Incremental forming by continuous bending under tension – an experimental investigation

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Abstract: The Continuous Bending under Tension test (CBT) has been applied to study aspects of incremental forming. Effects of experimental conditions like speed and bending angle have been studied in particular. The results illustrate an essential aspect of Incremental Sheet Forming (ISF): localized deformation. The actual bending radius is the most important influencing factor and this turns out to be controlled by both the pulling force and the bending angle (depth setting). Material thickness had only a minor effect. The maximum elongation before fracture of mild steel was significantly better than that of aluminium. The material is subjected to additional repetitive bending; this does affect material behaviour in general. The aspects of bending-under-tension as a governing mechanism in incremental sheet forming are discussed.

Keywords: incremental sheet forming, bending-under-tension, tensile tests, cyclic bending

1. Introduction

The last decade has shown a world-wide interest in what is called incremental forming. 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. Notably incremental sheet forming (ISF) is of interest, which 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; an extensive overview of this process has been given by Jeswiet et al. (2001).

Although ISF is generally very slow, it is of interest because no or only a simple and cheap tool is required, making the process ideal for small-series production. Another attractive feature of ISF is that strains can be obtained well above the common Forming Limit Curve (FLC). The increased formability has been demonstrated over and over again in recent years. This is not fully understood yet although several mechanisms have been proposed in the literature, these mechanisms are discussed in full detail in a recent review paper by the same authors (Emmens and van den Boogaard, 2008).

Early assumptions about governing through-thickness shear could not be confirmed by recent experiments of Jackson and Allwood (2009). Unexpectedly, in-plane shear was found and it has been argued theoretically how that can enable large deformations in sheet (Allwood et al, 2007)

Another possible mechanism that can create large stable deformations in sheet is bending under tension. Bending under tension has been proposed as a mechanism oper-
ating in ISF by Sawada et al. in 2001 based on FEM simulations, and by Emmens (2006) based on experiments carried out at Corus RD&T in the late 90's. It is postulated that in a relatively large area around the punch, the punch penetration induces a tensile membrane force in the sheet, while close to the punch, the sheet bends around the punch and bends back.

In ISF, the stress field around the punch is fairly complex, including double bending, for which direct measurement of membrane forces is almost impossible. To study the effect of bending under tension, the so-called Continuous Bending under Tension test (CBT) can be used, reducing the problem from an essentially 3-dimensional to a merely 2-dimensional case. Although possibly not immediately recognized as such, the CBT test is in fact an incremental forming operation by itself, the roller set acting as the punch in ISF to localize the deformation.

![Diagram](image.png)

**Fig. 1.** The test equipment. The specimen is held fixed at the top and is pulled downwards in the tensile testing machine; during that operation a set of three rolls is continuously moving up and down. Fig. 1a (left): schematic representation showing important geometry parameters (the roll diameter D, the roll distance L, and the centre roll depth setting P). Fig. 1b (right): picture of the roll set with a specimen mounted in position (two rolls are partially hidden by the strip).

The CBT test has been proposed by Benedyk et al. (1971) to study material properties at high levels of straining. Benedyk et al. have shown that indeed high levels of straining can be obtained for various materials, including hard-to-form materials like heavily cold-worked steel and copper. In 2002 Benedyk et al. published more CBT results on aluminium.

The CBT test is versatile. It can be used simply to obtain large uniform straining in plastic materials, but also to study processes that are based on repetitive bending. As such the test was used at the University of Delft in the early 70's to study the tension-levelling process (Mols 1972).

Unfortunately both Benedyk and Mols presented only very limited information about the experimental conditions of their tests, so that comparison of their results with the results presented here is restricted. Noteworthy however is that the maximum elongation
(strain?) that both authors mention is considerably lower that those described here, even for identical materials. However it is not clear how they have defined 'elongation', it is possibly just the total elongation at fracture.

Very recently the authors started using the CBT test to study incremental sheet forming following some exploring FEM simulations by Hadoush et al. (2007). The CBT test is based on bending-under-tension which is treated well in textbooks (see for example Marciniak et al., 2002). A well known aspect of bending under tension is that sheet material being bent can be stretched with a lower force than the same material not being bent. This paper presents extensive experimental results obtained recently at the University of Twente. The paper will concentrate on the influence of experimental conditions like pulling speed and bending angle.

