Comprehensive Digital Twin of a Beverage Can Body Forming Process and Performance Evaluation

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1 Introduction

Novelis is a world leader in aluminium flat rolled products and a major supplier to the beverage can-making industry. As such, Novelis is deeply involved in supporting the can-making industry to help shaping a more sustainable future together. Reducing the amount of metal used for each beverage can is a major driver for improving sustainability of the beverage can packaging, thus Novelis is actively investigating and developing state of the art modelling tools and approaches to support further optimization of the beverage can.
Novelis has developed a set of forming and performance finite element models for the beverage can body comprising the Novelis virtual can body line. The forming models comprehensively describe all aspects of can body forming, which are relevant to final product performance. The performance models re-create several industry standard tests, evaluating the mechanical performance of the can body. Together, this set of models allows for a comprehensive analysis of a given can body design for evaluation of formability considerations and if a given can body design is fit-for-purpose from a mechanical performance standpoint. The goal of developing the virtual can line is to optimize the can body for minimal material use, while maintaining the mechanical performance required for beverage packaging.
In this work, the virtual can line is presented with a description of the forming stages, the performance evaluation tests and their respective finite element models. An example of evaluation of a can body design is presented and the predictions of the models are validated against available test data for fully formed can bodies.

2 The can body forming process

Aluminium can bodes are manufactured from an AA3104 H19 aluminium alloy in what is known as a draw and wall iron (DWI) process. The DWI process is a multi-step, high-speed, high deformation sheet-metal forming process, in which a flat metal blank is converted into a tall cylindrical can body (Fig. 1).

Fig.1: Formed blank can body.

This process consists of several forming operations, which may vary slightly depending on the can plant configuration. These forming operations include:

- Cup draw
- Re-draw and wall iron
- Trimming
- Necking
- Flanging
- Re-forming (optional)

The cup-draw, re-draw and trimming operations are known in the industry as the “front end” and the necking, flanging and re-forming operations constitute the “back end”, owing to the traditional lay-out of a can plant.
In between the front end and the back end, the cans undergo an internal lacquering process and an external decoration process, followed by a washing process. The internal lacquer serves as a barrier layer between the beverage and the aluminium can material whereas the external lacquer mostly serves decorative purposes. In order to cure the applied coatings and dry the cans after the washer, the cans undergo several thermal cycles at temperatures exceeding 200°C. This causes work hardening recovery in the highly cold-worked metal and reduces the yield strength of the material by a significant amount.

3 Can body performance testing

Formed can bodies undergo an extensive mechanical testing regime to determine whether or not they are fit for purpose. These tests include (Fig. 2):

- Dome reversal pressure
- Axial buckle load
- Drop

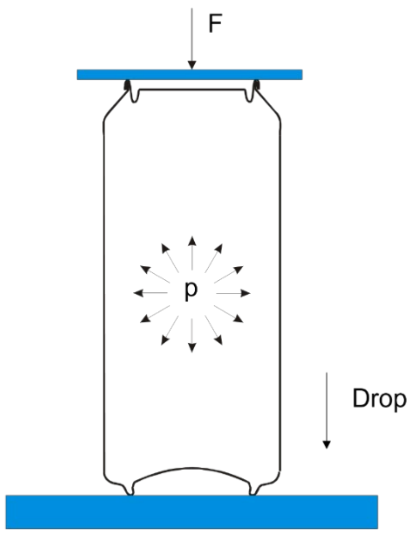


Fig.2: Can body performance testing schematic.

The dome reversal pressure or “DRP” test is an internal pressurization test, where the finished can body is sealed at its open end and then pressurized until the concave dome at the bottom of the can buckles outwards and reverses (Fig.3-a.)). This simulates a beverage can containing a highly carbonated beverage (e.g. a soft drink) being exposed to an elevated temperature. A common minimum pressure requirement in the DRP test is 6.2 bar (90 psi).
The axial buckle load is the peak load the can body can withstand in the axial direction. This is relevant for forming operations, such as necking, the can closing process where the can end is mated to the can body and vertical stacking of empty cans, where the can body is loaded axially. A typical specification for axial load is 1 kN. The can body exhibits two distinct modes of axial buckle:

- Side-wall buckle,
- Bottom squat (Fig. 3-b.))

depending on the morphology of the buckling mode. In side-wall buckle, the cylindrical wall of the can buckles in a stochastic manner, making it a highly perturbation dependant phenomenon. Bottom squat occurs if the side-wall is sufficiently strong to shift the buckling mechanism onto the bottom of the can body, which then buckles axi-symmetrically.
In the drop test, the can is filled with water and sealed with a specified internal pressure (e.g. 5.9 bar). The filled can is then dropped several times in succession (the same can is dropped several times) onto a rigid support from an incrementally increasing height until the dome at the bottom of the can body rolls

out to such an extent, that the can can no longer sit flat on a plane surface (Fig. 3-c.)). A typical starting drop height is 7 cm with 1 cm increments until failure and a typical minimal pass value is 12 cm.

a.) b.) c.)

