Chained simulations of forming and mechanical load cases to assess dome reversal pressure and drop resistance of beverage can body

Mouaad El Mouss[1], Gilles Guiglionda[1], Camille Linardon[1], Laurent Nguyen[1]
Lukasz Brodawka[2], Maciej Kociolek[2]

[1] Constellium Technology Center, C-TEC
[2] CANPACK S.A.

1 Abstract

This work presents a modeling approach to simulate can performance in two standard industry quality tests: the dome reversal pressure test (DRP test) and the can drop impact resistance test (also called drop test). To study the influence of the can bottom geometry on its mechanical response, key can body forming steps are first modeled. This allows to capture local plastic deformation, thinning and work hardening that have a significant impact on the mechanical resistance of the can bottom. Then, specific mechanical load cases corresponding to the DRP and drop tests are modeled.
The simulation results are comparable to experimental measurements obtained for two 25 cl can bottom designs differing by their internal reforming diameters and having a different balance of performances in DRP and drop tests. A numerical study of the influence of the reforming diameter on the performance in DRP and drop tests of this 25 cl can design was then conducted. While a linear increase in DRP with the reforming diameter is predicted, the performance in drop test shows a non-monotonic relationship with the reforming diameter. This numerical analysis suggests that an optimal reforming diameter can be defined to obtain the best combination of performances in DRP and drop tests.

2 Introduction

The aluminum beverage can is a highly engineered product providing excellent beverage conservation and combining impressive mechanical resistance with low weight and infinite recyclability. Lightweighting beverage cans to use less material is not only a cost-efficient solution for can producers but also supports their effort toward sustainability. Decreasing the weight of cans helps to reduce their environmental footprint. However, reducing the metal thickness while maintaining can bottom mechanical resistance requires the design of a bottom profile with improved characteristics. Although all standard can bottom designs are based on a central dome shape to better resist internal pressure, variations exist in the detailed can bottom geometrical profile.
Two specific qualification tests are used in the industry to validate the structural performance of a beverage can: the dome reversal pressure (DRP) test and the can drop impact resistance test (also called drop test). These tests consist in measuring the resistance of the can bottom to internal pressure and to an impact following a can drop, respectively. In both tests, can failure is considered when the dome shape at the bottom of the can reverses outward. The DRP test measures the minimum internal pressure which leads to dome reversal. The drop test measures the minimum drop height which causes dome reversal of a can filled with water and pressurized at a given internal pressure. Introducing a modification of the bottom geometry often leads to an opposite effect in the performance of these two tests.
Finite element analysis is a key tool to design new or optimized can bottom profiles. Several studies have analyzed the effect of the bottom profile of beverage cans on their performance but mostly in dome reversal pressure tests. Some of the studies [1], [2], [3] relied on geometrical optimizations of the can bottom profile to improve the performance in DRP test without considering profiles obtained after a reforming step. In a more recent study [4], can bottom forming steps were included in the simulation and the performance of reformed bottom profiles in DRP tests was analyzed. In [5], a set of forming and performance finite element models was described but results in DRP tests only were presented and discussed.
The purpose of this study is to develop with LS-Dyna reliable numerical models able to predict, for various can bottom profiles, obtained with or without reforming, their mechanical resistance not only in dome reversal pressure tests but also in drop tests. In this article, results are focused on the influence of the internal reforming diameter.

3 Numerical Models for Finite Element Analysis

3.1 Can forming

To study the influence of the can bottom geometry on its mechanical performance, the key can body forming steps are first modeled. This captures the material deformation history and thus any local thinning or work hardening. The material properties used are those of the AA3104 aluminium alloy. The H19 temper alloy is used for the initial forming steps that are performed in the bodymaker: redrawing and dome forming. For the reforming operation, the material softening due to the varnishing process (thermal treatment of 10 minutes at 204°C) is taken into account by using the constitutive behavior of H48 temper.
Chained simulations of the redrawing, dome forming and reforming steps are carried out using LS-Dyna. The following modeling strategy is chosen to give efficient and accurate metal forming simulation results. For the can body, the models are using 3D shell elements with full integration (**`ELFORM=16`**) and seven thickness integration points. This extends the calculation time but produces less convergence troubles during springback. The shell element thickness change is considered, and the material model **`*MAT_PIECEWISE_LINEAR_PLASTICITY`** is used for the can body. All tools use shell elements and rigid material. The contact type used between the tools and the metal is **`*CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE`**.
Each forming step is followed by a springback calculation for load release and uses the deformed mesh and the full stress-strain state of the can body resulting from the previous step. The keyword file "dynain" is used for this purpose.

