Introduction

In the production of drawn and wall ironed beer and beverage cans the material is subjected to different forming operations. First the material is deep drawn and then wall ironed. These forming operations harden the material, thereby limiting the formability of the can wall in successive operations such as necking, flanging and shaping. To optimise these forming operations the formability of the material in the can wall must be known. However not many methods are available to measure the formability of this particular material (hard, thin, round, small), therefore another approach is followed here: studying the change of the mechanical properties of the material during the manufacturing process.

Experimental Procedures

Figure 1. The product stages used for the tests. 1 = drawn cup, \( \beta=1.48 \); 2 = redrawn cup, \( \beta=1.39 \); 3 = wall ironed to original sheet thickness; 4-9 = wall further ironed, each stage with 20% thickness reduction with respect to the previous stage.

In the research described in this paper the change of the mechanical properties of the material in the can wall during deep drawing and wall ironing was studied. For this a series of nine stages in the production of a DWI beverage can has been selected as presented in figure 1, with some useful characteristic data in table 1. A top grade low-earring DWI quality low-carbon steel has been used for the experiments. Please note that the cans were specially wall ironed with a uniform wall thickness, there was no thicker upper part.

For studying mechanical properties of metals the tensile test seems most appropriate. Examples of stress-strain curves for specimens cut out of the can wall are presented in figure 2. These examples show that for materials hardened as much as here only little relevant information can be obtained from the tensile test, in fact only maximum stress and strain. As the maximum strain shows considerable scatter, only the tensile strength (maximum stress) is left as a useful parameter.

<table>
<thead>
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<th>stage</th>
<th>thickness at upper edge (( \mu m ))</th>
<th>total deformation at upper edge</th>
</tr>
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<tr>
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<td>245</td>
<td>0</td>
</tr>
<tr>
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</tr>
<tr>
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<td>3</td>
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<td>0.97</td>
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<td>4</td>
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<td>1.24</td>
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</tr>
<tr>
<td>7</td>
<td>101</td>
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</tr>
<tr>
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<td>81</td>
<td>2.28</td>
</tr>
<tr>
<td>9</td>
<td>68</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Table 1. Some characteristic data for the stages. The original undeformed sheet is indicated as stage #0. The deformation is defined as the total cumulative effective plastic strain.

Figure 2. Examples of stress-strain curves obtained from tensile test specimens cut out of the can wall.

Due to the specific nature of the can wall material only a very limited set of mechanical properties could be measured. These are:

- the hardness as measured using a micro-Vickers
hardness tester
• the tensile strength as measured in a normal tensile test

The hardness has been measured on a cross section of the wall, the load of 100 grf. being applied in a tangential direction. The tensile tests specimens have also been cut out the wall in a tangential direction. The hardness measurements were carried out at many positions on the wall (at different heights measured form the bottom), whereas for the tensile tests only three positions on the wall could be used for the higher cans, and two or only one for the lower products.

Results

![Figure 3](image)

**Figure 3.** Tensile strength (tangential) of the can wall as a function of the cumulative effective plastic strain, for three positions on the wall and the original sheet.

![Figure 4](image)

**Figure 4.** Tensile strength (tangential) of the can wall as a function of the material hardness (tangential), for three positions on the wall.

The tensile strength of the can wall has been plotted as a function of the total effective plastic strain in figure 3. These results show that the strength increases uniformly with increasing strain. The relation is roughly linear, there is little influence of the position on the wall. Furthermore the results indicate that there is no fundamental difference between deep drawing and wall ironing with respect to material hardening, as all points form a single curve.

In figure 4 a comparison is made between the strength and the hardness of the material. Please note that in general the scatter in the hardness results is much larger than the scatter in the strength.

The results of figure 4 show that there is a simple linear relation between strength and hardness, as one would expect. However the attentive reader will note that, although the relation is linear, it is definite not proportional! The mean strength is roughly three times the mean hardness, but the slope of the lines is almost 6. This indicates that the relation between strength and hardness is thought more complex than at first sight.

![Figure 5](image)

**Figure 5.** Tangential strength and hardness of the can wall, measured near the top of the can, for the different stages (see figure 1). The original undeformed sheet is mentioned as stage #0.

In figure 5 the strength and hardness are compared again, but in a different way. Hardness and strength have been plotted to different scales, but these scales are proportional, so that a direct comparison is justified. This figure can be interpreted as the evolution of the properties of a material point originally located near the edge of the blank.

The evolution of the strength is the same as already shown in figure 3, but the evolution of the hardness is different. In the deep draw operation the hardness increases significantly, and then remains more or less constant. During wall ironing the hardness increases again, but less than the strength. In other words: the evolution of the hardness during deep drawing differs from that during wall ironing.

This particular behaviour of the hardness needs to be studied in more detail.

In figure 6 the hardness of the can wall is presented as a function of the relative position. The latter is defined as a certain height on the can wall, a value 0 being near the bottom and a value 1 being at the top of the
can. By this definition a certain material point in the blank keeps the same relative position during all deep drawing and wall ironing operations. For the first draw cup with a larger diameter (figure 1) the positions <0.3 are still in the bottom plane.

Due to the large scatter in hardness measurements only regression lines are given. For the deep drawn cups the hardness increases rapidly with increasing position (read: increasing deformation), and then reaches a more or less constant value. For positions >0.8 the hardness barely increases in the stages 2 and 3, despite the considerable amount of plastic deformation that occurs!

![Figure 6](image)

**Figure 6.** Hardness of the can wall plotted against the relative position, for all nine stages and the original material (#0). For stages 8 and 9 only part of the hardness profile could be measured.