Fig.3: a.) can body after DRP test, b.) can body after axial load exhibiting bottom squat and c.) can body after drop test.

4 Can body forming models

In the current embodiment of the virtual can line, to evaluate the performance characteristics of the can body design described above, the following forming steps are considered:

- Cup draw,
- Re-draw and bottom forming,
- Re-forming.

The other forming operations are omitted in the standardized workflow, as they have little impact on the performance characteristics. The can body forming processes are modelled in separate simulations both with a 2D axisymmetric approach and a 3D approach using shell elements. The initial aluminium blank is generated for the first forming step (cup draw) and is then transferred, along with the forming history, through the successive forming stages using the `*INTERFACE_SPRINGBACK_LSDYNA` keyword and by including the dynain file in the subsequent step. In all cases, the tools are considered rigid and a penalty based contact with friction is applied to the tool-blank interface.
In the 2D workflow, fully integrated axisymmetric volume weighted elements are used (shell element type 15, number of integration points equal to 4) for the deformable workpiece, and volume weighted 2D axisymmetric shell elements (beam element type 8) for the rigid tools. Five elements through the thickness and an average element size of approximately 0.25 mm in the radial direction are used.
In the 3D workflow, fully integrated shell elements are used (shell element type 16) for both the workpiece and the rigid tools, with 5 gaussian integration points through the thickness. The element size in the radial direction is also 0.25 mm and in the circumferential direction 0.3 mm at the rim of the circular blank. One quarter symmetry is used to reduce calculation time in the forming stages, which can be rotated around the cylindrical axis in post processing to complete the model as required.

4.1 Constitutive model and hardening law

In order to ensure consistent material properties between the 2D axisymmetric and 3D shell element models, the Von Mises yield locus is used. The hardening behaviour of the aluminium alloy is described using an exponential equation:

$$\sigma_Y(\varepsilon_{pl}) = B + (A + K \cdot \varepsilon_{pl})\left[1 - e^{-\frac{c}{A}\varepsilon_{pl}}\right], \qquad (1)$$

where:
A … amount of hardening
B … initial yield stress
K … slope of linear region
c … shape coefficient

This has been found to represent the stress-strain behaviour of can body material well and gives good results in the simulations.
To simulate the softening of the material during recovery in the thermal processing of the can body, two separate flow curves are defined, one for the as-rolled material and one of the material after thermal exposure (Fig. 4). The material properties are changed in the spring-back simulation step following the re-draw simulation. This is a crude approximation of the material properties evolution from a metallurgical standpoint, but it captures the reduction of the mechanical properties of the can body sufficiently well.

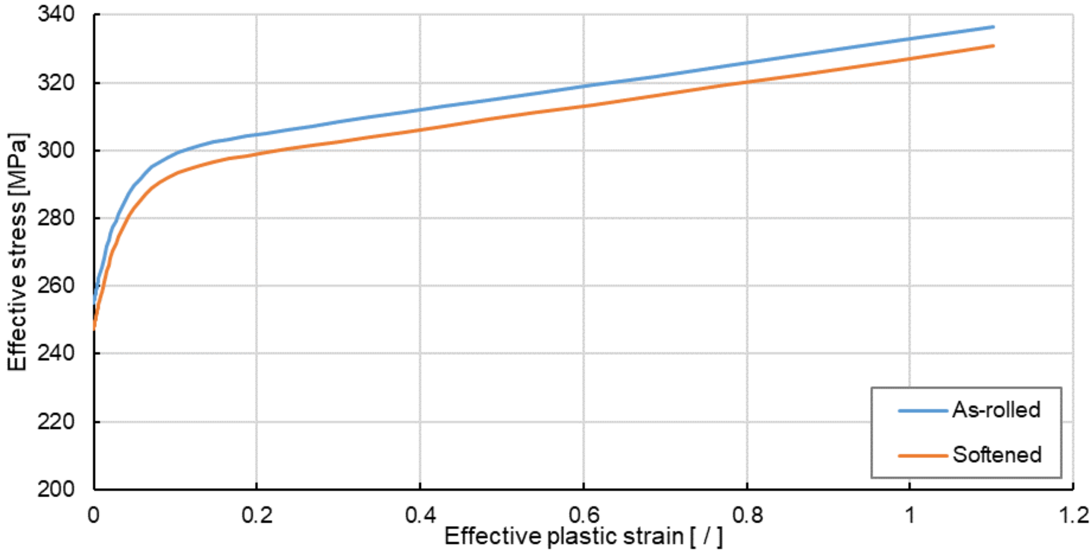


Fig.4: Flow curves of the as-rolled and softened material.