2. Background of the CBT test.

The CBT test can be imagined as a common tensile test, but during the test a set of three rolls is continuously moving up and down along the specimen repeatedly bending and unbending it as in a three-point bending test. This is schematically presented in Fig. 1. To better understand the experimental results presented below some basic relations between parameters in this test will be presented first.

Bending-under-tension means the simultaneous bending and stretching of a piece of material. The force needed to stretch the material depends on both the amount of bending strain and the amount of stretching strain. In case of a perfectly plastic, non-hardening material the tension force $T$ per unit width can be expressed as (ignoring second order effects):

$$T = \sigma \cdot t \cdot (e / e_b) = \sigma \cdot e \cdot 2R \quad e < e_b$$

$$T = \sigma \cdot t \quad e > e_b$$

where $\sigma$ is the material flow stress, $t$ is the sheet thickness, $e$ is the strain (elongation) at the strip centre, $R$ is the bending radius of the strip centre, and $e_b = t/2R$ is the bending strain of the outer fibre.

Fig. 2. Left: Graphical presentation of Equation (1) for a situation of constant bending radius $R$; $e_b = t/2R$. Right: distribution of strain and stress for the case $e = e_b/2$, shown for clarification. CL is the strip centre line; NL is the neutral line that has been shifted downwards.

For a situation of constant bending radius, as often encountered in practice, the relation between tension force $T$ and net strain $e$ is graphically presented in figure 2, left. Figure 2 shows an important phenomenon: until $e = e_b$ the tension force increases with
stretching strain, even without material hardening. This means that a small disturbance in the local strain field will be stable, since a higher force is needed to deform further. The condition of non-hardening material may look severe, but keep in mind that during the actual test the material is strained considerably, and this reduces the actual rate of hardening. This means that as a first approximation the material may be regarded as non-hardening, and a detailed analysis with realistic material properties (not shown here) revealed that indeed the actual relation between force and elongation does not differ principally from that shown in figure 2.

As material being bent requires a lower stretching force than material not being bent, only material actually bent at any moment will deform in the CBT test. This implies that only that region of the specimen 'visited' by the rolls will elongate, and the length of this region is determined by the stroke of the up-down roll movement. A simple relation between strain and total elongation can be derived, based on the well-known definition of true strain:

$$\varepsilon = \int \frac{dl}{l}$$

where \(l\) is the length of the region actually stretching. In the current tests this length is constant (it is the stroke of the up-down movement), so \(l = l_0\), resulting in:

$$\varepsilon = \int \frac{dl}{l_0} = \int \frac{dl}{l_0} = \frac{1}{l_0} \int dl = \frac{\Delta l}{l_0}$$

This result predicts that the true (logarithmic) strain will be proportional to the elongation (= cross bar displacement), this relation will be used below to verify if the deformation was truly localized incremental forming.

Another relevant relation is that between strain increment and speed, and that can be derived simply. Assume \(v_{ud}\) is the speed of the up-down movement, \(s_{ud}\) is the stroke of the up-down movement, and \(v_{cb}\) is the cross bar speed. The time between two consecutive passes of the roll set is (on average) \(t_0 = s_{ud}/v_{ud}\). In that time the specimen has elongated by an amount of \(t_0 \cdot v_{cb}\). Eq. 3 tells us now that the increment of strain is equal to \(\Delta ll_0 = t_0 \cdot v_{cb} / s_{ud} = v_{cb}/v_{ud}\). Assuming uniform elongation means that every part of the specimen has been subjected to the same strain increment. So:

$$\varepsilon_{incr} = \frac{v_{cb}}{v_{ud}}$$

where \(\varepsilon_{incr}\) is the strain increment at each passage of the roll set. Note however that the roll set has three rolls, and at each roll there is a bending and an unbending operation. This means that at each passage of the roll set there are three bending and three unbending operations, so in fact six bending operations. As a result, the strain \(e\) per bending or unbending operation that is to be used in Eq. 1 is given by \(e = \varepsilon_{incr}/6\).

The results presented in the following sections occasionally show data labelled as 'common tensile tests'. These refer to tensile tests without bending carried out using the same equipment and specimens, but with the roller set removed. A special test was carried out with stationary rolls: the rolls were mounted and tightened but held stationary at the lowest position, and the specimen was pulled through the roll set as a result of its own elongation. The measured stress strain curve is presented in figure 3, together with 4 curves for common tensile tests. The curves are almost identical indicating that just the presence of the roll set has no effect on the tension test, there is only an effect when...
the rolls actually move.

