**Water jet forming of steel beverage cans**

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**Abstract.** This paper describes the process of shaping fully formed beer & beverage cans with a rotating high-pressure water jet. This is a special variant of incremental forming and enables much larger strains in the product than would be expected from tensile tests. The paper presents experimental results describing the effect of various machine and material parameters. A possible mechanism is presented that explains the observations.

**Keywords:** Beverage Cans, Incremental Forming, Water Jet Forming.

1. Introduction

Beer and beverage cans are produced in large series by a combination of deep drawing and wall ironing. This results in a cylindrical can. In many situations it is desirable to give the can a more fanciful shape to emphasize a specific brand. This process is called shaping and needs further forming of the can wall. However, due to the manufacturing process the wall of the can is highly cold worked and as a result has hardened to such a degree that the ductility has reduced to zero: the material fractures immediately in a tensile test. Nevertheless several processes have been developed to form the can wall. One of these is water jet forming. Water jet forming is a special variant of incremental forming, where a high-pressure water jet has replaced the common steel punch [1]. This process is very flexible and fig. 1 presents a variety of products that have been produced.

This paper presents some basic results that have been obtained with this process.

![Fig. 1. Some products produced by water jet forming. Types A and B have no commercial application and are used for testing only. Note the screw thread at the top of type F that has been formed in the same operation. Types A, B, C and E are manufactured from standard 66 mm diameter cans.](image)

2. Process Description.

This process was developed by Ball Corporation [2] and is usually referred to as ‘rheoforming’ in the can-making world. In this process a can is placed inside a mould (die), and over a set of rotating nozzles (typically
2), see fig. 2. The rotating nozzles produce columnated (straight) high-pressure water jets that spray against the can wall and push the can wall outwards. At the same time the nozzles move vertically at a constant speed, so that the point of impact of the water jet travels over the can wall in a spiral trajectory.

At the time there was only one type of machine for this operation, the Belvac CSTR. This is a semi-production machine rated at 10 products/min and not very suitable for research. Some typical data: nozzle rotation 5000 rpm, water pressure 100-350 bar. The machine utilises standard nozzles that are used in dishwashers despite the much higher water pressure applied here; typical nozzle bore: 2 mm diameter. The machine at CORUS has no constantly operating high-pressure water pump but a medium-pressure water pump that activates an intensifier. This is a simple solution but limits the amount of high-pressure water available. The machine can perform four strokes (up-down-up-down) in one operation. As the nozzles have to pass through the can neck (see fig. 2) there is always a certain minimum distance between the nozzle and the can wall, typically 10 mm.

At 5000 rpm rotation and 66 mm can diameter the water jet impact position travels over the can wall at a speed of 16 m/s. This value is much higher than that obtained with mechanical incremental forming machines and illustrates the major advantage of this process: high speed. With a typical vertical feed rate of 0.03"/revolution the vertical speed is 62 mm/s, and the total process time is only a few seconds, which is nevertheless regarded as slow in the can making world. The second advantage is flexibility: Only a mould is required, no complicated process control, and the variety of products shown in fig. 1 illustrates this. This makes this process also suitable for prototyping. The only disadvantage is some possible erosion of the inner can wall by the water jet.

![Fig. 2. Schematic presentation of the process](image1)

![Fig. 3. Relation between expansion and water pressure for can types 1-8 (table 1) in a single stroke operation. Nozzle #16.](image2)

3. Experimental Results

In general two parameters are to be determined: the amount of expansion (increase of the can diameter) obtained with a certain water pressure, and the maximum expansion that can be obtained without fracture. Typical relations between water pressure and expansion are presented in fig. 3.

The following paragraphs show results that have been obtained over the years. Unless specifically mentioned otherwise the results presented below have been obtained with rotational-symmetrical shapes where the expansion is constant in all directions. A wide mould is used so that the expansion is not limited by the mould but by the process and material properties (free expansion), like product B in fig. 1. In such cases the expansion is initially not constant but increases with (vertical) nozzle travel. All numerical values presented in this paper have been measured at the end of the stroke where the expansion has become constant.