The hardness profiles of the wall all start with a region of strong increase (positions <0.3), followed by a region where the hardness increases only slightly. This behaviour is already present in the redrawn cup (#2) and remains rather unchanged during successive wall ironing stages. This cannot be ascribed to the lower deformation in the wall area near the bottom; the transition from bottom to wall occurs at positions <0.07. So it seems that during deep drawing a certain distribution of the hardness is created, and that during wall ironing this distribution is not changed but just lifted to a higher overall level.

This indicates that during deep drawing a certain condition is created in the material, and that remnants of this condition remain in the material during wall ironing, despite the considerable plastic deformation that takes place.

We will now treat the wall ironing and the deep drawing operations separately. The increase of the average hardness of the wall during wall ironing has been plotted in figure 7. The results show that the hardness increases linearly with the deformation, and that there is no indication that hardening reaches a maximum of some sort. In this respect these results resemble those of figure 3.

![Figure 7](image)

**Figure 7.** Increase of hardness during wall ironing.

The hardening during deep drawing is presented in more detail in figure 8. The hardness of several positions on the wall of the deep drawn cups is presented as a function of the total deformation (effective strain) at that position. Two phenomena strike. Firstly the hardness reaches a maximum value, identical for both products. Secondly, the two products do not produce one single curve, despite the fact that both the deformation mode is identical for both products, and the total strain path is straight for every position.

![Figure 8](image)

**Figure 8.** Hardness of the wall of deep drawn cups.

**Discussion**

We have studied the work hardening during deep drawing and wall ironing by measuring the change in two mechanical parameters, the hardness and the strength. Both parameters provide some measure of the resistance of the material against plastic deformation,
and more in detail the amount of hardening that has occurred in the material of the wall. Despite that, both parameters give different results.

The strength in a tensile test is obtained under a clearly defined condition of uni-axial stress, although the condition shifts to plane-strain when yielding. The strength however is always related to actual failure of the material, failure will not occur in the products.

The hardness measurement produces a much more complicated deformation mode in the material, and little is known of its particular characteristics. However the parameter is not related to failure and from that point of view possibly more representative of the actual conditions during deep drawing and wall ironing.

For the hardening during wall ironing both parameters produce similar results: a linear relation with the amount of deformation (figures 3 and 7). It is now interesting to compare the slope of both hardening curves (figures 3 and 7). This cannot be done directly because of the different dimensions of the mechanical properties. The Vickers hardness can be converted into true surface stresses in MPa by multiplying by 9.8. According to a rule of thumb the hardness (expressed in true stress units) should be about 3 times the strength, and this is in general agreement with the findings here as far as the mean absolute values are considered (figures 4 and 5).

After correcting the hardness values as mentioned the slope of the hardness/strain relation becomes approximately 350 MPa indicating that an equivalent strength/strain relation should have a slope of about 120 MPa. However the results of figure 3 show a slope of about 230 MPa showing again a difference between the two parameters.

An absolute check can be done by comparing these results with hardening laws from other sources. For cold rolling of low-carbon steel (a process similar to wall ironing) the Bergström hardening model has proven its validity. This model is based on dislocation behaviour and predicts, after an initial amount of deformation, a more or less linear relation between momentarily yield stress and deformation, with a slope of approximately 100 - 120 MPa for many grades of low carbon steel (although exceptions exist). This value agrees with what has been predicted from the hardness measurements. This indicates that the hardness measurements may not be so bad after all.

The situation of the deep drawn cups remains puzzling. It is unclear why the two cups do not produce a single curve. Let us look at figure 8 again, and in particular to the material points at a strain of 0.3. In the first draw that point has a hardness of about 190, while in the second draw it has a hardness of about 170. These two points have been subjected to the same amount of plastic deformation, and in the same deformation mode (this is known from earlier experiments). That means we have two pieces of identical material with the same deformation history, but the amount of hardening is different! The opposite situation is also present. The material near the upper edge in stages 1, 2 and 3 all have the same hardness (about 200), but the amount of deformation there is quite different as shown in table 1.

Concluding, the work hardening as characterised by the strength differs from the hardening as characterised by the hardness. The strength results show a work hardening which is mainly controlled by the total cumulative effective strain, although the limited number of tests imposed by the size of the specimens precludes a detailed analysis. The hardness results show a work hardening which is not only controlled by the strain but apparently also by other parameters. We can only speculate which those will be.

The obvious question now would be: which of the two parameters studied here (strength or hardness) is right, and which one is wrong. But this question is incorrect. The correct question is: which parameter describes best that aspect of work hardening that I am interested in. To answer this question more fundamental knowledge of both ways of characterising the hardening is needed. The answer however is not without consequences. The hardness measurements show that remnants of the material condition after deep drawing are still visible in the wall after severe ironing. If this is true, then the deep drawing operation has a much larger influence on the properties of the final product than is generally thought today.

Conclusions

The tensile strength and the hardness reveal different aspects of work hardening in sheet metal forming. The hardening as characterised by the tensile strength is largely controlled by the total cumulative effective strain.

The hardening as characterised by the hardness depends on the deformation mode (strain path), and other parameters so far unknown. The material condition created during deep drawing remains visible after wall ironing.

More understanding of the hardness measuring test is needed.

The tensile test has limited use in characterising can wall material.

* Note: this is not exactly true. In general the strain path in deep drawing is straight. However in redraw small deviations may arise from the stretching of the material over the punch nose in the first draw, and from bending and unbending over the die radius and blank holder radius. It is not known if this has any effect on the generation of dislocation structures (hardening).