![Force-displacement curves for tests without moving rolls. The thick curve was obtained with rolls that were held stationary, the thin curves without rolls.](image)

**3. Experimental procedures**

Fig. 1 presents the essential detail of the test equipment. A roll set was manufactured with three identical rolls that are rotating freely on roller bearings. Rudimentary variation of the depth of penetration $P$ (following referred to as: depth setting) can be achieved by using washers. The roll set was attached to a computer controlled INA linear drive using a high-precision screw shaft, similar to mechanical testing machines. This up-down device was installed in an MTS 810 hydraulic tensile testing machine. The size of the up-down device prevents the jaws from coming close together; therefore very long specimens had to be used. The dimensions of the specimens are shown in Fig. 4. Several materials have been used; these are presented in table 1. All materials are commercial grades that are used in the automotive industry. An overview of the test settings is presented in Table 2. Note that the depth setting $P$ as defined here does not take into account the actual sheet thickness; a value of 0 will still result in some bending. Force-displacement curves were recorded for all tests with a sampling rate of 20 Hz, two examples of actually recorded curves are presented in Fig. 5. In this figure, the additional (positive or negative) contribution of the up-down movement can be noted, superposed on an average force-displacement curve. At each reversal of the up-down movement, the velocity $v_{ud}$ is reduced for a short time, resulting in an increased tensile force.

Most specimens were tested either until fracture or until the maximum machine stroke of 160 mm. A limited number of tests have been stopped at lower elongations to study intermediate effects. If the maximum machine stroke was reached without fracture of the specimen, that test has been repeated with a lower up-down stroke: for example 100 mm compared to 140 mm for the 'standard' tests. The elongation at fracture was then converted back to a stroke of 140 mm, simply by multiplying it by 140/100 in accordance with Eq. (3). In the following sections, the converted elongation is used where applicable.
Table 1. Overview of material properties as determined in standardized tensile tests.

<table>
<thead>
<tr>
<th>label</th>
<th>grade</th>
<th>thickness (mm)</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>unif. elong (%)</th>
<th>r</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>DC04</td>
<td>0.8</td>
<td>160</td>
<td>290</td>
<td>22</td>
<td>2.5</td>
<td>0.21</td>
</tr>
<tr>
<td>S2</td>
<td>DC04</td>
<td>1.0</td>
<td>160</td>
<td>300</td>
<td>24</td>
<td>2.2</td>
<td>0.22</td>
</tr>
<tr>
<td>S3</td>
<td>DC06</td>
<td>0.7</td>
<td>140</td>
<td>300</td>
<td>25</td>
<td>1.8</td>
<td>0.24</td>
</tr>
<tr>
<td>A1</td>
<td>AA5182</td>
<td>1.15</td>
<td>120</td>
<td>270</td>
<td>25</td>
<td>0.76</td>
<td>0.32</td>
</tr>
<tr>
<td>A2</td>
<td>AA6016</td>
<td>1.0</td>
<td>110</td>
<td>210</td>
<td>18</td>
<td>0.64</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 2. Overview of the relevant experimental conditions.

<table>
<thead>
<tr>
<th>Specimen size</th>
<th>overall 30 x 800 mm²; effective 20 x 180 mm² (see Fig. 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up-down speed</td>
<td>66.7 mm/s (constant)</td>
</tr>
<tr>
<td>Up-down stroke</td>
<td>max. 140 mm</td>
</tr>
<tr>
<td>Roll diameter D</td>
<td>15 mm.</td>
</tr>
<tr>
<td>Roll distance L</td>
<td>35 mm.</td>
</tr>
<tr>
<td>Depth setting P</td>
<td>varying 0.3 - 2.3 mm.</td>
</tr>
<tr>
<td>Pulling speed</td>
<td>varying 0.15 - 10 mm/s</td>
</tr>
<tr>
<td>Pulling distance</td>
<td>max 160 mm.</td>
</tr>
</tbody>
</table>

Fig. 4. Tensile test specimen as used in the tests, drawing not to scale.

Fig. 5. Actually recorded force-displacement curves with moving rolls (material S1). The up-down movement can be recognized as vertical peaks and shifts. The speed labels denote pulling speed (cross bar speed), up/down speed was 66 mm/s, up/down stroke was 140 mm.
4. Experimental results 1: primary observations

This section will present the primary observed experimental results. The next section will interpret these results and discuss them in terms of influence of experimental conditions.

