Formability in Incremental Sheet Forming and Cyclic Stretch-Bending

W.C. Emmens, A.H. van den Boogaard*

University of Twente, dept CTW; P.O.Box 217, 7500 AE Enschede, the Netherlands

* Corresponding author: E-mail address: a.h.vandenboogaard@utwente.nl; Tel.: +31 53 4894785

Abstract

Bending is investigated as a mechanism operating in Incremental Sheet Forming (ISF). Bending-under-tension (stretch-bending) suppresses instabilities and raises the formability of sheet metal. Effects on forming limits are investigated using adapted tensile tests with simultaneous bending. The results are compared to what has been observed in actual ISF operations, notably concerning effects of sheet thickness, tool radius and step-down. Also fatigue is discussed. Many similarities are observed, substantiating the role of bending in ISF

Keywords: Incremental Sheet Forming, Cyclic Stretch-Bending, Formability

Introduction

It is a well established fact by now that in Incremental Sheet Forming (ISF) levels of deformation can be achieved well above the conventional Forming Limit Curve (FLC). Several mechanisms have been proposed that are able to raise the formability: shear, contact stress, bending and cyclic effects; an overview has been presented in another paper by the authors (Emmens and van den Boogaard, 2009a). All these occur in ISF to some extent, see **Fig.1**.

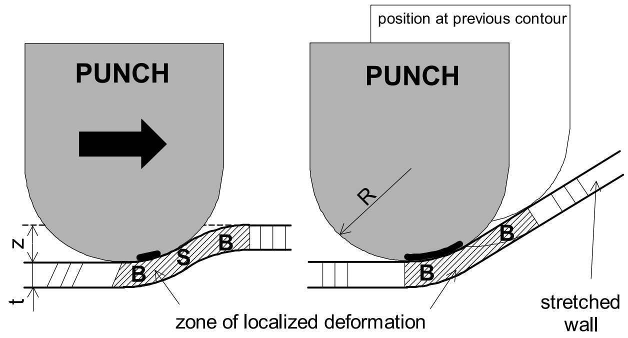

Figure 1. Situation around the punch contact in ISF in two perpendicular orientations, schematically. The thick line denotes the area of high contact stress, B denotes bending, S denotes shear, the triple cross section lines indicate stretch or shear. The arrow indicates the direction of punch movement..

Less attention however has been paid to the actual mechanisms that do limit ISF operations, or at least can limit the process. Silva et al (2008) have addressed this problem. They observed no visible necks and concluded that ISF is not limited by necking; the absence of necks is attributed to their inability to grow. They further proposed that the process is limited by damage, the increased formability being related to the low triaxiality ratio. However the detailed analysis presented by Silva et al. is based on membranes, and "bending effects were only indirectly included". The present paper will focus on bending as a mechanism that can raise the formability. The effect of bending is studied by adapted tensile tests, and the observed relations will be compared to those observed in ISF, notably regarding parameters that affect formability.

Formability in ISF

The main factors that are influencing the formability in ISF, besides the material grade and the tool path, are: sheet thickness, tool radius and vertical step increment (step down, pitch). These parameters are frequently studied in a large context using DOE that however obscures the results. Direct measurements where all other parameters are kept constant are more rare. The following presents the results found in over 400 papers, some of these results appear in more than one paper. Note that the data may have been converted, or present mean values, or have been read from graphs, restricting the accuracy. The results will be discussed farther below.

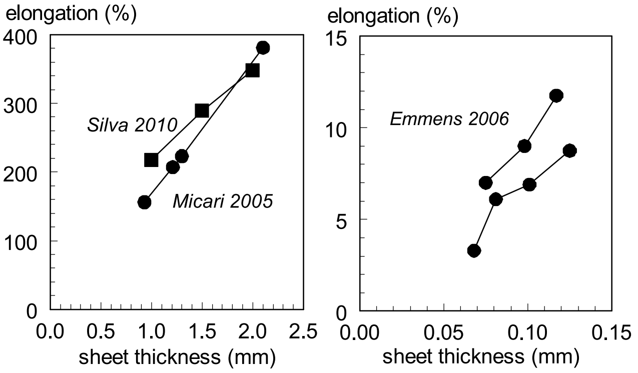

Figure 2. Effect of sheet thickness on formability in ISF. Left: ISF with steel punch, right: ISF with a high-pressure water jet.