4.2 Cup draw

The initial stage in the can body forming is drawing of a cylindrical cup. This is an example of a cylindrical deep-drawing process, where a cylindrical punch draws a cup from a circular blank, which is held between a fixed draw-die and a constant-force blank-holder (Fig. 5). The gap between the side of the punch and the inner diameter of the draw die is set to approximately 25 % over initial material thickness, resulting in a small amount of ironing at the top of the cup, as the material thickens during drawing. This effect is captured in the 2D axisymmetric model, but not in the 3D shell model.

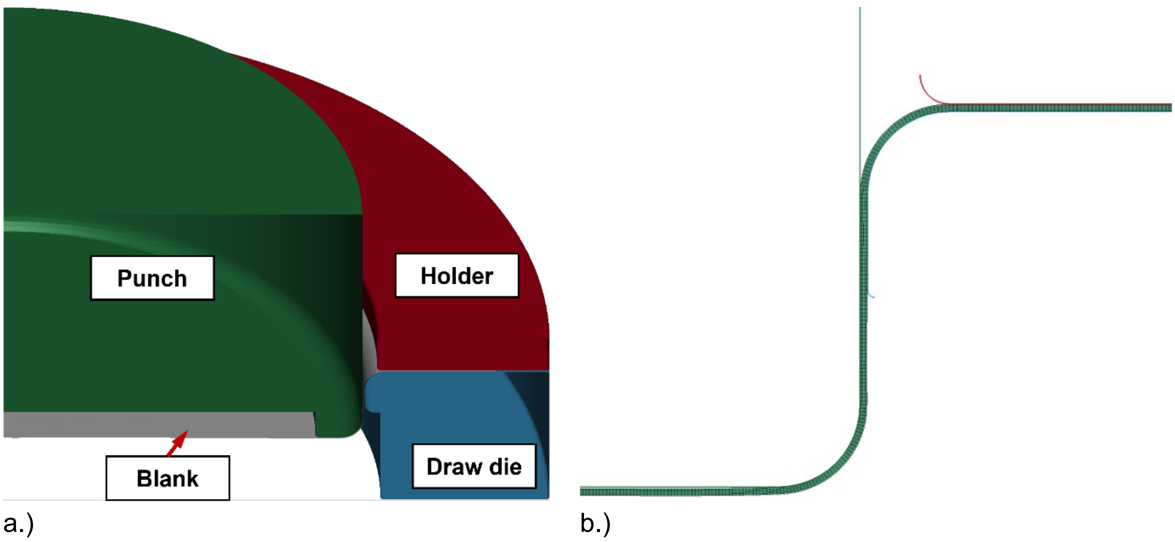
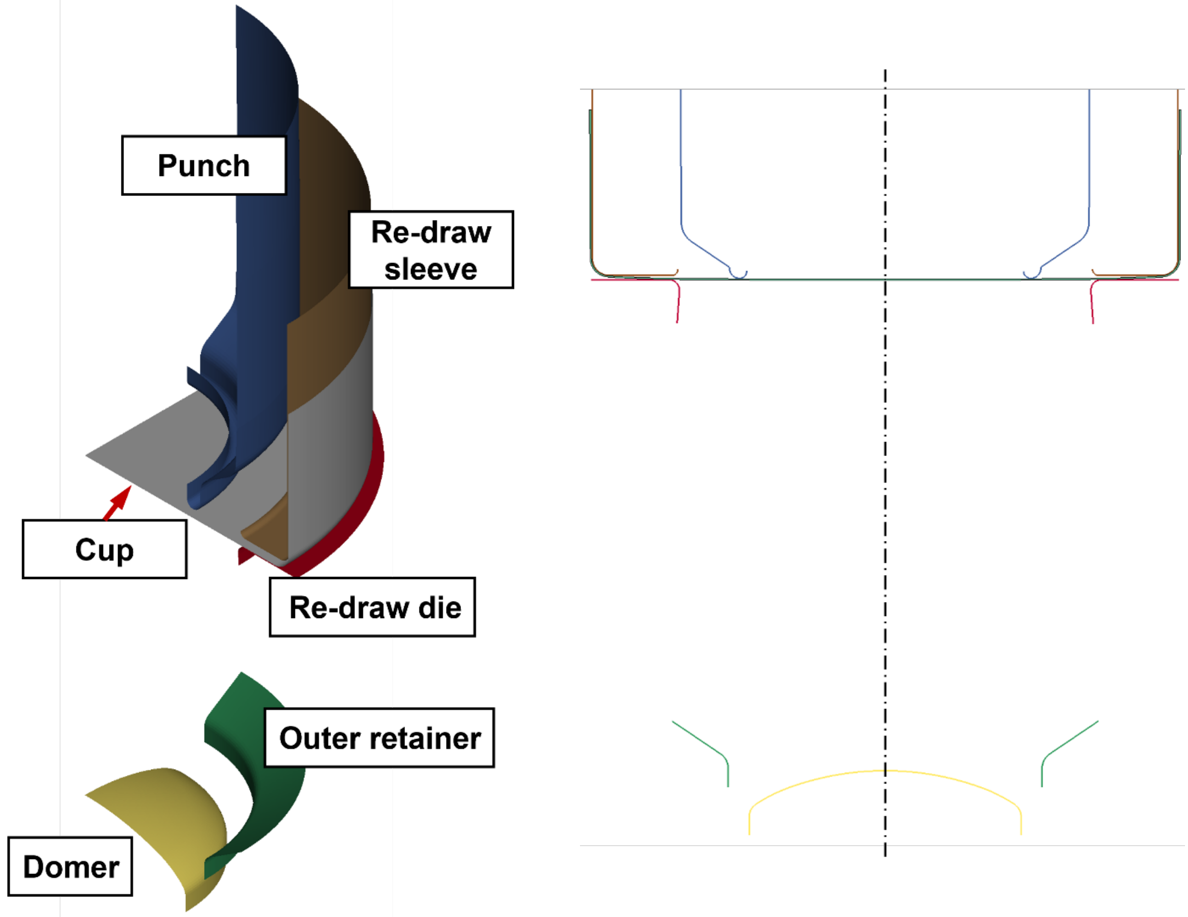