Fig. 6. Three specimens. Top: untested specimen. Centre: specimen tested in a common tensile test; note the diffuse and local neck. Bottom: specimen tested with rolls until the maximum elongation (160 mm). The rectangle indicates the zone of uniform deformation. Material S1.

In Fig. 6 an untested specimen is presented, together with a specimen tested in a common tensile test and one tested in a CBT test. One aspect of the current CBT test is that the deformation is not uniform over the complete length of the specimen, mainly because material is pulled out of the zone where deformation takes place during the test and partly because the outer ends of the deformation zone are visited by only 1 or 2 rolls instead of all 3. However, there is a zone of uniform elongation, in Figure 6 denoted by the rectangle. Grid analysis has confirmed that indeed in that zone the strain is uniform to a high extent, both over the length and over the width of the specimen. All results concerning strain presented next have been derived from that zone. In Fig. 6 the deformation in the uniform zone may not look very spectacular, however, this is caused by the fact that the strain state shifts towards plane strain, and consequently the reduction in width is much lower than the reduction in thickness.

In some cases the fractured specimens showed a small diffuse neck, notably when tested at high pulling speeds. Note however that all results following refer to the uniform zone besides the neck, and never to the localized strain in the neck.

4.1 Strain

As mentioned above the specimens show a region of uniform elongation, even after fracture. The actual length strain of that region could not be measured directly, therefore the width strain and the thickness strain have been measured after the tests by hand. Both have been measured at different locations in the uniform section and averaged, but the scatter was in general very low. From these the length strain was determined assuming constant volume, and this is plotted in Fig. 7 as a function of total elongation for all specimens. All points form a single line, independent of the used material, corresponding to the relation presented by Eq. (3) where \( l_0 \) is the up/down stroke, in this case 140 mm.

The strain state in the specimens can be characterized by the ratio between width strain and thickness strain. This parameter is similar to the well-known r-value (Lankford’s parameter) but should not be confused with the material’s actual r-value that is presented in Table 1. The parameter defined here is just an ‘apparent r-value’, and
is presented in figure 8. The curves show that the strain state shifts towards plane strain, and more for thicker material and for deeper roll setting. This is consistent with an increasing influence of bending.

![Graph showing strain state in specimens](image)

Fig. 7. True length strain as measured in the uniform part of the specimens plotted as a function of total elongation. The dashed line shows the expected relation according to Eq. (3).

![Graph showing strain state in specimens](image)

Fig. 8. Strain state in the specimens defined as ratio between width strain and thickness strain for all materials.

4.2 Force/Stress

For all recorded stress-strain curves the maximum force has been determined after smoothing using the method of moving average over one complete up/down cycle. All recorded curves had approximately the same shape, and the maximum occurred at approximately the same elongation for all tests (see Fig. 5). Consequently the maximum force can be used as a parameter to study the overall stress level. The results for material S1 are plotted in Fig. 9, the other materials showed basically identical results. The effects of speed and depth setting are clear: the maximum tension force increases with increasing speed and decreases with increasing depth setting (the limit line will be discussed later).

The data for the four depth settings make up four individual curves that run more or less parallel. This raises the question if they can be united into a single curve by shifting the individual curves horizontally. This implies multiplying the speeds for a single curve with a constant factor. This was indeed the case and the 'correction' factors are presented in figure 10, taking the curves for 2.3 mm depth setting for each separate material as a reference. The results indicate that apparently depth setting and speed effect
the maximum pulling force through a common phenomenon, and also that the interaction between speed and depth settings seems material independent.

![Graph showing maximum pulling force plotted as a function of pulling speed for material S1. Symbols denote depth settings; the square symbols at the top show the values for common tensile tests.](image1)

![Graph showing speed correction factor denoting the positions of the force-speed curves as described in the text, for all materials.](image2)

4.3 Formability

As the aim of the current tests is to investigate prolonged uniform elongation, the elongation at fracture was determined and the results for materials S2 and A2 are presented in Fig. 11, the other materials showed basically identical results. The figure shows that with increasing speed the elongation at fracture initially increases, but that after a certain speed the elongation at fracture drops. This indicates that there is a maximum obtainable elongation for each depth setting (read: test geometry), and that this maximum is obtained for a certain pulling speed. The results further indicate that the effect of depth setting on the strain at fracture depends on the speed: at low speeds a deeper setting reduces the elongation at fracture, but at high speeds a deeper setting increases the elongation at fracture considerably.