3.1.1 Redrawing

Redrawing is the first forming operation in the bodymaker. It consists in reforming the cup by pushing the metal with a punch through the redraw die while a load applied to the redraw sleeve helps to prevent wrinkles.
The model setup is described in Fig 1. Only a quarter of the cup geometry is simulated while a half of the geometry is considered for the tools to avoid contact problems on the cup sides. Symmetry boundary conditions are imposed on both the cup and the tools.
As shown in Fig. 2, the initial cup geometry definition has a linear thickness profile along the height of the cup wall in order to mimic the thicker top wall that is obtained after drawing a cup in a cupper.

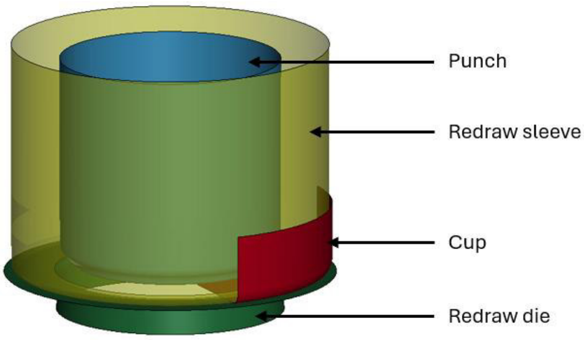

Fig.1: Redrawing model setup.

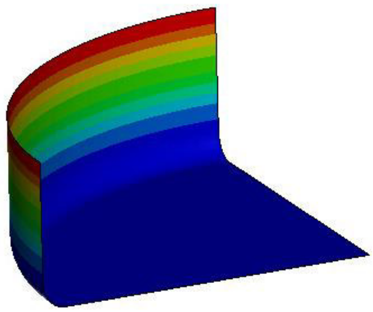

Fig.2: Cup initial thickness profile.

3.1.2 Dome forming

In the dome forming step, the punch moves with the can bottom towards the domer and hits the clamp ring to form the peripheral chime.
The model set-up is described in Fig 3. The clamp ring is connected to a viscous spring to avoid vibration. The velocity imposed to the punch is computed from the bodymaker stroke per minute and associated acceleration. The imposed velocity is a function of the punch displacement and becomes zero at the final displacement corresponding to the theoretical dome depth, as shown in Fig. 4.

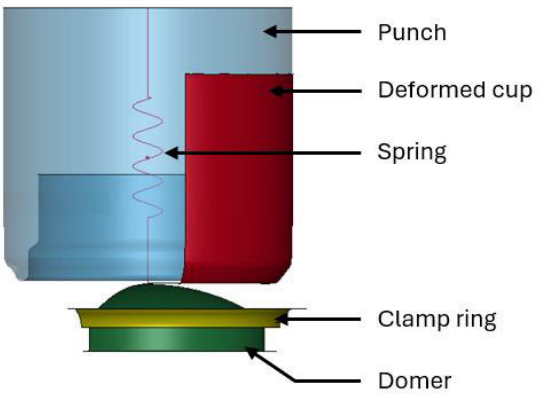

Fig.3: Dome forming setup.

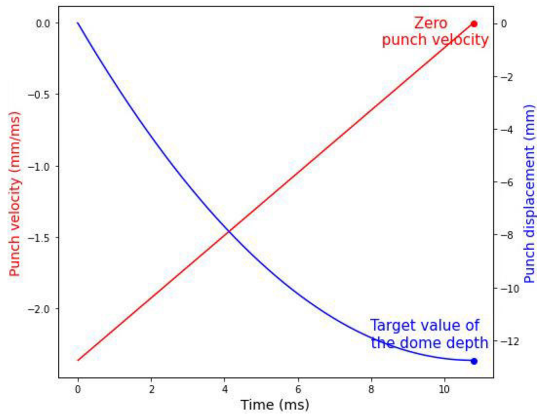

Fig.4: Imposed velocity to the punch.