Fig.5: Cup drawing model: a.) 3D shell model and b.) 2D axisymmetric model.

4.3 Re-draw and bottom forming

The formed cup model is transferred to the second forming stage, consisting of the re-draw and bottom forming. The wall iron portion of the physical process is omitted from this model, due to the length-scale incompatibility of the deformation process, i.e., modelling the through-thickness deformation of the side-wall during ironing requires a significantly finer mesh to capture the local deformation gradient.
The cup is placed between a re-draw sleeve and a re-draw die, and a cylindrical punch re-draws the cup to a smaller diameter. At the bottom of the punch stroke, a second set of tools form the dome at the centre, and the stepped periphery of the bottom (Fig. 6).



a.) b.)

Fig.6: Re-draw and bottom forming tooling, a.) 3D shell model and b.) 2D axisymmetric model.

4.4 Re-forming

Re-forming is an additional forming operation used to improve the dome reversal pressure of the bottom of the can body. It is best described as an incremental roll-forming operation where a roller, or a set of rollers, rotate eccentrically to further re-form the legs of the centre dome towards a concave shape, which is otherwise not possible in the drawing operation (Fig. 7).

The formed can body is placed into a fixed receptacle at the bottom and a load is applied to the free edge of the side-wall to prevent the can body from sliding out. A single disc at the middle of the can bottom dome is prescribed a motion along an elliptical path to incrementally re-form the inner legs of the dome. The disc is otherwise fixed in the axial direction.

