Tensile tests with bending: a mechanism for incremental forming.

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ABSTRACT: In incremental sheet forming (ISF) large uniform strains can be obtained well above the common forming limit. Bending-under-tension has been proposed as a possible mechanism. This paper describes tension tests with repetitive bending to simulate this effect. Indeed very large levels of uniform elongation have been obtained, up to 300 %. The maximum strain increases with decreasing bending radius, and is reached at a certain optimum pulling speed. The material hardening seems little affected by the cyclic bending operations, and a hardening curve for large strains could be constructed.

Key words: Incremental forming, Tensile testing, Bending-under-tension

1 INTRODUCTION AND BACKGROUND

In incremental sheet forming (ISF) large uniform strains can be obtained well above the common forming limit curve making it an attractive forming process. Little effort has been done so far to discover the underlying mechanism. Common ISF comprises the forming of the sheet over a hemispherical punch. This requires repetitive bending and unbending. It has been proposed that bending-under-tension might be acting as a mechanism allowing large uniform straining, based on observed relations in incremental forming [1,2]. Bending-under-tension can be investigated in several ways. Well known is the pulling of a strip over a single 90^o radius with back tension. This paper describes tests with repetitive bending. In such a test a long tensile test specimen is tested, but at the same time a set of three rollers as in a three point bending test is continuously moving up and down, as presented in figure 2.
In a situation of combined bending and stretching the net pulling force is governed by both the bending strain and the stretching strain. In case of a perfectly plastic, non-hardening material, and ignoring second order effects, the net tension force per unit width T is given by:

$$\begin{aligned} T &= \sigma \cdot t \cdot (e / e_b) = \sigma \cdot e \cdot 2R \qquad & e < e_b \\ T &= \sigma \cdot t & e > e_b \end{aligned} \tag{1}$$

where σ 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.

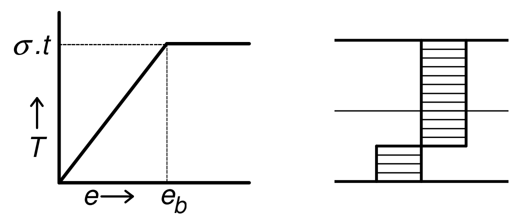

Fig 1. Left: Graphic presentation of equation (1) for a situation of constant bending radius R; e_b=t/2R. Right: stress distribution for the case e=e_b/2.

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 1. This illustrates an important phenomenon: a strip being bent can be stretched with (much) lower force than the same strip not being bent. This implies that in our tests only material actually being bent at any time will elongate as that requires the lowest tension force: a true incremental mechanism.

Consequently material not 'visited' by the rolls will not elongate, and the effective length of the specimen is equal to the stroke of the up-down movement. The figure illustrates also a second important effect: initially the force increases with strain, a situation of stable deformation!

The condition of non-hardening material may look severe, however a detailed analysis shows that in a situation of pre-stressed material the actual situation is not that much different. In our tests this is the case after a certain amount of stretching, say 50%.

Based on the assumption that only material being bent will elongate we can derive a simple relation between strain increment and speed:

$$\varepsilon_{incr} = \frac{v_{cb}}{v_{ud}} \tag{2}$$

where ε_{incr} is the strain increment at each passage of the roll set, v_{cb} is the cross-bar speed, and v_{ud} is the up-down speed of the roll set. Note that the roll set has three rolls, so that each passage shows several bending and unbending operations; in the ideal case we have $e = \varepsilon_{incr}/6$.

