Method to Determine the Stress-Strain Response of As-Formed Thin-Walled Tubular Structures Using a Flaring Apparatus

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Abstract. Finite element simulations are used extensively to refine the forming steps of draw and wall iron (DWI) aluminum bottles; therefore, accurate material data is required. Unfortunately, the material properties of the base sheet cannot presently be used for simulation of the later forming stages due to preceding significant deformation (ironing) and thermal treatments. Measuring the stress-strain response using traditional methods (e.g. tensile test) becomes increasingly difficult at later stages of the bottle forming process due to a significant diameter reduction of the bottle neck from successive die-necking stages. Moreover, failure during forming tends to occur in the final deformation stages when the bottle opening is rolled over, creating a brim roll, at which point brim roll splits may occur. Knowledge of the stress-strain response prior to the roll over may lead to improved product design, reduced waste, and an optimized product. Therefore, this work details a flaring apparatus and data analysis method to determine the stress-strain response in the die-necked region of thin-walled aluminum bottles fabricated from AA3104 sheet metal.

1. Introduction
The draw and wall iron (DWI) process of manufacturing metal food and beverage containers, e.g. beverage cans, is widely accepted in the industry as the most efficient way of producing high volumes of light and durable containers. Aluminum bottle production is an extension of this technology which allows bottles to be produced using largely the same production methods during the initial stages of forming. In this process, a flat sheet of metal is blanked, deep-drawn and re-drawn into a cylindrical cup then finally, the sidewalls are ironed to reduce the thickness and obtain a cylinder of appropriate dimensions. This cylinder is then mechanically shaped in a necking die by inserting it from the top into successively smaller diameter dies to obtain the shape of the bottle neck. Finally, finishing operations are carried out to create the necessary features required for the bottle to accept a sealing closure. The final stage of bottle forming is an incremental curling process, where the top edge of the bottle is curled outwards to create a sealing feature and an aperture that is safe to drink from.

The die necking and finishing process is of particular interest in forming analysis as the most common modes of material failure are either wrinkling during die-necking or material fracture in the curling process, as shown in Figure 1. In order to carry out useful numerical analysis of this portion of the forming process, the mechanical properties of the material need to be known. Ideally, the evolution of
work hardening during die-necking could be determined. Tensile testing is of limited usability in this respect as the neck diameter and various features on the bottle become too small to allow for tensile test specimens of acceptable size to be extracted directly from the bottle.

![Figure 1. Example of a brim roll split.](image)

Alternative methods, such as micro-pillar compressions tests [1] and micro tensile tests (with specimen length on the order of 5mm), and inverse analysis of instrumented micro hardness indentation, have been evaluated; however, their usability has been found to be limited for several reasons: 1) difficult, costly, and time consuming sample preparation, 2) complex measurement techniques, 3) only local material properties of a very small region can be measured, and lastly 4) high scatter of measurement results.

For these reasons, a need for a new approach was apparent, one that can measure the global mechanical properties of a larger region, requires relatively little sample preparation and can be carried out using simple testing methodology. Several methods of controlled expansion of a cylindrical wall were evaluated as presented by Dick et al. [2] (flattened tension test, tube flaring, tube inflation, and ring hoop tension test). Of these methods the tube flaring test was deemed the most appropriate as limited specimen preparation was required. Additionally, there have been several published works detailing modeling methods of the tube flaring process[3, 4, 5, 6, 7, 8]. Kim et al. [8] developed a concise closed-form analytical solution that was shown to have good accuracy and was easy to use and, therefore, it was adopted for the present work to calculate the flow stress based on the measured load-diameter response. Kim et al. proposed that flaring load, $F$, could be approximated as

$$F \approx m \bar{\gamma} \left[ \frac{1 + B}{B} \right] \left[ 1 - \left( \frac{D_2}{D_1} \right)^B \right] \left( \frac{\pi D_2 t}{\cos \alpha} \right),$$

where $\alpha$ is half the flaring tool angle, $\mu$ is the coefficient of friction, $t$ is the current thickness, $m$ is a constant related to Tresca’s yield criterion, $D$ is the current diameter, $\bar{\gamma}$ is the flow stress, and $\beta = \mu \cot \alpha$. In the present work, the formula was rearranged to determine the flow stress based on measured load and diameter. Thickness was measured before and after testing and a linear change was assumed. Friction was assumed to be constant and was determined by comparing the predicted flow stress to uniaxial tensile measurements. A finite element model was developed to study the effect of flaring angle and coefficient of friction.