An artificial spring is introduced between the punch and the top of the can to simulate a vertical force coming from the ironing that is not modelled here. The values of spring stiffness, clamp ring force and coefficient of friction between tools have been adjusted based on a comparison to experimental measurements performed on a can prototyped at C-TEC. A series of simulations were conducted to identify the set of parameters that provides the best fit in terms of thickness profile and metal sliding during redrawing and dome forming.

3.1.3 Reforming

During the reforming step, a roller is moved around against the dome wall in order to reform it.
The model set-up is described in Fig 5. The can bottom is first reconstructed from a quarter to the full bottom using symmetry. The can bottom is then maintained on a fixed holder thanks to an axial load, while a prescribed motion is applied on the roller center axis to follow a parametrized trajectory in both rotation and displacement. The vertical position of the roller and its trajectory determine the dimensions of the reforming height and the reforming diameter. An internal pressure of 1.2 bar is applied inside the can during the reforming operation.

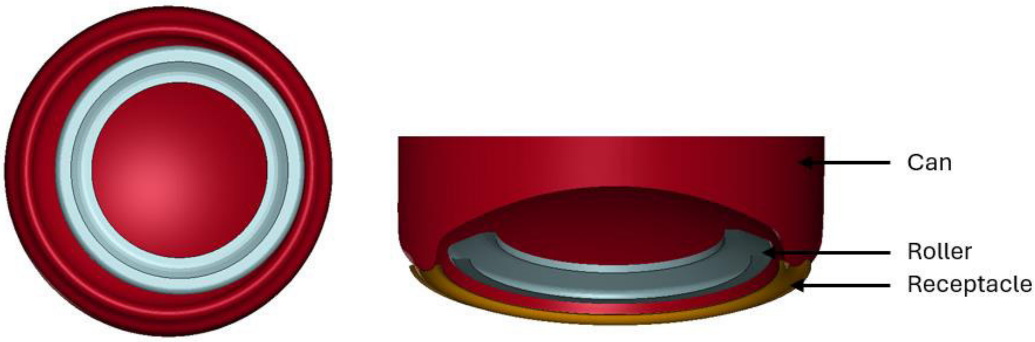

Fig.5: Reforming model setup.

3.2 Dome reversal pressure test

The dome reversal pressure test consists in analyzing the resistance of the can bottom under an increasing internal pressure to determine the minimal internal pressure leading to an irreversible buckling of the dome.
The numerical model uses the deformed mesh and the full stress-strain state of the can body resulting from the previous forming steps. The model then relies on the construction of a closed volume defined as an airbag, assuming a uniform internal pressure distribution by applying normal forces to the defined airbag surfaces. Pressurization is controlled using a mass flow rate method (shown in Fig 6) to reproduce the physical test and to better identify the dome reversal pressure as the pressure suddenly decreases right after reversal. The non-linear analysis starts in implicit dynamic solver and automatically switches to explicit when reversal occurs.
The closed volume is composed of the can bottom, a wall and a lid. The wall thickness is predefined in the model as described in Fig 7.

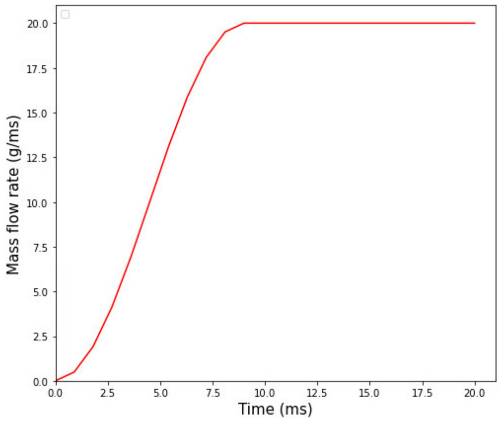

Fig.6: Controlled flow rate.

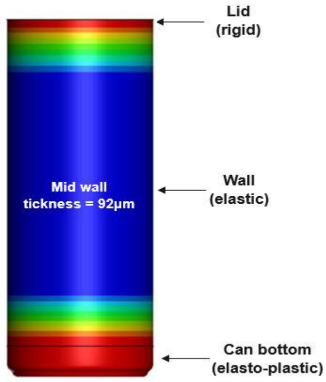

Fig.7: Thickness distribution of the closed volume.