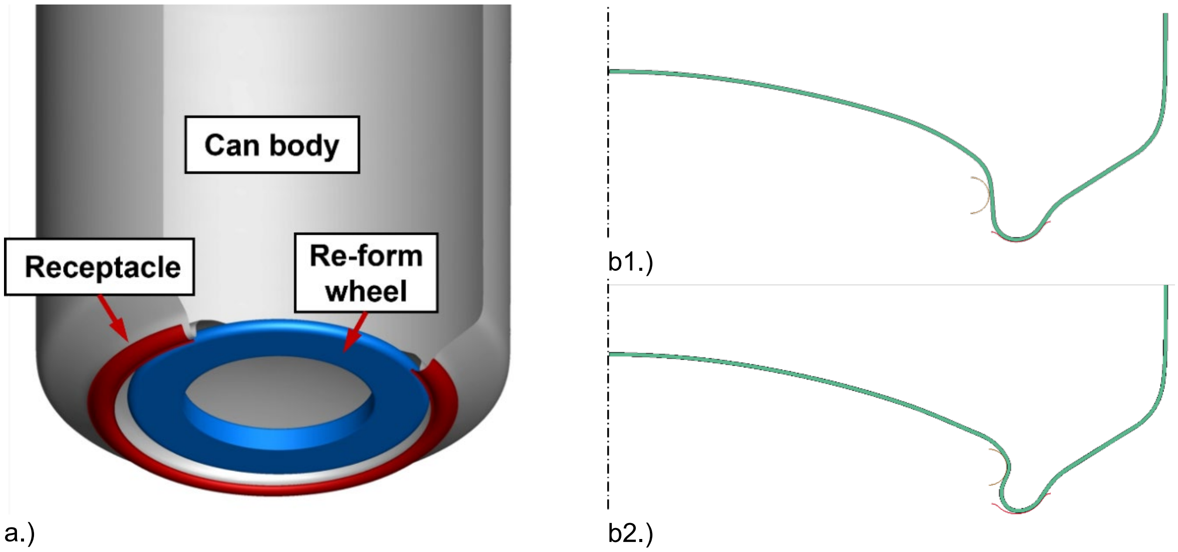


Fig.7: Re-forming operation, a.) 3D shell model, b1.) 2D axisymmetric model initial state and b2.) re-formed state.

5 Can body performance models

The can body performance evaluation models use ether the 2D axisymmetric, or the 3D shell element modelling approach selectively, depending on the load case. In performance testes where the failure mode is approximately axisymmetric, the 2D approach can be applied for increased computational efficiency, otherwise, a full 360° 3D shell element model must be used.

5.1 Dome reversal pressure

The DRP test simulation is performed on the 2D axisymmetric model, with the assumption that the deformation of the dome of the can body remains approximately axisymmetric up to the onset of instability, at which point the pressure carrying capacity of the dome is sufficiently reduced to facilitate an instantaneous system jump.
The formed can body model is fully fixed at the free end of the sidewall using constrained boundary conditions and a distributed segment load is applied to the internal free edge of the axisymmetric mesh to simulate an internal pressure. The pressure is then increased uniformly until the dome reverses. The simulation is stopped as soon as the apex of the dome moves below the lowest point of the initial can geometry (Fig. 8), which is why the fully reversed dome is not shown in this instance.

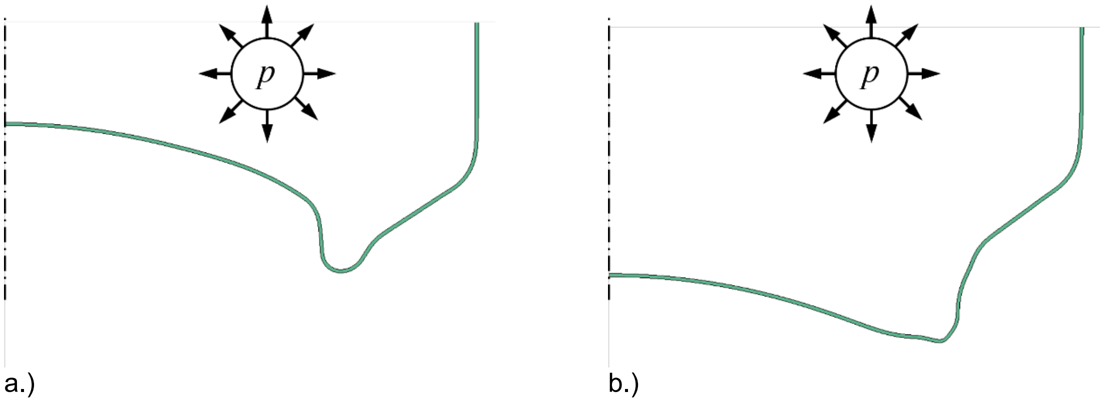


Fig.8: DRP simulation, a.) the initial state of the can body (un-re-formed) and b.) final state of the simulation

5.2 Axial buckle load

The axial buckle load test simulation is limited in this instance to simulating the bottom squat phenomenon, as the complexity of the axial buckle of thin-walled cylindrical structures exceeds the scope of this work. This allows the axisymmetric 2D approach to be applied to the model because of the symmetrical nature of the buckling mode.
A rigid wall is placed at the bottom of the can body and a prescribed displacement with a constant velocity along the axial direction of the can is applied to the nodes on the free edge of the side wall. The reaction force on the rigid wall is tracked as a function of simulation time (Fig. 9). The force-displacement behaviour usually exhibits a clear single maximum in the load, which is taken to be the buckle load.