Sheet thickness. It is commonly accepted that increasing the sheet thickness increases the formability. Direct measurements however are rare, as this requires a set of materials of different thickness but with identical mechanical properties. Only two series for ISF with a punch have been found, these are presented in **Fig. 2,** left, showing the total elongation. A special case is ISF with a high-pressure water jet. The omission of a metal tool eliminates friction forces, and limits the normal surface pressure in the forming zone, so favouring bending. Results obtained from can-shaping experiments are shown in **Fig. 2**, right.

Tool radius. It is also commonly accepted that decreasing the tool radius increases the formability. Effects of tool radius are easier to study, and more results can be found in literature. But again, direct measurements are not common. Results are presented in **Fig. 3**.

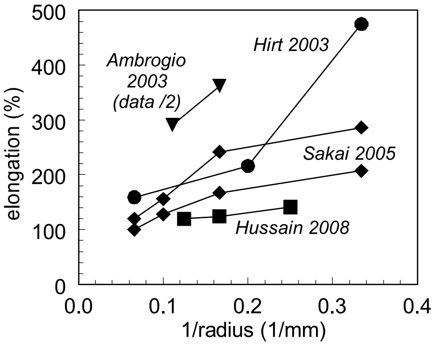

Figure 3. Effect of tool radius on formability in ISF. The Ambrogio data have been divided by 2 for layout reasons.

Step down. It has been claimed by several authors that decreasing the step down will increase the formability, but the results found in literature are far from conclusive. Changing the step down is relatively easy to do, but nevertheless direct measurements are not common. Results that have been found are presented in **Fig. 4** that shows the logarithmic strain, not the elongation. The relative step down in the Obikawa results is defined as the step down divided by the sheet thickness.

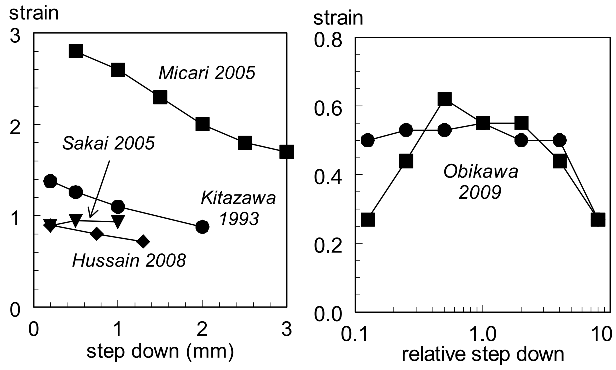

Figure 4. Effect of step down on formability in ISF.

Bending Under Tension

It is known that simultaneous bending can raise the formability of sheet metal. The underlying mechanism however is not fully clear. The contact stress at the tool contact changes the stress state raising the instability limit, but the effect of this is limited. Bending may also cause shear that has a similar effect. The formability can also be increased by *bending-under-tension* (stretch-bending). This is a situation where the bending is so severe that the fibres at the concave side are in compression. The effect however differs from that of for example shear. Simultaneous shear or contact stress changes the stress state in the material, this raises the instability limit to a higher value. This is an absolute increase of formability. Bending-under-tension however suppresses the instability as long as the elongation is not too large. As the fibres at the concave side are in compression, the pulling force is reduced without changing the flow stress, and this is the basis of the increased stability. The stable elongation may be small, but it occurs at every bending operation, so by applying multiple bending and reverse bending operations the formability can be raised to high levels.

The limit elongation in each bending operation depends on both the sheet thickness and the bending radius, to be more precise: the elongation is stable as long as:

$$e < e_b = t/2/R \tag{1}$$

where e is the elongation of the centre fibre, e_b the bending strain of the outer fibre, t the sheet thickness, and R the bending radius of the centre fibre. This condition is not limited to 2D situations, it applies in 3D situations as well as long as the compressed fibres reduce the tension force. Two situations can now be distinguished.

Constant radius. A situation of constant radius is for example encountered when the material is pulled over a radius at high forces, so that the bending radius is in fact the tool radius Noteworthy is that in that case the limit strain becomes proportional to the sheet thickness as can be deduced easily from equation (1).