The maximum recorded length strains are further presented in figure 12, together with the speed at which the maximum length strain was obtained. These two graphs should be interpreted carefully, as a maximum value is by definition based on a single
observation, and therefore will be subjected to scatter. Nevertheless the overall trend is clearly visible: for all materials both the maximum strain and the speed at which this was obtained increase with increasing depth setting. There is however a notable influence of material type: for aluminium the maximum length strain is considerably lower than for steel and the maximum is obtained at higher cross-bar speeds. Apparently the failure mechanisms for aluminium differ from that for steel.

Fig. 11. Elongation at fracture plotted as a function of pulling speed for material S2 (left) and material A2 (right); the relation between elongation and actual strain can be found in Fig. 7. Symbols denote depth settings; open symbols indicate tests where failure by overload was detected (see section 5.2).

Fig.12. Maximum recorded length strain (left), and speed at which the maximum length strain occurred (right) plotted as a function of depth setting, for all materials.

Prior to failure multiple necking bands occur as is shown in Fig. 13. Note however that this is an extreme example: multiple fracture is rare, and the amount of multiple necks is usually less. This phenomenon has also been observed by Benedyk et al. (1971) and also showed up in the simulations carried out by Hadoush et al. (2007). This does not mean that the material has lost its ductility, it is consistent with the principle of localized deformation. If by whatever reason the incremental mechanism cannot suppress necking any longer, necks can occur at any place, but will not immediately grow into a crack. When the deformation zone moves along the neck stops growing, and another neck may originate at another place. In a few cases multiple necking indeed resulted in multiple fractures, and often a fractured specimen showed some secondary necks.
5. Experimental results 2: effects of formability

In this section, the influence of the experimental conditions on the maximum achievable strain is discussed more specifically.

5.1 Influence of depth setting

The results, presented in Figures 8-12 and 14, show a significant influence of depth setting. The depth setting determines the angle over which the strip is bent around the rolls, as can be seen in Figure 1. However, the bending angle is not supposed to be of influence, only the bending radius takes part in Eq. (1). Careful examination of the strips during the tests revealed that the strip is not bent around the rolls like a membrane, but that the actual bending radius is (much) larger due to the bending stiffness of the material. A deeper setting of the centre roll forces the strip to a smaller actual bending radius. With more bending and equal stretching strain, the required tensile force is lower, in agreement with Eq. (1). This explains why the pulling force decreases with increasing depth setting. Fig. 9 shows a line labelled 'limit'. This line presents a predicted pulling force for a situation that the strip is bent tightly around the rolls, and based on Equations (1) and (4):

\[ F = \sigma \cdot \frac{V_{cb}}{6u_{ud}} \cdot 2R \cdot w \]  

with \( w \) is the width of the strip, \( \sigma \) is the ultimate (engineering) stress, and \( R \) the bending radius at the strip centre which in this case is taken as the roll radius + half the strip thickness. The large distance between the measured pulling forces and the calculated force from Eq. (5) illustrates that the actual bending radius is much larger than the roll radius.

5.2 Influence of cross-bar speed

The effect of cross-bar speed can easily be seen from Eq. (5). A higher speed means a larger strain increment at each passage of the roll set (Eq. 4), and consequently a higher pulling force. This is indeed observed, as presented in Fig. 9. A larger pulling force however also means that the strip is bent more tightly around the rolls, meaning that a smaller bending radius is obtained. So both the depth setting and the pulling speed have an effect on the actual bending radius and this explains the interaction between both conditions. The results of Fig. 10 indicate that the interaction between speed and depth setting is material independent, suggesting that the relation is governed by the characteristics of the test method only and not by the material behaviour.
Fig. 14. The results from Fig. 11 for material S2, plotted as a function of the maximum pulling force. The open symbols indicate tests were failure by overload was detected.

