin of hydrostatic pressure and the local geometry as discussed here, and the contact stress as discussed above. The single observation of hydrostatic pressure, however, does not stabilize the plastic deformation process, because the hydrostatic stress is commonly assumed not to influence plastic deformation in metals. There is a well-known effect on the evolution of voids and this will have an effect on the fracture limit, but it cannot explain stable deformation above the FLC.

8. Final discussion

In the previous sections several mechanisms have been discussed that may enable stable deformation above the FLC. The mechanisms are based on theoretical considerations and some of them have been validated experimentally. The relation between the mechanisms and ISF was ascertained and it can safely be assumed that if the isolated mechanism explains stability it will also contribute to the stability of deformation in ISF. The question which mechanism plays a major role and which contribution is only marginal cannot be answered at the moment and it is reasonable to believe that the answer will depend on process parameters like sheet thickness, tool radius, lubrication and material behaviour. It is important to keep an open mind and not to judge too quickly ‘it is this *or* that mechanism’.

The goal of this paper is to give an overview of mechanisms that are able to stabilize deformation in ISF, such that the classical FLC can be overcome. Further research is necessary to determine which mechanisms are of major relevance under particular process conditions. For that, it is necessary to quantify the stabilizing effects of the single mechanisms separately.

To guide future research, a classification of mechanisms may be useful. Two aspects are distinguished: localization and stabilization.

The formulation ‘local reduction of the tensile yield force’ is introduced. By this is meant the flow force in tension in the plane of the sheet needed for plastic deformation. The term force is used here deliberately as, for example, in bending-under-tension the actual stress varies over the thickness of the sheet, and the integrated stress (=tension force per unit width) determines the characteristics of the process.

Localization of deformation can be due to:

- geometric effects,
- local reduction of the tensile yield force.

Geometric effects are for example apparent in a point loaded membrane. In every point only membrane forces act (at least theoretically) and the stresses are the highest near the loading point, which is a singularity. Clearly, plastic deformation will be localized near the loaded point. To avoid the singularity and consequently direct plastic collapse, the point load must be substituted by e.g. a sphere, which will also introduce local bending, shearing and contact stresses.

Stabilization of deformation can be performed by

- reversible local reduction of the tensile yield force by:
    - reduction of the in-plane flow stress
    - introduction of a gradient in thickness direction
- mechanisms that change the material behaviour compared to monotonic proportional loading situations.
- mechanism that geometrically restrict the growth of a neck.

Local reduction of the tensile yield force only stabilizes the deformation if the reduction is relaxed ‘automatically’ upon further deformation. This is generally the case if the method to reduce the yield force is mainly displacement controlled, e.g. by a prescribed tool path. If this is the case, local reduction of the yield force can both initiate and stabilize local deformation. The material behaviour based stabilization and the geometrical restriction of growth however depend on other mechanisms to start localization of deformation.

The main message of this paper is that there are several mechanisms, some very well documented, that are capable of lifting the formability above the conventional forming limit curve, and that are related to typical aspects of incremental sheet forming.

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