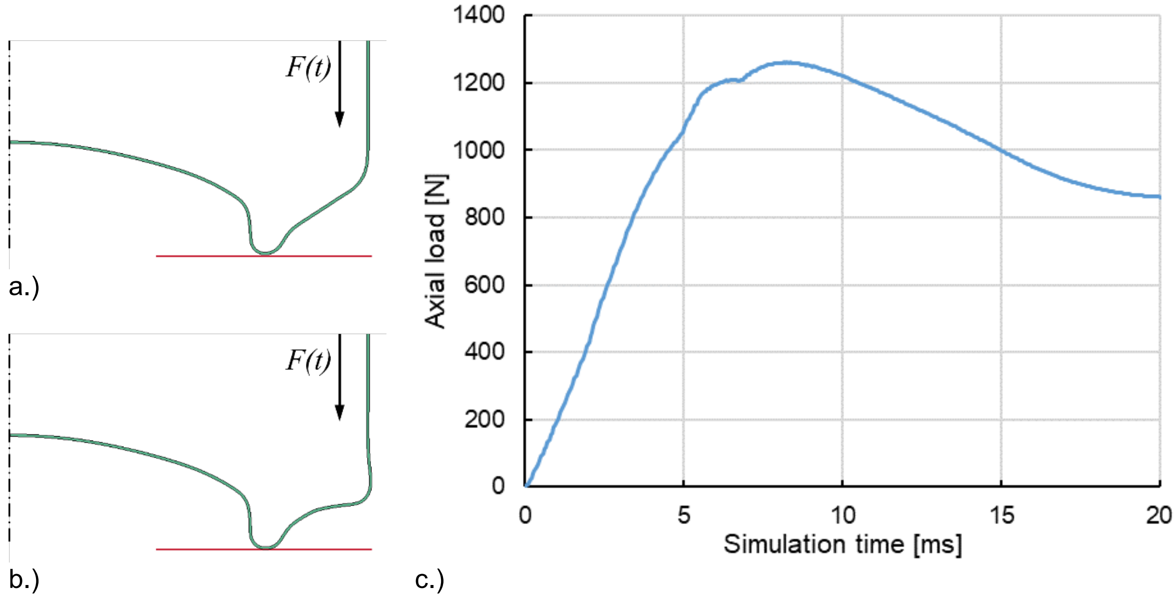


Fig.9: Bottom squat simulation, a.) initial state, b.) deformed can bottom and c.) axial load as a function of simulation time.

5.3 Drop test

In the drop test, the buckle mode was found to be asymmetric, as shown in Fig. 3-c.), which necessitates the used of a full 360° 3D model.
The formed 3D shell element can body model is completed by a top section of the can, including the necked portion and closed top representing a simplified can end geometry, which is added in a post-processing step (Fig. 10). This comprises of shell elements which do not include the previous forming history, as this section of the can does not deform plastically during the drop simulation.
A part representing the liquid is generated using 3D hexahedron solid elements and assigned a **`*MAT_ELASTIC_FLUID`** material model representing the properties of water. The space above the liquid is assigned an equation of state property, to represent the correct pressure change corresponding to the change in volume caused by the deformation of the can.
The entire model is then assigned an initial velocity corresponding to the free-fall velocity from the desired drop height and the impact against the rigid wall at the bottom is simulated.

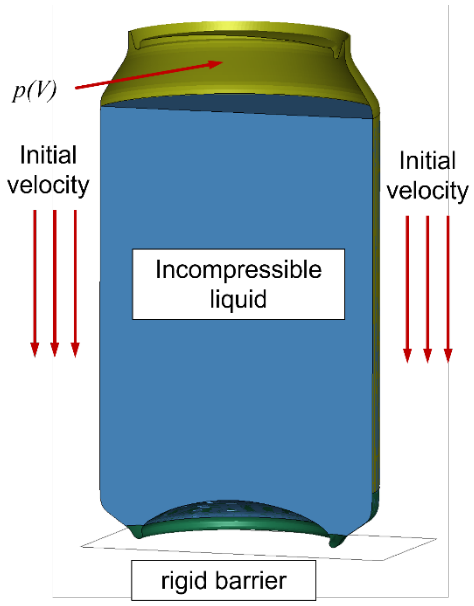


Fig.10: Can body drop model cross-section.