2. Finite Element Model

The finite element analysis method using the commercial code LS-DYNA was applied to the tube flaring concept to determine the feasibility of the test, establish base process parameters, and identify likely functional tooling geometry.
A 2D axisymmetric modelling approach was adopted for its simplicity. This allows for a good level of spatial fidelity coupled with acceptable simulation run times. The model, shown in Figure 2, consists of a conical indenter, modelled as rigid using axisymmetric beam elements and the top portion of a bottle at a pre-determined stage in the necking process. The bottle is modelled using axisymmetric, fully integrated shell elements in a uniform mesh of 0.075 mm element size. The used material model was an isotropic elasto-plastic model with a von Mises yield locus. The stress-strain response was input directly as a load curve. Placeholder data considered to be typical of such an alloy was used for the initial analysis. It should be noted here that the isotropic von Mises yield locus assumption is not strictly valid for these alloys, thus deviations in simulation results from actual experiments are expected. In particular, the reduction in thickness due to expansion is not accurately captured in the model.

![Figure 2. Finite element model of the bottle flaring test.](image)

Several cases were evaluated using the model, focusing on the taper angle of the conical indenter and the influence of friction on the test. The angle is the included angle of the cone and three taper angles were evaluated: 30°, 45°, and 60°. Friction was introduced into the model using Coulomb friction. The friction coefficient $\mu$ was varied as well: $\mu = 0.0$, 0.1, and 0.2.

2.1. FEA Results
The force-displacement curves calculated using simulations were evaluated. During the results analysis four distinct modes of deformation became apparent. These modes included:

1. Initial bending,
2. Loss of contact at the top,
3. Uniform expansion, and
4. End of bottle neck straight region.

The deformation modes are illustrated in Figure 3 against the predicted force-displacement curve for the case of a 60° taper angle and $\mu = 0.1$. Initially, the bottle top is bent outwards gradually until it conforms to the cone sidewall. At this point, a short loss of contact between the cone and bottle occurs at the top edge of the bottle. After the contact is re-established, a region of uniform expansion follows. This is likely the region most useful for flow curve determination. Since the bottle neck consists of
several steps, when the indentation depth reaches a step on the neck, the measurement region is fully exhausted. A similar deformation pattern was reported by Daxner et al. [7] and Kim et al. [8].

![Finite element predicted deformation modes during bottle flaring.](image)

Figure 3. Finite element predicted deformation modes during bottle flaring.

Influence of the coefficient of friction on the predicted force-displacement response is shown in Figure 4a. The friction influence investigation was carried out using a cone angle of 60°. The coefficient of friction influences the results in the expected way, linearly increasing the force as the coefficient of friction increases, while maintaining the four deformation modes. For the case \( \mu = 0.2 \), at the end of the uniform expansion region, the bottle top buckled, causing the decrease in force.

Influence of the cone angle is shown on Figure 4b. All cone angles were evaluated with a coefficient of friction of \( \mu = 0.1 \). In much the same way as the coefficient of friction, increasing the cone angle increases the force for a given cone displacement. Changing the cone angle slightly influences the loss of contact region, where the effect becomes less pronounced and occurs over a larger region of indentation as the cone angle decreases.
3. Experimental Methods

Tensile testing was performed to calibrate the results from the flaring tests and analytical modeling approach. Flaring of bottles at three different stages in the necking process, called T2, T3 and T4, corresponding to three bottle opening diameters of approximately 32, 25, and 22mm, respectively, was performed to predict the stress-strain response at the top of the bottles.