Non-constant radius. In many cases the tension force is not high enough to pull the material tight over a tool radius, and the actual bending radius of the material is determined by an equilibrium between pulling force and bending moment. In that case the actual radius, and consequently the limit strain depends on the momentary pulling force, so in general on the experimental conditions. Equation (1) still applies, but as R is now a function of e the situation is more complex. This situation has been studied in detail using the so-called Continuous-Bending-under-Tension (CBT) test.

Description of the CBT test

The CBT test is in fact a conventional tensile test carried out on a large tensile test specimen, whilst at the same time a set of rolls (two or three) is continuously moving up and down this specimen; this is schematically presented in **Fig. 5**. The test method has been described in detail in Emmens and van den Boogaard 2009b. The main characteristic is that at any moment the deformation is concentrated into a number of small transverse zones, two for each roll. This makes the test an incremental forming operation, albeit only 2D. The bending of the strip by the rolls is considered to be bending-under-tension (hence the name of the test), meaning that the level of bending is so severe that at the concave side of the specimen the fibres are actually in compression. This effectively suppresses the instability that normally limits a tensile test. Uniform strains of 200% are easily obtained for several materials, strains of over 400% have been measured in a few occasions for mild steel. In the test the up/down speed of the roll-set was kept constant, and the pulling speed (cross-bar speed) is varied. Two types of test can now be distinguished. Obvious is a type of test where in a single test the pulling speed is constant, and the pulling force changes with elongation just as in a conventional tensile test. However it is also possible to keep the pulling force constant in a single test, and the pulling speed will vary with elongation instead. The mechanics of both types are the same, and the relations between force and speed are identical.

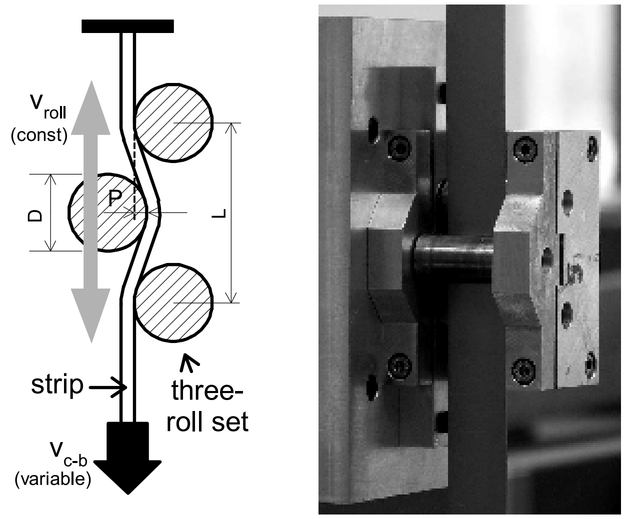

Figure 5. The test equipment. The specimen is held fixed at the top and is pulled downwards in the tensile testing machine. Left: schematic representation, right: picture of the roll set with a specimen mounted in position.

Results on formability

Formability can now be defined in two ways: 1: the maximum level of uniform strain that can be obtained by successive operations, and 2: the level of uniform strain that can be obtained in a single pass. These will be discussed separately. Note that only a minor part of all results is presented here; see Emmens and van den Boogaard (2011) for a complete overview.

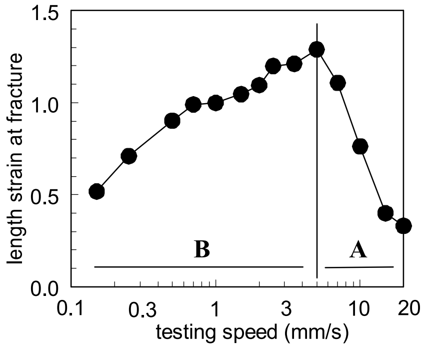

Figure 6. Length strain at fracture as a function of testing speed, a typical example. Material: mild steel.

Maximum elongation. Fig. 6 presents a typical collection of results obtained with constant speed tests, all with the same material and experimental settings. The graph shows two parts, a part where the strain at fracture increases with increasing speed, and a part where it decreases with increasing speed; in this example the transition is at 5 mm/s. The two zones are labelled A and B.

For all the experiments in this graph the recorded force-displacement curves have been converted into true-stress / true-strain curves. These curves are collected in **Fig. 7**, the kink at the end of the curves should be ignored. In this diagram the zones A and B form two very distinct forming limits, indicated by the two dashed lines. This suggests different failing mechanisms.