6 Results and validation

The preliminary validation results are focused on the dome reversal pressure test only. The validation was carried out against test data collected at the Novelis Global R&D Centre Kennesaw, GA, USA. Can bodies were formed using several different variations of process parameters. The can bodes were produced on a laboratory scale can production line using equipment that is comparable to the state of the art in the canning industry.
The forming parameters are varied in such a way, as to achieve variations of the final can body geometry in the following parameters (Fig 11.):

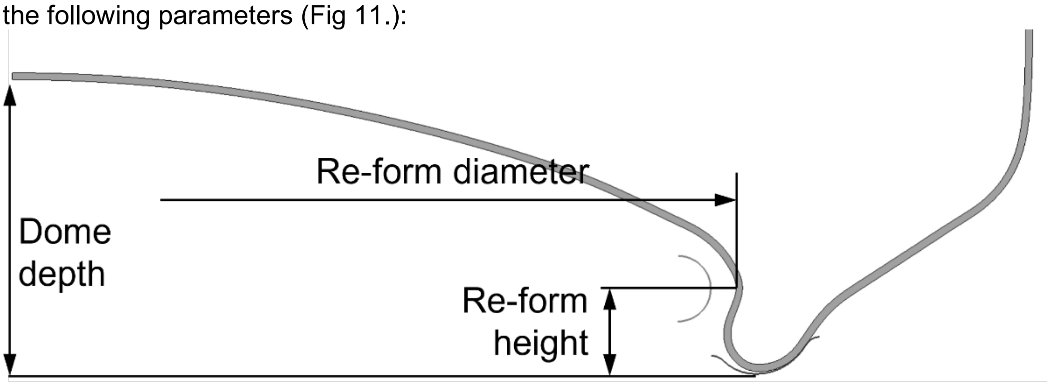


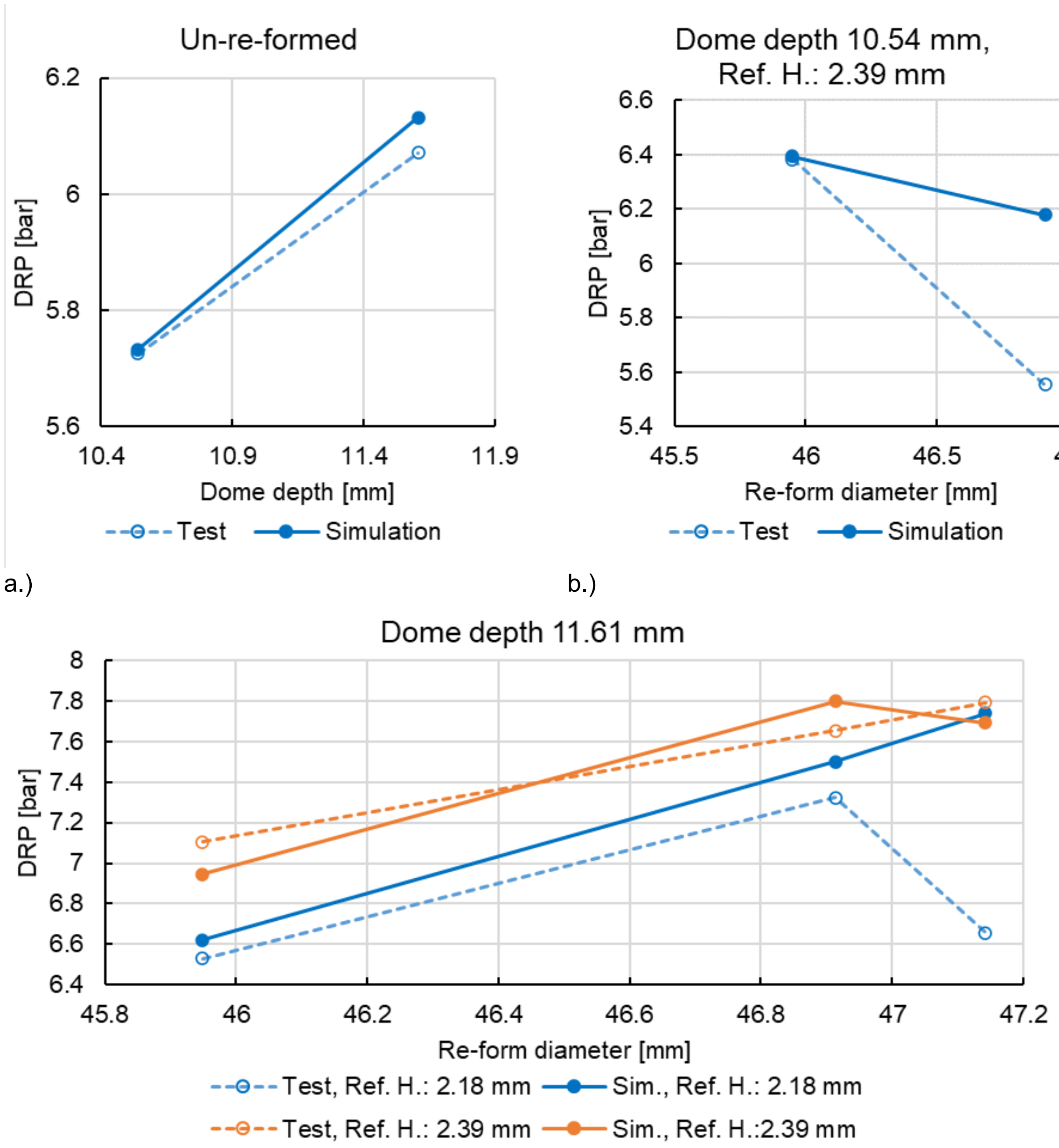
Fig.11: Can bottom geometrical parameters.