3.1. Tensile Testing

Sub-miniature tensile specimens, with dimensions modified from ASTM B557 [9], were extracted from the top of the bottles at the T2 stage in the hoop direction. The hoop direction was chosen to closely match the expansion experienced during the flaring process. T2 was chosen to ensure a suitable amount of material for specimen extraction. Some specimen curvature was present after specimen fabrication; however, the effect of this curvature was minimal considering the sheet thickness. A total of four specimens were tested; two from each bottle. Specimen size and bottle diameter limited testing to one specimen from the very top of each bottle and one below the first specimen. Figure 7b shows the engineering stress-strain results from the sub-miniature specimen testing and demonstrates small tensile elongations due to the considerable cold work applied to the material.

3.2. Bottle Flaring

The bottle flaring apparatus consisted of a load frame, a set of flaring tools, and a vision system with custom analysis software. A displacement controlled compression platen was used to apply load to the bottom of an inverted bottle at a constant crosshead speed of 0.5mm/s. Three sets of steel flaring tools (with included angles of 30°, 45°, and 60°) were machined based on the aforementioned finite element modeling results; however, only the 45° and 60° tools were used for the present work due to limited test specimen supply. As shown in Equation 1 both load and diameter are inputs to determine the flow stress. Diameter could have been determined from crosshead displacement and flaring tool angle; however, the elastic deflections and bottle buckling could lead to incorrect measurements. Therefore, an imaging system consisting of a digital camera, telecentric lens, and telecentric illuminator were positioned to measure the bottle diameter. Figure 5 shows a mock-up of the flaring system. Telecentric lenses and illuminators are ideal for this type of measurement as they produce high-contrast transitions between objects and background simplifying edge detection methods as demonstrated by the inset of Figure 5.

![Figure 4. Finite element predicted force-displacement curves. a) effect of coefficient of friction, and b) effect of cone angle.](image-url)
The figure clearly shows the edges of the bottle (on top), the flaring tool (on bottom) and the flared edge (middle). Edge clarity was sufficient that thickness measurements of the flared material could be estimated. A disadvantage to this imaging system is the inability to detect deformation anisotropy; however, the constrained nature of the flare should minimize the potential error. Due to limited supply of progression bottle specimens only one test was performed for each bottle/flaring tool combination.

4. Results
Figure 6a shows the measured load-diameter increase for the two flaring tools at the three stages in the necking process. The increase in diameter was used to effectively normalize the curves for improved visualization. A similar response is observed compared to the finite element predictions; however, the loss of contact was experimentally observed to occur midway through the expansion phase instead of at the beginning. Reasons for this loss of contact are currently being investigated. The data from Figure 6a along with Equation 1 was used to determine the stress-strain response at the top of the bottle as shown in Figure 6b. As the results show, the stress starts very high before tapering off to values of approximately 300MPa. The high start of the stress-strain curve is believed to be a result of the initial bending that the analytical model is not equipped to deal with. Comparing the load-diameter increase response with the stress-diameter increase shows that bending is the culprit for the high initial stress, as shown in Figure 7a. By selectively ignoring this bending region, a more suitable stress-strain response is obtained as shown in Figure 7b. The tensile curves are also included for reference. It is immediately evident that the achievable strains are significantly higher with the new method. However, the consistency of the data needs improvement. Additionally, the decreasing stress as a function of increasing strain requires investigation, but may be related to the Tresca assumption in Equation 1.
Figure 6. a) measured load-diameter increase, b) calculated engineering stress-strain.

Figure 7. a) Determination of expansion zone and b) comparison of adjusted flaring stress-strain curves and tensile curves.

5. Conclusions

It has been demonstrated here that a tube flaring test can provide quantitative data about the mechanical properties of thin-walled die-necked bottles at bottle opening diameters that exclude other forms of mechanical testing, or at least make them prohibitively impractical. The stress levels calculated from the measured load-diameter increase relations are in line with expectations; however, the materials work hardening response over a larger range could not be captured. In this investigation, the available sample size was not large enough to allow for in depth testing and optimization of the methodology. Additional work is required to better evaluate the analytical solution and to improve the repeatability. It is unclear at this point whether the results scatter is a consequence of the tests itself or of actual differences in the tested samples.
The finite element analysis showed some qualitative agreement with the measurement results and was useful in the initial stages of test development. The use of an inverse numerical method to determine the flow curves might have advantages in accuracy over the current analytical method if a representative numerical model can be established. This inverse approach could also account for the observed early-stage bending.

References

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