Most results have been obtained with cans for which the major properties are presented in tables 1 and 2.
Note that in the wall of typical commercial steel cans (similar to type 4) the total effective (true) strain is in the range of 1 – 2, and the tensile strength is 700 – 900 MPa.

### Table 1. Overview of major can properties.

<table>
<thead>
<tr>
<th>can type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>material grade</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>Q</td>
<td>Q</td>
<td>Q</td>
<td>Q</td>
<td>Q</td>
</tr>
<tr>
<td>sheet thickness [mm]</td>
<td>0.23</td>
<td>0.23</td>
<td>0.27</td>
<td>0.23</td>
<td>0.23</td>
<td>0.23</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>blank diameter [mm]</td>
<td>152</td>
<td>152</td>
<td>152</td>
<td>136</td>
<td>152</td>
<td>152</td>
<td>136</td>
<td>152</td>
</tr>
<tr>
<td>final wall thickness [µm]</td>
<td>121</td>
<td>124</td>
<td>145</td>
<td>75</td>
<td>117</td>
<td>123</td>
<td>98</td>
<td>143</td>
</tr>
<tr>
<td>wall ironing reduction [%]</td>
<td>47</td>
<td>46</td>
<td>46</td>
<td>67</td>
<td>49</td>
<td>46</td>
<td>64</td>
<td>47</td>
</tr>
</tbody>
</table>

Overview of major can properties. All cans are of 66 mm diameter and produced out of a round blank by deep drawing and successive wall ironing. Can type 4 resembles commercial steel beer & beverage cans.

### Table 2. Mechanical properties of the sheet materials and can walls.

<table>
<thead>
<tr>
<th>grade</th>
<th>yield stress [MPa]</th>
<th>tensile strength [MPa]</th>
<th>uniform elong. [%]</th>
<th>n</th>
<th>r</th>
<th>can wall strength [MPa]</th>
<th>can wall elong. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>270</td>
<td>380</td>
<td>17</td>
<td>0.16</td>
<td>1.25</td>
<td>760</td>
<td>0.5</td>
</tr>
<tr>
<td>Q</td>
<td>200</td>
<td>320</td>
<td>25</td>
<td>0.21</td>
<td>0.85</td>
<td>645</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Overview of major material properties measured by tensile testing. The can wall strength has been measured on cans with 46% wall ironing reduction (types 1, 3, 6 and 8), in circumferential direction.

### 3.1 General observations.

By performing several subsequent forming operations on the same can large expansions can be obtained. Levels of 20% expansion (diameter increase) have been obtained on several occasions without major problems (can B in fig. 1). The maximum (theoretical) expansion is as yet unknown, it may be quite high.

Despite the sometimes impressive diameter increase the can height changes only slightly during the forming process. This indicates that the strain mode is basically plane-strain and this has been confirmed by grid measurements.

![Fig. 4. Effect of feed rate (vertical movement per revolution) for can types 4 and 7 (see table 1). Nozzle #16.](image1)

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![Fig. 5. Effect of nozzle type. Type number (2-16) indicates the water flow in l/min at 20 bar pressure. The results are obtained on commercial cans similar to can type 4.](image2)

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### 3.2 Influence of machine parameters.

The influence of the water pressure can be seen in fig. 3 and many other figures in this paper. A certain minimum pressure is needed to overcome the yield stress of the can wall, after that the expansion increases rapidly with pressure until fracture. Fig. 3 also indicates that a maximum level of expansion is obtained, depending on the can type (see also section 3.3); however this level can be increased by performing multiple operations.
For commercial applications the machine builder recommends a speed of rotation of 10,000 rpm! The Belvac machine can operate at this speed, but this requires careful balancing of the nozzles and has not been used in the tests. There is no reason to expect any influence of the speed of rotation other than the overall process time (see also discussion about inertia effects in section 4). Some tests have been carried out at 4000 rpm and 5000 rpm, these showed no difference at all.