3.3 Drop test

The drop test is designed to determine the minimum drop height leading to the dome reversal of a can filled with water and pressurized at a given internal pressure. In the experimental test, it is deemed that a can fails when the can bottom is deformed so that the can rocks on a flat surface.
In this work, the modeling of the test is simplified thanks to the use of water columns to reflect the effect of the water on the can bottom during the final impact. The principle of this concept is to associate each element of the bottom part of the can with a column of water as illustrated in Fig 8. The mass of each column is computed for each shell element depending on its surface and orientation (see Fig 9). This mass is then distributed on the nodes of the element. No mass is applied on elements in the reformed area as shown in Fig 11.

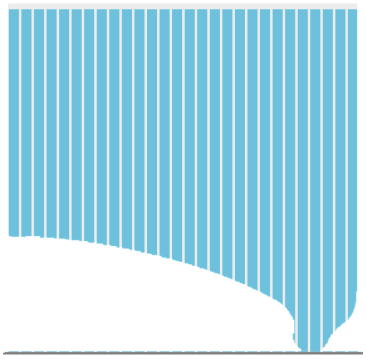

Fig.8: Water column concept.

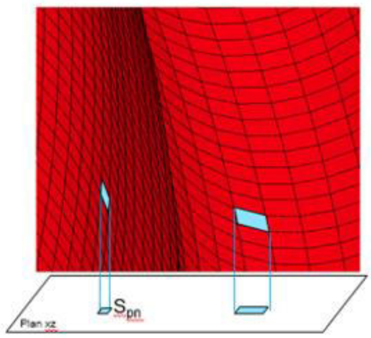

Fig.9: Illustration of shell projection.

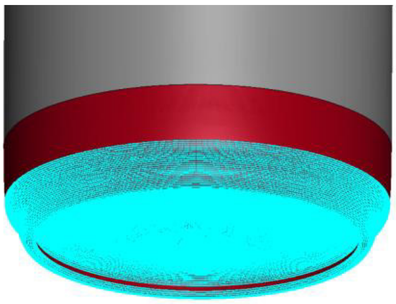

Fig.10: Bottom nodes where a nodal mass is applied.

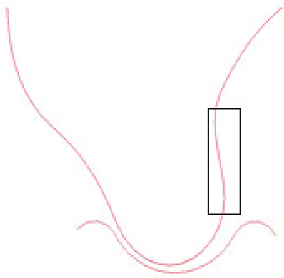

Fig.11: No mass in the reformed region.

The drop test is subsequent to a can pressurization step which is computed separately. The applied internal pressure is 5.9 bar to be consistent with the experimental test data provided by CANPACK. The application of this internal pressure is maintained during the drop simulation of the filled can. The impact velocity representative of a drop from a certain height h is defined as $V = \sqrt{2gh}$, where g is the gravity.

In this study, only a single drop test is modeled to determine the drop height leading to failure, while in the experimental test, the can is successively dropped from a height that is incrementally increased until failure occurs.

4 Results and comparison with experimental data

The numerical models previously described have been used to simulate performances in DRP and drop tests of 25 cl slim can designs having different internal reforming diameters.
First, the numerical predictions have been compared to experimental data for two specific sets of reforming parameters (defined on Fig. 12): a reforming height of 2.4 mm for both cases and two internal reforming diameters of 44.13 and 44.52 mm.
Then, the model has been used to extend the study of the influence of the internal reforming diameter on the can bottom performance in DRP and drop tests over a larger range of values.

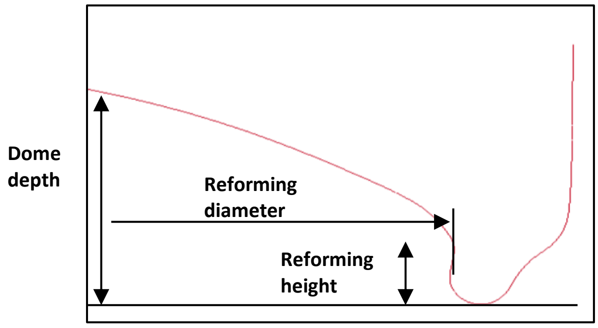

Fig.12: Schematic of the key geometrical dimensions after reforming: reforming diameter and reforming height.