2 EXPERIMENTAL PROCEDURES

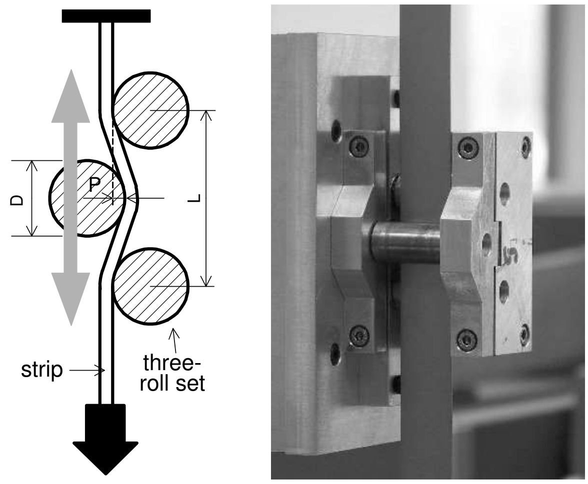

Fig. 2. Left: schematic representation of the test; right: picture of the roll set.

A simple three-roll device was constructed that was installed in a standard MTS testing machine, see figure 2. The device allowed provisional change of the centre roll depth setting P. This setting determines the angle of bending, but indirectly also the actual bending radius of the strip (deeper setting = smaller actual radius). Note that a value of 0 still implies some bending of the material. Roll diameter D was 15 mm, distance L was 35 mm. The speed of the up-down movement was held constant at 66 mm/s, the stroke was held constant at 140 mm. The testing speed (cross-bar speed) was varied during the tests. Testing material was common DC04 steel of 0.8 mm thickness and 20 mm width.

3 RESULTS

In the following reference is made to 'common tensile tests' occasionally. These are tests carried out with the same equipment and specimens, but without any rolls, so only tension and no bending.

3.1 Strain

A charactersitic of this test is that the strain is not uniform over the length of the specimen. However there is always a zone of uniform elongation and fixed length, being the zone 'visited' by the rolls. The width strain and thickness strain of that zone has been measured, and the length strain was calculated from that. Figure 3 presents the relation between the true length strain in that zone and the total elongation (cross-bar displacement). The relation is proportional, this contrary to ordinary tensile tests were the engineering strain increases proportionally to the elongation. This is a direct consequence of the specific nature of the test and confirms that indeed only material being bent at any time does elongate and that we are dealing with a proper incremental mechanism.

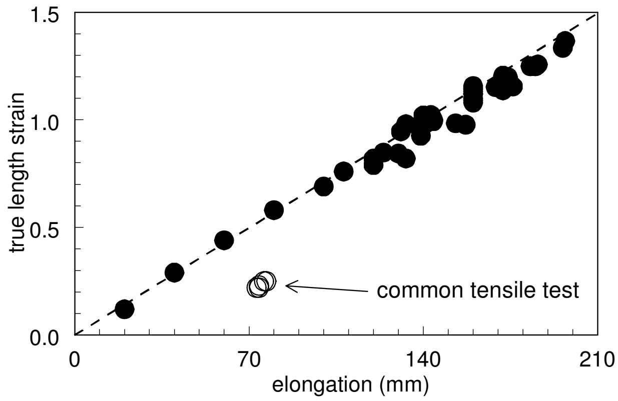

Fig. 3. Relation between measured uniform strain (true strain) and total elongation of the specimen.

The dashed line shows the expected relation: the true strain becomes 1 when the elongation is equal to the up-down stroke (= 140 mm). Note that the highest recorded length strain is 1.37 (≈300%).

The ratio between length strain and thickness strain is plotted in figure 4 as a function of depth setting. This ratio can be regarded as an 'apparent r-value', the actual r-value of the material was 2.5. The results show that a deeper setting (read: smaller actual bending radius) shifts the strain state towards plane-strain.

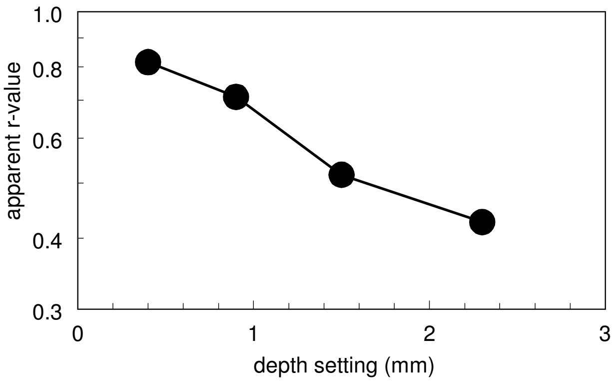

Fig. 4. Ratio between width strain and thickness strain plotted as a function of depth setting.