The influence of the nozzle feed rate (the vertical movement per revolution) is presented in fig. 4. At higher feed rates a higher pressure is needed to obtain the same level of expansion. This means that the process cannot be speeded up by simply increasing the feed rate. Besides, at high feed rates the trajectory of the water jet on the can wall becomes visible as a spiral track, deteriorating the general appearance. The feed rate of 0.75 mm (0.03”) that is normally used in our tests is an optimum. Note that the feed per revolution is smaller than the water jet diameter (typically 2 mm) so that the spiral overlaps.

During forming the can is internally pressurized. This is done by pressurizing the can prior to the operation with compressed air at 4 bar, and by installing an over-pressure valve in the exhaust pipe so that the water that is sprayed into the can makes the internal pressure increase even more. Note that for a standard 66 mm can with 80 µm wall thickness an internal pressure of 4 bar introduces a hoop stress in the wall of about 165 MPa! The machine has no possibility to actually control the internal pressure, other than by removing the over-pressure valve. Eliminating the internal pressure reduces the expansion at a given water pressure by roughly 25%. However, more importantly, the can wall becomes very crumpled without internal air pressure, causing premature failure of the wall. Apparently the main effect of the internal air pressure is to keep the can wall tight.

The effect of the nozzle bore diameter is presented in fig. 5. The nozzle type number (2-16) indicates the water flow in l/min at 20 bar pressure. The cross-section area is proportional to the type number, and so the diameter is proportional to the square root of the type number; for type #11 the bore diameter is 2.0 mm. As the force on the can wall is proportional to the cross-section area (\( F = 2c.A_p \), see [1]), we expect the expansion to be a function of water-pressure x bore-area. However the results of fig. 5 do not confirm that, and rather show the expansion to be a function of water-pressure x bore-diameter (see also discussion in section 4).

![Fig. 6. Results of two-stroke operations to show the effect of thickness and strength as described in section 3.3. Relative pressure = actual pressure / wall thickness. Nozzle #16. Lable 1, 2, 3, 6, 8 = can type (see table 1).](image)

![Fig. 7. Maximum expansion obtained in a single stroke as a function of wall thickness. Line A is derived from fig. 3 (can types 4, 5 and 7). Line B is from other experiments not described in this paper. Dotted lines show proportionality.](image)

3.3 Influence of can (product) parameters. The relevant can properties are primarily wall thickness and wall strength. However since both are determined by the same forming operations (deep drawing and wall ironing) these effects are difficult to separate; fig. 3 shows the combined effects. A more detailed analysis is
presented in fig. 6. This rather complex figure shows results for a two-stroke operation in which a single stroke is repeated twice. The second stroke is performed after 9% expansion in the first stroke. In this figure a relative water pressure has been defined as: relative pressure = actual pressure / wall thickness. Both the expansion level shown in fig. 6 and the wall thickness refer to the actual can dimensions, so for the second stroke to the can as expanded after the first stroke. The can types used for fig. 6 (1, 2, 3, 6 and 8) all have the same forming history and therefore may be compared. The results form two (nearly) identical groups, one for each material grade. Within each group the influence of thickness has disappeared (compare to fig. 3), indicating that the required water pressure is proportional to the can wall thickness. The results for the first stroke and the second stroke are also basically identical, apart from low expansions where the first stroke requires somewhat higher water pressure. This shows that there is no fundamental difference between first and second (and subsequent?) strokes.

Fig. 6 also shows that the harder material grade P (1,2,3) requires a higher water pressure to form, which is as expected. For low expansions (<5%) the required pressure is 18% more than for grade Q. This is the same difference as the difference in can wall strength (see table 2), indicating that the required water pressure is also proportional to the can wall strength. For higher expansions the difference is less, which may be either a systematic effect or just scatter.

In early tests it rapidly became clear that thick can walls are much easier to shape (less critical) than thin can walls. This is a general principle in sheet metal forming, thicker material being less critical, but never was this borne out as strongly as in these experiments, see fig. 7. As a first approximation the maximum expansion that can be obtained in a single stroke is proportional to the wall thickness!