As mentioned above an increasing cross-bar speed means an increasing pulling force (Fig. 9). However there is a limit to that. Remember that the incremental mechanism claimed to operate in these tests is based on the assumption that only material being bent will deform. If the pulling force becomes very high this assumption is no longer valid and other parts of the strip start to deform plastically as well. In that case the incremental mechanism cannot operate fully, and the test resembles a common tensile test more and more. A consequence is that the elongation at fracture drops rapidly. This can be observed in the failed specimen as in that case the actual fracture is at an oblique angle to the strip length just as in a common tensile test, and for steel the fractured specimen shows a diffuse neck. This phenomenon is called here: 'failure by overload'. It can be illustrated by plotting the measured elongation at fracture as a function of the measured pulling force as is done for material S2 in Fig. 14. Presented in this way, the data points for 'failure by overload', denoted by an open symbol, tend to form a single curve. This occurs for all tests when the maximum pulling force exceeds 4400 N, clearly indicating a force controlled phenomenon. The same effect was observed for the other materials as well; for the steel variants a limit value was found above which failure by overload occurs, for the aluminium variants a transition range was observed, as indicated in Fig 15.

Fig. 15. Force limits above which 'failure by overload' was observed. The force is expressed as a percentage of the material's UTS.
The observations indicate that an infinite pulling speed would reduce the test to a common tensile test. Apart from strain rate effects, an infinite pulling speed has the same effect as a zero up/down speed, conform Eq. (4). This is in agreement with the findings of the tests with stationary rolls as presented above in Fig. 3.

There is yet another relevant effect of speed that however is related to material behaviour, and this will be discussed in the next section.

5.3 Influence of material

A limitation of the tests described in this paper that only material has been tested with comparable mechanical properties, see Table 1, so that any conclusion about the effect of mechanical properties is risky. Testing of materials with significant different hardening properties like multi-phase materials would be clarifying in this respect, and this is intended for the future. Nevertheless the general performance of aluminium is found to be much worse than that of steel, see Table 3. It is doubtful if this can be described to the only difference in properties, the anisotropy, so there should be another explanation.

Table 3. Overview of general material performance. The uniform elongation in a tensile test (column 3) is the conventional strain at force maximum measured following standardized procedures; the uniform elongation in the CBT test (column 4) is the largest recorded length strain in any test with that material, measured in the uniform zone of fractured specimens as described in section 4.1.

<table>
<thead>
<tr>
<th>label</th>
<th>grade</th>
<th>uniform elongation in a tensile test (%)</th>
<th>uniform elongation in the CBT test (%)</th>
</tr>
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<tbody>
<tr>
<td>S1</td>
<td>DC04</td>
<td>22</td>
<td>290</td>
</tr>
<tr>
<td>S2</td>
<td>DC04</td>
<td>24</td>
<td>430</td>
</tr>
<tr>
<td>S3</td>
<td>DC06</td>
<td>25</td>
<td>320</td>
</tr>
<tr>
<td>A1</td>
<td>AA5182</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>A2</td>
<td>AA6016</td>
<td>18</td>
<td>110</td>
</tr>
</tbody>
</table>

In a CBT test the material is subjected to repetitive bending and unbending, superimposed on the average elongation. It can be expected that this will have some effect on the material behaviour, but at the moment it is not fully clear how and this requires more research. The repetitive bending causes fatigue to some extent and it must be taken into account that possibly material will fail by low-cycle fatigue. Assuming that under some experimental conditions the material indeed fails by low-cycle fatigue, we can speculate that:

- material that is known to be sensitive to low-cycle fatigue like aluminium will show poor performance
- in tests carried out with a higher depth setting the material is bent more than in test carried out with a low depth setting (at the same speed) expecting to reduce the performance; this is observed in the tests (see Fig. 11), notably for aluminium, but only at lower speeds where failure is not induced by overload.

The observations do agree with these speculations, so a possibility that indeed the material fails by low-cycle fatigue must not be ruled out beforehand. Also both Bene-
Dyk and Mols have observed lower formability for aluminium as compared to mild steel (Benedyk et al. 1971, Mols 1972) but they have tested different aluminium grades (presumably), so the results are not directly comparable. More research is needed for a final conclusion.

The pulling speed also affects the strain rate during the tests, and this will have an effect on strain rate sensitive materials. After the test, some aluminium samples showed a peculiar herring bone shaped roughening, presented in Fig 16. This effect has also been observed by Benedyk et al. (2002). The current tests show that this effect is speed dependent. The phenomenon is clearly noticeable on samples tested at low speed, it reduced at higher speeds and is completely absent on samples tested at the highest speeds. This is consistent with the general observation from the automotive industry that certain surface defects on aluminium like stretcher-strain marks preferably occur at low strain rates. On the other hand, the roughening was not present on specimens tested without rolls, even when tested at low speeds, hinting to a relation between this roughening and the repetitive bending.