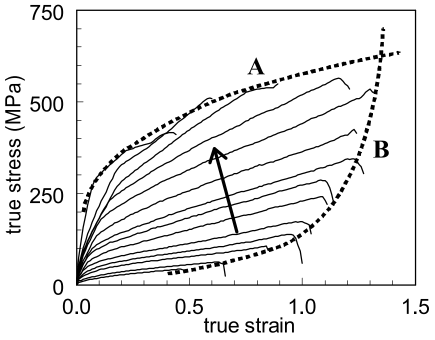

Figure 7. Collected stress-strain curves for the tests from **Fig. 6**. The arrow indicates the direction of increase of speed.

Further investigation revealed that limit A is caused by *instability*, and line A is the normal hardening relation of the material. During a test the material thins considerably, and finally the neutral line shifts out of the material. From that moment the test is a conventional tensile test, and, as the material has hardened considerably, this causes immediate failure. Limit B is a *damage* limit; microscopic examination shows that it is caused by low-cycle fatigue. This limit is highly dependent on the type of material, and is basically the reason that the maximum observed length strain shows strong material influences. Mild steel and stainless steel show excellent formability, dual-phase steel, titanium and yellow brass medium formability, and aluminium and leaded brass poor formability.

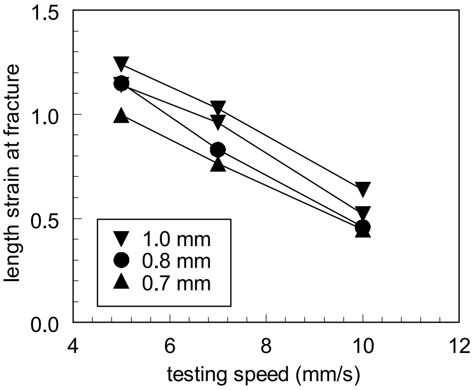

Figure 8. Effect of sheet thickness on fracture for limit A. Materials: mild steel DC04.

In view of the purpose of this paper it is more appropriate to look at limit A only. **Fig. 8** shows results obtained with some variants of mild steel DC04 with different thickness. The data are from samples of which the fracture morphology made it clear that fracture was indeed caused by instability. The data shows that, when tested under identical experimental conditions, thicker material shows larger formability.

Elongation in a single pass. In the CBT test the elongation in a single pass is equal to the ratio of cross-bar speed and roll-set speed. As the latter was kept constant in all tests, only the variations in the cross-bar speed need to be investigated. The following presents results obtained with constant force tests. A constant force was applied to the specimen, and the roll set was started. The speed *in the first stroke* was measured, and this was converted to the elongation per passage of a single roll (both are proportional). That is plotted in **Fig. 9a** as a function of relative force defined as the measured pulling force divided by the ultimate tensile force (UTF) of the material. This figure shows that there is a considerable difference between the various materials, for a certain relative force the strain increment varies more than a factor 2.