3.2 Force

For all tests a force-displacement curve was recorded just as in a common tensile test. The maximum recorded force for each test is presented in figure 5. The force shows a strong influence of the pulling speed. This is not surprising, a higher pulling speed means a larger strain increment (equation 2), and hence a higher pulling force (equation 1).

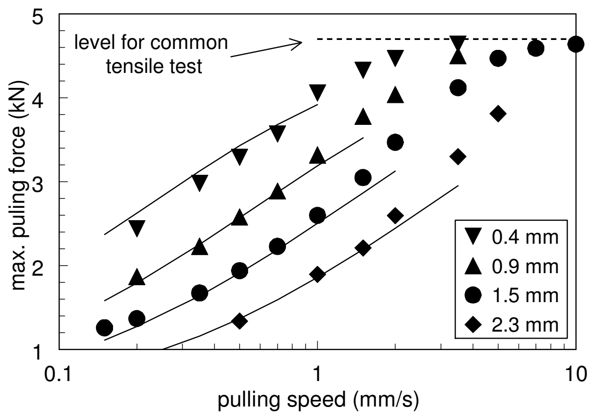

Fig. 5. Maximum pulling force plotted as a function of pulling speed with the depth setting as parameter.

The influence of depth setting can be understood by realizing that the actual bending radius was actually much larger than the roll radius due to the bending stiffness of the strip, and that a deeper setting reduces the actual bending radius, and hence the pulling force. Similar is a second effect of the speed: a higher pulling force also means that the strip is tightened more, also resulting in a lower force.

Basically this graph shows the combined influence of strain increment *e* (read: pulling speed), and bending radius *R*. The solid lines are predictions by a simple model that calculates the actual bending radius by a balance of forces according to equations (1) and (2); the agreement with the measured data indicates that indeed this actual bending radius is controlling the pulling force.

3.3 Formability

The maximum obtained elongation is plotted in figure 6; the relation between elongation and true length strain can be derived from figure 3. This figure is rather complex but it can be noticed that - with an exception for the lowest depth setting of 0.4 mm - the largest level of elongation is obtained at a certain optimum speed, and this optimum speed increases with increasing depth setting. Furthermore the largest level of elongation increases with increasing depth setting, or better: decreasing actual bending radius.

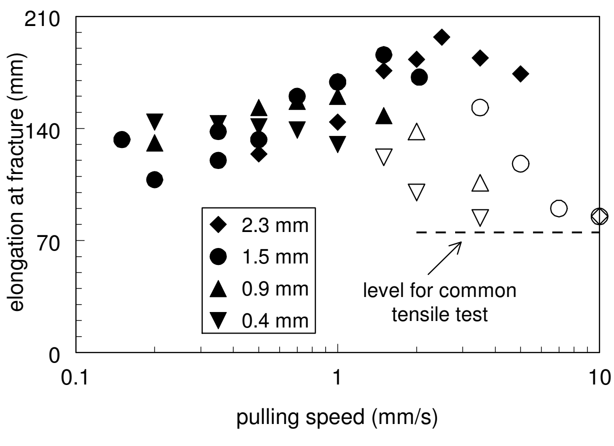

Fig. 6. Elongation at fracture plotted as a function of pulling speed with the depth setting as parameter.

The points in figure 6 denoted by an open symbol require further discussion. These are points taken from experiments where the maximum pulling force as shown in figure 5 exceeds 4 kN. Investigation showed that in those cases the elongation is no longer restricted to the zone 'visited' by the roll set, but that other areas deform plastically as well. This means that the proposed incremental mechanism cannot operate fully, and a consequence is that the elongation at fracture drops rapidly. A further effect is that the relation between elongation and true length strain deviates from that shown in figure 2 (the corresponding points have been omitted in that figure for reasons of clarity).