Fig 16. Herring-bone type roughening as noticed on aluminium (material A1).

6. Discussion

The goal of this investigation was to study aspects of incremental sheet forming. Unfortunately the actual radius of curvature of the material turned out to be much larger than the roll radius. This means that the conditions in the tests were not close enough to the conditions in practical ISF operations to allow a one-to-one comparison. However, the tests have emphasized an essential aspect of ISF: localized deformation. Based on the assumption of localized deformation a relation between strain and elongation was derived (Eq. 3) that was validated by the experiments (Fig. 7). If for whatever reason the deformation is no longer localized (in our test by a too high pulling force) the deformation becomes global and is limited by the usual stability limits for global deformation, in many cases the common forming limit curve.

The results showed that the formability defined as the maximum possible uniform elongation before fracture depends on both process and material properties. This raises the question what mechanism or mechanisms finally do limit the process, not only the CBT test but also ISF in general. This is far from clear yet. It has been shown that bending under tension creates a zone of stable deformation as the tension force increases with elongation initially (see Eq. 1 and Fig 1). It is not known if such an additional stabilizing effect is essential for ISF operations to be successful and if so to what extent. However for the sake of reasoning let us assume that this effect is governing the opera-
tion, meaning that deformation is successful as long as \( e < e_b \), but fails if \( e > e_b \) (\( e_b = t/2R \)). The allowable strain increment \( e \) then depends on the sheet thickness. In the CBT tests the strain increment is constant (determined by the testing speed) but a limit will be reached as the material gets thinner and thinner. A consequence is that the strain state as shown in Fig. 8 is of influence as this affects the length strain at which a certain thickness is obtained. Both the strain state and the maximum elongation are affected by the depth setting, but the results do not contradict the assumption of a limiting thickness. A second effect is that thicker material will simply perform better as more elongation is required to obtain a certain thickness. This is in agreement with general observation. The test results presented in this paper show the same trend (Fig. 12, compare materials S1 and S2), but the results are obscured as the thickness also affects the actual bending radius.

In many forming tests the thickness is constant (just the sheet thickness) and the strain increment is increased until fracture. If also the bending radius is constant, the formability defined as the limit strain in a single operation should become proportional to the sheet thickness assuming the bending-under-tension mechanism to operate. Viewed from this perspective it is interesting to have a new look on results obtained some time ago in the shaping of two-piece cans (Emmens 2006). The wall of two-piece beverage cans consists of material that is heavily cold-worked by deep-drawing and wall-ironing, and that has lost all its ductility, the material fractures immediately when stretched. However this material could be formed using incremental techniques, both by water-jet forming and by spinning. In the water-jet forming experiments it was noticed that the actual bending radius is largely controlled by geometrical considerations and the diameter of the water jet, and appeared to be highly material independent, and in spinning the actual bending radius was simply controlled by the tool radius. So both processes satisfy the condition of constant bending radius and indeed it was found that the formability is proportional to the material thickness as is shown in Fig. 17. This strongly hints to bending under tension as the forming mechanism, in these cases presumably the sole source of formability.

![Fig 17. Relation between max. strain and material thickness observed in incremental forming of two-piece-can walls. The figure presents actually measured data from different types of experiments carried out at CORUS RD&T. The dashed lines simply indicate proportionality](image-url)
However, in many studies on ISF including the CBT test it was found that different materials show different levels of formability. This means that, apart from the stability issue, there is a material effect as well and different mechanisms may be at work at the same time.

7. Conclusions

The overall conclusion is that the CBT test is suitable for studying bending-under-tension as a mechanism in ISF, but the conditions should be changed to ensure a much smaller actual bending radius, for example by increasing the depth setting. Such test will be carried out in the future.

The experimental conditions like pulling speed and depth setting have a significant effect on the final results, notably on the maximum level of uniform elongation that can be obtained. Both affect the actual bending radius, and a smaller radius allows more straining.

At a fixed geometry there is an optimal pulling speed for obtaining maximum uniform straining. This speed is usually just below the speed where locality of deformation is lost and failure by overload starts. At lower speeds, the formability is reduced because of the increased number of bending-unbending cycles.

8. References