3.4 Other results. When forming details such as in can A in figure 1 the strain state shifts to biaxial. The deformation becomes more and more like simple stretching and a certain maximum expansion is obtained regardless of the forming procedures. A maximum equi-biaxial strain of 9% was measured for the triangles of can A.

Moulds (dies) can be made from plastic or metal. Hard plastic moulds can be cast which is cheap but the dimensional accuracy is less than for machined metal moulds. Moreover, plastic moulds damage more easily by fractured cans (which occurs frequently in testing). On the other hand plastic moulds yield a smoother can surface than metal moulds, and the trajectory of the water jet is less visible on the can outside. The reason for this is not quite understood.

4. Discussion

Compared to other types of incremental forming water jet forming is very fast, but how fast is it? In a special test on cans of type 1 a momentarily outward speed of 10 m/s, an acceleration of $10^5 \text{ m/s}^2$, and a strain rate of 300 /s have been measured (the strain increment was 5%). These are considerable values and come into the range of true high-speed processes like electro-magnetic forming. This is an extreme case indeed and in many practical situations the values will be lower but these results give an idea of the order of magnitude. This makes the question arise if inertia effects are to be taken into account.

If there are no inertia effects there will always be a balance between the expanding force (the water impact) and the counteracting forces (wall strength x thickness). If there are inertia effects the situation becomes more complicated but generally speaking the influence of can wall strength and thickness will decrease. The observations in section 3.3 however make clear that if there are any inertia effects they must be small.
As a first approximation it can be justifiably stated that the forming resistance of the can wall is proportional to both wall thickness and wall strength (this has been confirmed by other tests not presented here).

The strains obtained in the can wall (basically plane-strain!) by water jet forming are much higher than obtained in a tensile test in which the material fractures immediately due to the large amount of cold work. This is a well-known aspect of incremental forming in general, but the question is how this is caused. A clue can be found in fig. 7 showing that the maximum strain is proportional to the wall thickness. Common theories do not explain such behaviour, unless bending is involved. It was noticed that expansion of the can always starts with some local bending. If there is a situation of stretching with simultaneous bending, it can be shown that under certain (general) conditions the stress-strain curve of a non-hardening material will assume the form shown in fig. 8. The quasi hardening until ε_b will disable necking and the material can be stretched until that value without encountering problems (this analysis will be published in detail elsewhere).

In our tests the bending radius was found to be 3 mm in most cases; for a wall thickness of 0.1 mm the ‘safe’ strain becomes 1.67 %. This is lower than the values shown in fig. 7. Note however that the nozzle feed per revolution is smaller than the water diameter, so that a certain element of the can wall ‘sees’ several passes of the water jet in one stroke, typically 3. This means that in one stroke the elongation will become larger, more in agreement with the data in fig. 7. However, this is still a simplified impression, the actual bending is 3D, and there is a considerable stress in the wall due to pressurisation. Nevertheless, this mechanism can explain all observations qualitatively.

In the analysis presented above we needed the impact force but we cannot measure this force by simple methods. We did assume a simple relation between impact force and expansion: if the expansion is identical in two cases, then the impact force is also identical. But this seems only true if the diameter of the water jet (nozzle bore) remains constant. If the diameter changes, the water jet acts on a different area, and this (apparently) also changes the relation between impact force and expansion. A force exerted on a larger area causes less expansion than the same force exerted on a smaller area. This however may be typical for can shaping where the material thickness is low and deformations are very local. For thicker material this jet diameter effect may be smaller.

5. Conclusions

Forming by a high pressure water jet is a type of incremental forming that shows large flexibility as no complicated process control is needed, only a dedicated mould (die). For the forming of cylindrical products a rotating water jet can be used that enables high forming speeds and consequently high production rates. The procedure stretches the product well beyond the maximum strains found in a tensile test, even if the deformation mode is plane-strain. This enables the forming of highly cold-worked materials like the walls of two-piece beer and beverage cans.

Despite the high process speeds the process shows negligible inertia effects, and the forming can be regarded as a simple force-equilibrium based operation resulting in simple relations with material properties. This will simplify modelling of the process.

References