4.1 Validation of the numerical models on a 25 cl can with two different reforming diameters

To validate the numerical models, several simulation results obtained for a 25 cl can design with two different reforming diameters have been compared to experimental results.

First, a geometrical comparison of the influence of the reforming step on the dome depth is shown in Fig. 13. Both simulations and experimental measurements show that during the reforming step, the dome depth is affected and that using a larger reforming diameter leads to a lower final dome depth. However, the simulations tend to overestimate the dome depth after reforming.

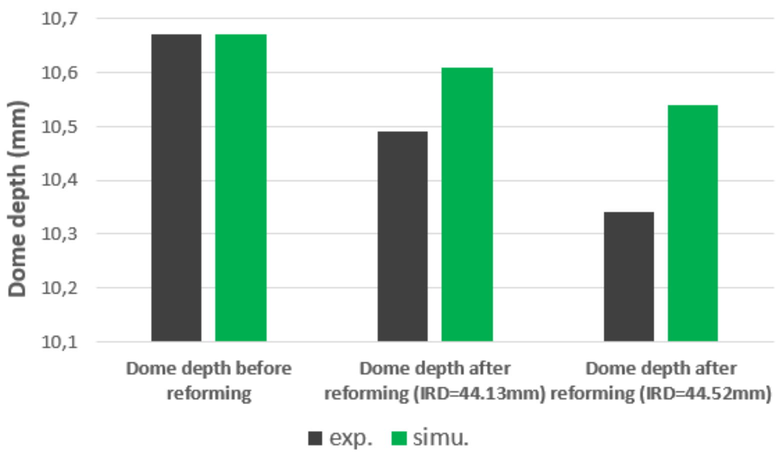

Fig.13: Comparison of the dome depths between simulation and experiment.

The output of the numerical model for the dome reversal pressure test is illustrated in Fig. 14 showing a graph of the dome growth as a function of the increasing internal pressure. The dome growth refers to the displacement of the central node of the simulated bottom profile during pressurization.
When the bottom buckles, the internal volume of the can suddenly increases and the internal pressure drops as can be seen in Fig. 14. The maximal internal pressure reached thus corresponds to the Dome Reversal Pressure value.

In Fig. 15, the simulated dome reversal pressure is compared to experimental results. In the graph, the average and minimum values of the experimental data obtained for each can configuration are represented in black and grey respectively. The values in green correspond to the simulation results.
The simulation results in terms of Dome Reversal Pressure are rank the two can configurations correctly but underestimate the values compared to experiment.

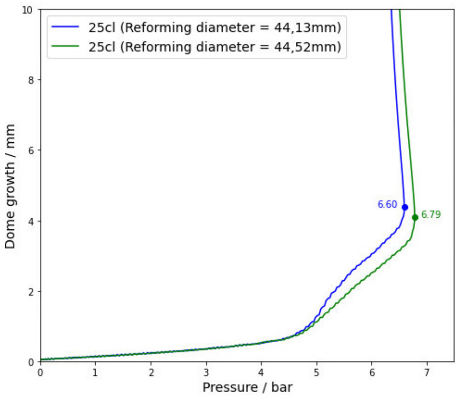

Fig.14: Output of the DRP numerical model.

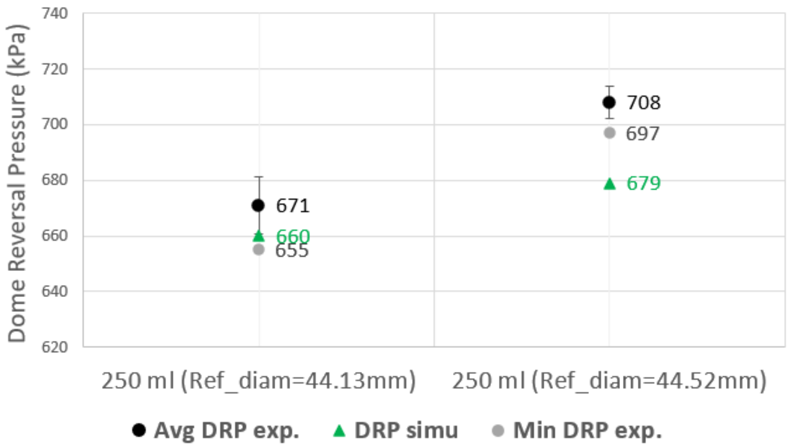

Fig.15: Comparison of simulation results with experimental results for DRP test.