The forming parameters used in the validation are shown in Table 2, along with their minimum and maximum bounds where applicable:

Parameter	Min.	Max.
Dome Depth [mm]	10.54	11.61
Reform Diameter [mm]	45.95	47.14
Reform Height [mm]	2.18	2.39
Gauge [mm]	0.260	
Yield strength [MPa]	253.7	

Table 1: Validation test forming parameters.

The dome reversal pressure results of the finite element simulations are shown in Fig. 12 below. Several variations of the dome depth and re-forming set-up are considered.



c.)

Fig.12: Dome reversal pressure comparison between test results and simulation predictions: a.) as a function of dome depth of the un-re-formed can body, b.) as a function of re-form diameter, dome depth 10.54mm and re-from height of 2.39 mm, and c.) as a function of re-form diameter at a dome depth of 11.61 mm for two different re-form heights.

Fig. 12-a.) shows the comparison of the dome reversal pressure for the un-reformed can body at different dome depths. The simulation results match the test data well, with the finite element model over-predicting the test data slightly. The difference is larger at the larger dome depth, where the relative error is approximately 1.0 %.

Fig. 12-b.) shows the comparison of the dome reversal pressure at different re-from diameters, at a dome depth of 10.54 m and a re-form height of 2.39 mm. The simulation results fit well at the lower re-form diameter, however, the error at the higher re-from diameter is significant at approximately 11.2 %.

Fig. 12-c.) shows the comparison of the dome reversal pressure at different re-from diameters and different re-form heights for a dome depth of 11.61 mm. The fit shows good correlation for both re-form heights at the lower re-form diameters of 45.95 mm and 46.91 mm, where the error is below 2.5 % for all cases. At the highest re-from diameter of 47.14 mm there is significant divergence from the trend, where the test data shows a significant drop in dome reversal pressure, which is not captured by the simulation. The largest difference is for the re-form height of 2.18 mm, with an over-prediction by the finite element model of approximately 16.3 %.

The trend of over-predicting the test data at high re-from diameters is consistent between all variants, indicating that there might be a physical phenomenon present in the forming process which is not captured by the finite element model. Possible sources of inaccuracy could be material modelling, stemming from the Von Mises yield locus assumption, or inaccurate description of the friction properties in the tool to can contacts, or an accumulation of those influences.

7 Summary

A full suite of finite element models has been developed simulating all forming processes and performance tests relevant to the performance of the can body bottom. These models allow for full virtual fit-for-purpose testing of a can body design, which can be used for design analysis and optimization purposes, such as down-gauging and general reduction of material usage, or for failure root cause and process optimization.

The accuracy of the finite element model has been quantified on the case of dome reversal pressure simulation. It has been shown, that for a large range of can bottom forming scenarios, the accuracy of the FEA predictions is sufficient to facilitate informed design decisions, with a relative error of approximately 2.5 %. Particularly at high levels of re-forming, there is an effect in the physical system which is not adequately captured by the finite element model, which causes the accuracy to significantly decrease. Further work is required to understand these effects and improve the model accordingly.

Work on evaluating the accuracy and validating the axial buckle load and drop tests is ongoing, however, producing beverage can bodies in a controlled environment that can be accurately reproduced in the virtual models is resource intensive and the available data is often not complete.