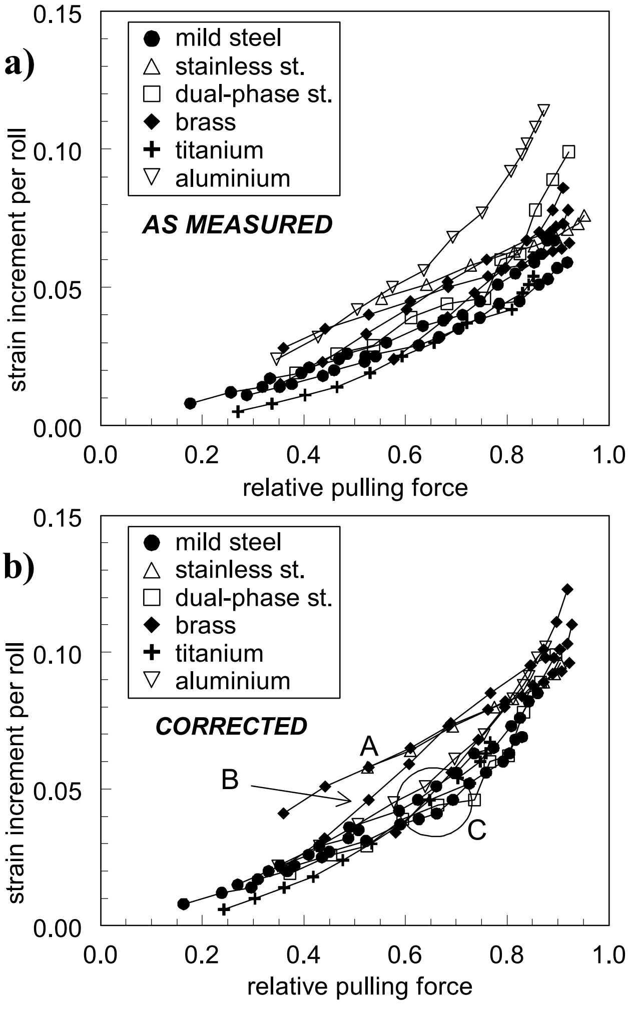

Figure 9. Strain increment per roll passage for a collection of materials. **a)**: as measured; **b)**: corrected as described in the text.

Detailed analysis reveals that there are a number of factors influencing the relation shown in **Fig. 9a**.

Strain-rate hardening. As the actual deformation is concentrated into a number of small zones, the actual strain rate in the CBT test is much higher than the apparent strain rate; a detailed analysis of the test showed that the strain rate is increased by a factor 100. This means that for materials showing strain-rate hardening like mild steel and titanium, the UTF should be corrected for that as in fact the UTF used in **Fig. 9a** is too low, so the relative forces are too high. This correction is based on an assumed power law strain-rate hardening relation, and the conventional strain-rate hardening coefficient m has been derived from the force maxima in tensile tests carried out at 0.2, 1 and 5 mm/s for each material. The correction is then: corrected-UTF = measured-UTF * 100^m.

Thickness. There is an influence of sheet thickness that is not understood. For a certain relative force thicker material shows larger strain increment, proportional to the thickness. This effect may not be obvious from **Fig. 9a**, but it is consistently present in all results, also those obtained from constant speed tests. A consequence is that when a certain strain increment is imposed, thicker materials require less force. Nevertheless, thickness primarily affects the strain increment. This effect can be eliminated by correcting the pulling speed (read: strain increment!) by: corrected-speed = measured-speed / thickness-in-mm.

The results shown in **Fig. 9a** have been *corrected* for both strain-rate and thickness, and the results are shown in **Fig. 9b**. The difference between the materials has been reduced clearly, but now a third effect becomes visible.

Work hardening. Both stainless steel 304 and soft yellow brass show high levels of work-hardening. In **Fig. 9b** these are presented by the two lines labelled A, barely distinguishable. Unless for very high levels of relative pulling force, these materials do show larger strain increments per roll passage. Half-hard brass has a medium level of work-hardening, this is presented by line B. For the other materials the result are identical within an acceptable range of scatter, group C.

This effect of work hardening was mainly present in the first stroke. In the subsequent strokes the material has already hardened, reducing both the absolute and the relative level of hardening. Consequently, for example, the mean strain increment per passage over a complete test showed no significant influence of work-hardening. However, ALL other results showed the same effect of strain-rate (obvious) and thickness (surprising), including those of constant speed tests. After correcting for these effects the results ALWAYS resemble that of group C in **Fig. 9b**, with the only exception the speed in the first stroke or any related data.

Discussion 1: comparison of results

Detailed simulations of ISF with a metal punch have showed that the sheet is pulled tight over the punch creating a situation of *constant radius*. Also, in the experiments referred to in **Fig. 2**, right, it was observed that the actual radius of curvature was highly independent of the sheet thickness, also creating a situation of constant radius. In such a situation the stabilizing mechanism of bending-under-tension predicts a formability proportional to the *sheet thickness*. The results shown in **Fig. 2** indeed show a very strong influence of thickness and in first approximation proportionality can be assumed. The right-hand figure showed results obtained by water-jet forming. In that case there is no shear and only minor contact stress, leaving only bending as the major mechanism. Indeed it was found that the absolute level of strain shown in **Fig. 2**, right, is in good agreement with what is to be expected based on equation (1). Besides that, all results obtained with the bending tests described above show a strong influence of thickness on formability even in situations of non-constant radius, except for situations where the specimen failed by fatigue. In fact, the influence of thickness is the strongest influence observed in both ISF and the bending tests.