Drop test simulations have also been performed for both 25 cl can configurations and compared to experimental values. The simulation results represented in green in Fig 16 correspond to the minimum drop height leading to a dome reversal. A drop from a height below this value does not lead to a reversal. The Fig. 16 shows a very good correlation between simulation results and experimental results. For both configurations, the drop height at failure obtained in simulation is in the range [μ, μ-σ], where μ is the average experimental height represented in black in the figure, and σ is the standard deviation.

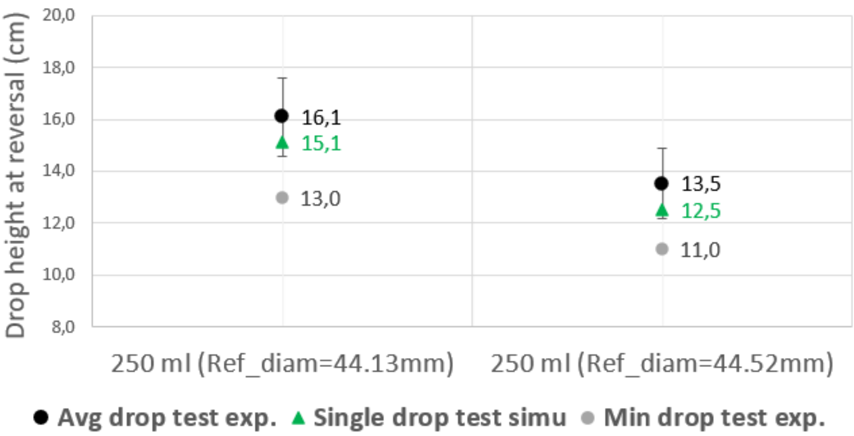

Fig.16: Comparison of simulation results with experimental results for drop test.

4.2 Numerical study of the influence of the reforming diameter on the can performance in DRP and drop tests

The simulation results presented above show a good correlation with the experimental results. Therefore, a numerical study of the influence of the reforming diameter on a 25 cl can performance in DRP and drop tests has been launched to extend the experimental study.
By adapting the parameters describing the movement of the roller in the reforming step, dome profiles with various reforming diameters have been obtained. The reforming diameters studied are in the range between 43.25 mm and 44.52 mm. The height of the reforming diameter, on the other hand, is kept constant at 2.4 mm for the different bottom profiles, as shown in Fig 17.

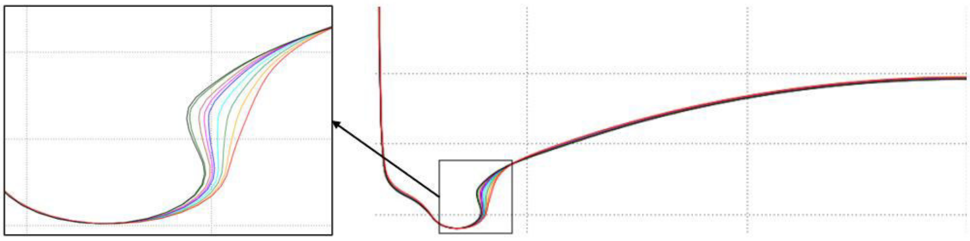

Fig.17: Dome profiles with different reforming diameters.