3.4 Hardening

As mentioned before, all specimens showed after testing a zone of uniform elongation. That zone was often large enough to measure the level of hardening of the material by performing a second, conventional tensile test. The results allowed the construction of a true hardening curve, see figure 7.
Al results form a single curve within an acceptable level of scatter. This is surprising as the specimens have been subjected to bending and unbending operations. Some data are taken from specimens tested at high speed with only a few bending cycles, others from specimens tested at low speed subjected to a large number of bending cycles. Yet this does not show any effect. It suggests that the bending-unbending operations do not affect the hardening of the material, the latter only being determined by the level of length strain, and fitting perfectly to the Ludwuk-Nadai curve constructed from *C* and *n* values measured at undeformed material.

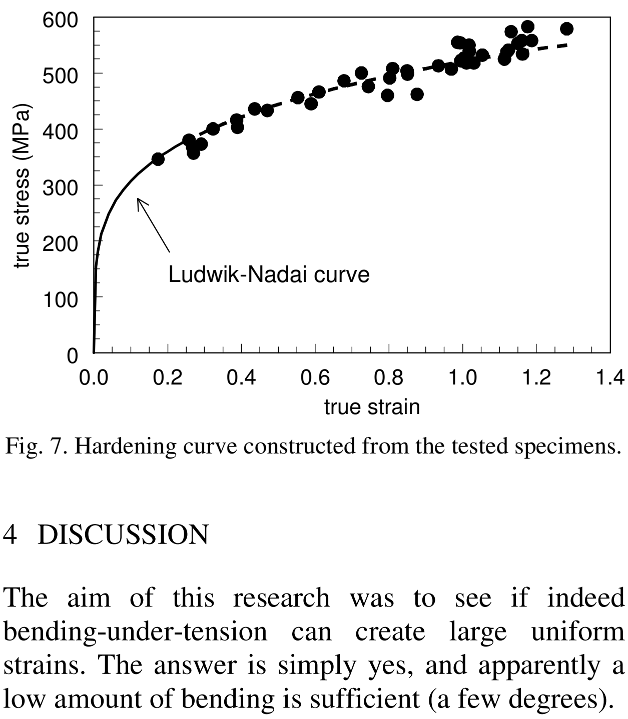

Fig. 7. Hardening curve constructed from the tested specimens.

4 DISCUSSION

The aim of this research was to see if indeed bending-under-tension can create large uniform strains. The answer is simply yes, and apparently a low amount of bending is sufficient (a few degrees).
The influence of experimental conditions is considerable, a fact sometimes overlooked in other publications [3]. The simple formulae presented at the introduction predict two major parameters: the pulling speed governing the strain increment at each passage of the roll set, and the actual bending radius *R*. Both are observed clearly, although the actual bending radius could only be affected indirectly.
The speed also presents a limitation: a too high speed results in a pulling force so high that the incremental mechanism fails, rapidly lowering the maximum elongation. However, as the pulling force decreases with increasing depth setting, or better: decreasing actual bending radius, this limit is less severe in cases of a small bending radius.
Analysis shows that the actual radius is still much larger than the roll radius, so much larger strains can still be expected if the actual bending radius is reduced further. This will also bring the situation more closely to situations occurring in actual incremental sheet forming operations. This will be the subject of future investigation.

5 CONCLUSIONS

1. Stretching with simultaneous bending does allow large uniform straining even in cases where the angle of bending is low.
2. The underlying mechanism is that at any moment only material actually being bent is deforming. This mechanism fails if the pulling force (or indirectly: pulling speed) becomes too high.
3. The actual bending radius of the material seems to be much larger than the roll radius introducing an influence of bending angle (penetration depth).
4. The maximum obtainable level of uniform strain increases with increasing bending angle and is obtained at an optimum pulling speed.
5. The level of hardening of the material seems only little affected by the cyclic bending/unbending operations.

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