The bending mechanism predicts an equally strong effect of the *tool radius*, as in all analyses both the thickness t and the radius R only appear as the ratio t/R. This is not observed in actual ISF. Although there is strong evidence that the formability increases with increasing $1/R$, proportionality is not found, see **Fig. 3**. This can have different causes. A possible cause can be that the actual sheet is not pulled tight after all so that the actual radius of curvature is larger than expected from the tool radius. This would reduce the influence of tool radius, but this effect requires further investigations. Another cause can be that the step down is not reduced in accordance with the tool radius. It can be reasoned that simultaneously reducing the tool radius and the step down in the same ratio should have the same effect as increasing the sheet thickness, ignoring second order effects. So keeping the step down constant, notably in cases where that is relatively large, might also reduce the influence of tool radius.

The effect of *step down* in ISF is similar to the effect of testing speed in the bending experiments: the same final geometry is obtained with another number of steps. The results shown in **Fig. 6** indicate that formability increases with decreasing speed when the process is limited by instability, but decreases when the process is limited by fatigue. If this could indeed be translated into the effect of step down in ISF, it would explain the observations, at least qualitatively. It would certainly explain the inconsistency. The results of **Fig. 6** show a sharp transition between the two mechanisms, in many other cases the transition was much smoother, more like that observed by Obikawa in **Fig. 4**.

Fatigue is present in all cases of cyclic straining. The bending tests showed a strong effect of fatigue, and this is the main reason why different materials show a very different overall formability. Noteworthy is that such a strong material effect is not observed in ISF. For example the overview presented by Micari (2005) shows some material effect, but by far not as dramatic as observed in the bending tests. This could implicate that fatigue is but slightly present in ISF. The number of bending/reverse bending cycles in the bending tests at which fatigue becomes apparent ranges from just a few for fatigue-sensitive materials like AA6016-T4 and leaded brass, to well over 100 for fatigue-insensitive materials like mild steel. The latter number will not easily be encountered in practical ISF operations unless by applying a very small step-down in combination with a large tool radius, however the former number indicates that fatigue should be encountered at least for some materials. Apparently this is not the case, and this might be caused by the high levels of negative contact stress present at the tool contact, that slows down damage development. Another reason might be that in the CBT tests bending is followed by reverse bending reversing the curvature, but in ISF bending is followed by unbending back to flat, at least in the direction of major straining, see **Fig. 1**. Fatigue in ISF is rarely mentioned in the literature. An exception is made by Kitazawa (1993) who however concludes from his results as shown in **Fig. 4** that the limits agree with a modified Manson and Coffin model for low-cycle fatigue.

The bending results also showed an effect of *strain-rate hardening* caused by the high local strain-rates. Clearly in ISF operations the deformation is also concentrated in a small zone, so high local strain-rates are expected there as well. It is not clear if the material behaviour is affected by strain-rate hardening. One might speculate that, if the forces in the deformation zone are restricted by the surrounding material that is not deforming, materials that do show high levels of strain rate hardening show lower formability, just as observed in the uncorrected results of **Fig. 9a**. This is pure speculation indeed, however it indicates that a high level of strain rate hardening is not necessarily beneficial.

A necessary condition for bending-under-tension as a stabilizing mechanism is that the fibres at the concave side are in *compression* in the direction of major straining. It is not known if this is the case in practical ISF operations. Several detailed simulations of ISF have been carried out and published, and these revealed that the contact stress at the tool contact is high, but no mentioning of compressive fibres is made. However several researchers have noticed that at the concave side the hydrostatic stress is negative which was contributed to the high contact stress. On the other hand, in bending-under-tension the fibres at the concave side are subjected to (approximate) plane-strain compression that also creates a negative hydrostatic stress. So this leaves this matter undecided.