Figure 18 shows the simulation results of DRP test and drop test as a function of the reforming diameter. The internal pressure at reversal in the DRP tests are plotted in blue for each of the dome profiles. The obtained results indicate a linear relationship between the dome reversal pressure and the internal reforming diameter. As the internal reforming diameter increases, the dome profile becomes more resistant to internal pressure.
On the other hand, the minimum height leading to a dome reversal in the drop tests (shown in green) displays a parabolic shape with a maximum when plotted as a function of the reforming diameter. The performance in drop test first increases with reforming, then reaches a maximum for reforming diameters in the 43.64 mm to 44.13 mm range and finally decreases with further increase in the reforming diameter. This numerical analysis suggests that an optimal reforming diameter can be defined to obtain the best combination of performances in DRP and Drop tests. For the 25 cl can design considered in this study, an optimal reforming diameter at a fixed reforming height of 2.4 mm would be greater or equal to about 43.8 mm.

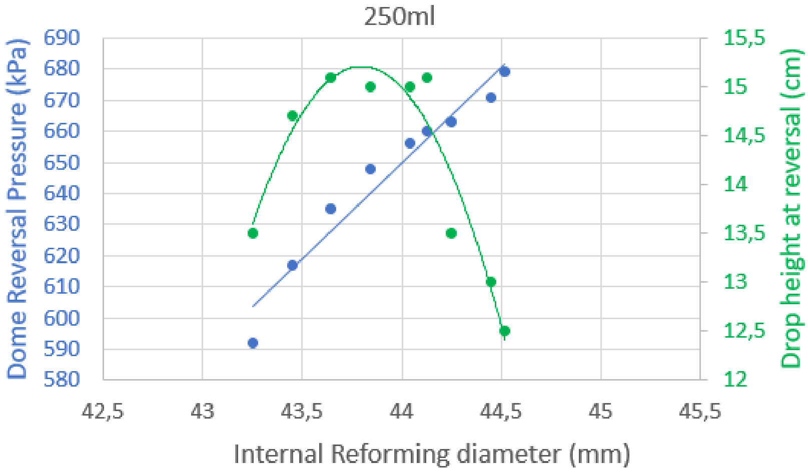

Fig.18: Numerical DOE on internal reforming diameter.

5 Conclusions

A modeling approach based on chained finite element models has been developed to simulate can bottom performance in two standard industry quality tests: the dome reversal pressure test (DRP test) and the can drop impact resistance test (also called drop test).
In this approach, three key forming steps (i.e. can body redrawing, bottom forming and reforming) are first modeled in order to capture the entire material deformation history and account for any local thinning or work hardening in the can bottom. Then, specific mechanical load cases corresponding to the DRP and drop tests are modeled.
The simulation results have first been compared to experimental measurements obtained for two 25 cl can bottom designs differing by their internal reforming diameters and having a different balance of performances in DRP and drop tests. The simulated can bottom geometry, dome reversal pressure and drop height leading to can bottom reversal were close to the experimental values with acceptable deviation for the two cases.
A numerical study of the influence of the reforming diameter on the performance in DRP and drop tests of this 25 cl can design was then conducted. While a linear increase in DRP with the reforming diameter is predicted, the performance in drop test is showing a non-monotonic relationship with the reforming diameter. The performance in drop test is first improved by the reforming operation but then decreases when the reforming diameter exceeds a certain value. This numerical analysis suggests that an optimal reforming diameter can be defined to obtain the best combination of performances in DRP and Drop tests.

6 References

[1] Bhakuni N.D, Trageser A.B., "Structural optimization methods for aluminum beverage can bottoms", Proc. ASME,17th Design Tech. Conf., (1991), p. 265-271

[2] Utsunomiya H., Nishimura H., "Effect of base profile of a DI beverage can and material properties on the dome reversal pressure", Journal of Materials Processing Technology 97 (2000), 54-60

[3] Khan, M., Levy, C., Hameed, A., Khan, Z., Orakzai, K. et al., "An Analysis of Dome Reversal in Metal Beverage Container Based on Finite Element Methods", *Structural Durability & Health Monitoring*, *6(2)*, (2010), 53-68.

[4] Rekas A., Latos T., Brodawka L., Kociolek M., Siedlik M., Budzyn R., Fijalkowski M., "Numerical analysis of relationship between height and geometry of bottom of a beverage can and its resistance to increase in internal pressure", 10th European LS-DYNA Conference, Würzburg, Germany, (2015)

[5] Jurendic S., Weiser M., "Comprehensive digital twin of a beverage can body forming process and performance evaluation", 14th European LS-DYNA Conference, Baden-Baden, Germany, (2023)