Discussion 2: formability in general

All sheet forming operations will finally fail by damage. The strain level at failure however strongly depends on the history of both strain and stress, for example in cold rolling extreme levels of deformation can be obtained without any damage at all. Two mechanisms can lower that ultimate formability limit, both well known. The first one is fatigue. In cases of cyclic straining failure can occur at relatively low levels of elongation, although obviously the amount of cumulative strain may be considerable. The second one is instability. The effect of instability is that the deformation becomes concentrated into a narrow zone. Although in that zone the final strain at failure may be very high, it limits the strain of the major part therefore creating a practical forming limit. The conventional tensile test is the best known example of that. In sheet metal forming the instability limit depends on the strain state, and is often expressed by the so-called Forming Limit Curve (FLC). However in several sheet metal forming operations strains are observed well above the FLC. This increased formability can have two causes. The first one is that the forming limit has simply been raised to a new absolute value, for example by shear or thickness stress. The second one is that in an otherwise unstable situation necking is suppressed locally under certain conditions. The CBT test is an excellent example of the latter. Instability is effectively suppressed by repetitive bending, and when the strain increments remain below a certain limit high levels of straining can be achieved by successive operations, unless for fatigue. It is to be expected that the occurrence of fatigue in the tests described in this paper can be reduced by a clever test procedure, like adjusting the speed and/or force real time, but this has not been tried. More important is that when the stabilizing mechanism fails at a certain moment by whatever reason, the test becomes a conventional tensile test, but performed on a material that has hardened considerably, so well beyond the conventional stability limit. As a result failure is almost instantaneous. This could be seen for example in recorded force-displacement curves, where frequently the force completely drops to zero between two consecutive readings without any warning. When the materials did not show strain-rate hardening, and certainly when the material had already accumulated some damage, failure was truly instantaneous and the samples fractured without a visible neck. Nevertheless, failure is still by instability.

Conclusion

The investigations presented above have showed many similarities between formability in ISF, and formability created by cyclic stretch-bending. This by itself does not prove that bending is the prevailing mechanism in ISF, but it shows that any relevant analysis of ISF must include bending, or better: variations of stress over the thickness of the sheet.

References

Ambrogio, G., Filice, L., Fratini, L., Micari, F., 2003. Some relevant correlations between Process Parameters and Process performance in Incremental Forming of metal sheets. In: Proc. 6th ESAFORM Conference, Apr 28-30 2003, Salerno, Italy, p. 175-178.

Emmens, W.C., 2006. Water Jet Forming of Steel Beverage Cans. Int. J. of Machine Tools & Manufacture, vol. 46-11, p. 1243-1247.

Emmens, W.C., van den Boogaard, A.H., 2009a. An overview of stabilizing mechanisms in incremental sheet forming. J. Mat. Proc. Technology, 209, p. 3688-3695.

Emmens, W.C., van den Boogaard, A.H., 2009b. Incremental forming by continuous bending under tension - An experimental investigation. J. Mat. Proc. Technology, 209 p. 5456-5463.

Emmens, W.C., van den Boogaard, A.H., 2011. Cyclic stretch-bending: mechanics, stability and formability. Submitted to J. Mat. Proc. Technology

Hirt, G., Junk, S., Bambach, M., Chouvalova, I., 2003. Process Limits and Material behaviour in Incremental Sheet Forming with CNC-Tools. Mat Science Forum 426-432 p. 3825-3830 (Thermec'2003).

Hussain, G., Gao, L., Zhang, Z.Y., 2008. Formability evaluation of a pure titanium sheet in the cold incremental forming process. Int. J. Adv. Manuf. Techn. vol. 37 p. 920-926.

Kitazawa, K., 1993. Incremental Sheet Metal Stretch-Expanding with CNC Machine Tools. In: Proc. 4th ICTP, Sept. 5-9 1993, Beijing, China, p. 1899-1904.

Micari, F., 2005. Some remarks on material formability in single point incremental forming of sheet metal. In: Proc. 8th ICTP, Oct. 9-13 2005, Verona, Italy, paper #469.

Obikawa, T., Satou, S., Hakutani, T., 2009. Dieless incremental micro-forming of miniature shell objects of aluminium foils. Int. J. Machine Tools & Manufacture 49, p. 906-915.

Sakai, O., Aida, S., Gotou, T., Magara, K., Iseki, H., 2005. Development of an incremental forming center for sheet metal. In: Proc. 8th ICTP, Oct 9-13 2005, Verona, Italy, paper #457.

Silva, M.B., Skjoedt, M., Atkins, A.G., Bay, N., Martins, P.A.F., 2008. Single-point incremental forming and formability-failure diagrams. J. Strain Analysis 43 p. 15-35.

Silva, M.B., Alves, L.M., Alves, M.L., Martins, P.A.F., 2010. Fracture Forming Lines in Single Point Incremental Forming. In: Proc. IDDRG 2010 Int. Conf, May 31 - June 2, Graz, Austria, p. 451-460.