 SDHM, vol.6, no.2, pp.53-67, 2010

An Analysis of Dome Reversal in Metal Beverage Container Based on Finite Element Methods

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Abstract: Aluminum metal beverage container is used in packaging foods and chemical industries because of its superior hold, formability, corrosion resistance and join ability. The 80 percent of the container cost is material and aluminum metal is expansive one. The beverage container industry is struggling for potential saving from weight reduction in each container, while meeting the three structural performance standards which have been established to assess the adequacy of the container design. These are axial column load, drop resistance and internal pressure. This paper relates to the internal pressure standard which states that container must withstand at least 90-100PSI or more internal pressure without buckling (reversal of dome). The purpose of this research is to minimize the weight of an aluminum beverage container as well as fulfilling the entire remaining design parameters such as applied loads, maximum stresses at critical locations and keeping in view all other constraints. A number of alternative solutions are analyzed at a very low cost, using simple FE analysis. Based on these results, promising designs are further analyzed using more complex but accurate FE techniques. A series of different designs are developed, analyzed and an optimum design is considered. The linear analysis is done using Cosmos Works, Solid Works and ANSYS. The results are validated using available experimental and numerical data.

1 Introduction

The profile of the bottom of a beverage can is generally defined by a series of intersecting arcs and lines. Dimensional parameters can be derived based on the size of the intersecting arcs and lines and their positions relative to one another. The dimensional parameters include such things as the radii of arcs, the degree of slant of lines and the height and length of certain intersection points relative to a fixed

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reference. The performance properties evaluated are often those of dome reversal pressure and response to axial loading. Dome reversal pressure is the amount of internal pressure required for the dome at the bottom of the can to be reversed in direction from concave to convex and depends largely on the geometrical features inside the bottom rim or stand. Corona (1998) studied the dome reversal of metal beverage container. Nardini et al. (2003) presented a method for development of the can bottom profile and a can with a domed bottom structure. Han et al. (2005) worked at shape optimization of the two-piece aluminum beverage bottle bottoms structures.

2 Experimental Scheme of Input and Output Data

In this research paper we have investigated the effect of the change of the base profile of aluminum beverage containers on the dome reversal pressure. The major emphasis in our research is on how to reduce the dome reversal by varying different design variables of the base profile of a typical aluminum beverage container.

Experiments were performed using three Aluminum Beverage Cans at the "Crown Cork & Seal" Research Center at Wantage UK. A very basic hand operated pressurizing device was used, and the pressure was displayed on a digital meter in terms of Bars of pressure. The beverage can used was open at the top i.e. no lid was present, water was filled in that open top Aluminum can and was sealed with a special device having a small hole where the pressure pipe was attached in order to pressurize the can. A dial indicator was used to get the movement of the dome outwards as we applied the pressure using the pressurizer. The schematic is shown in the Figure 1a.

The pressure was applied gradually and reading from the Dial Indicator was taken after each consecutive pressure rise. The pressure is applied gradually on a specific

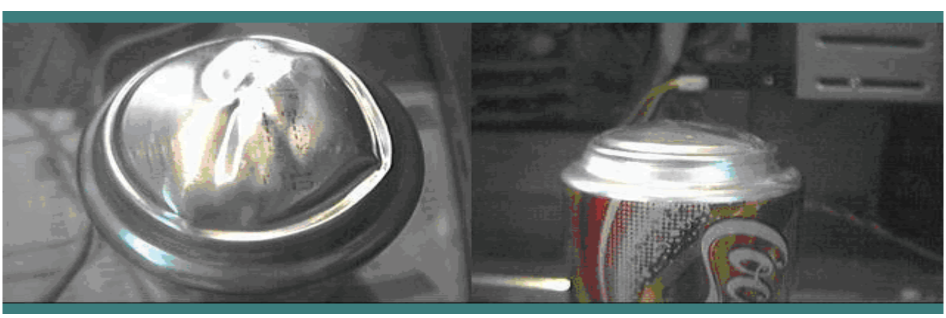

Figure 1: Dome reversal phenomenon in beverage container

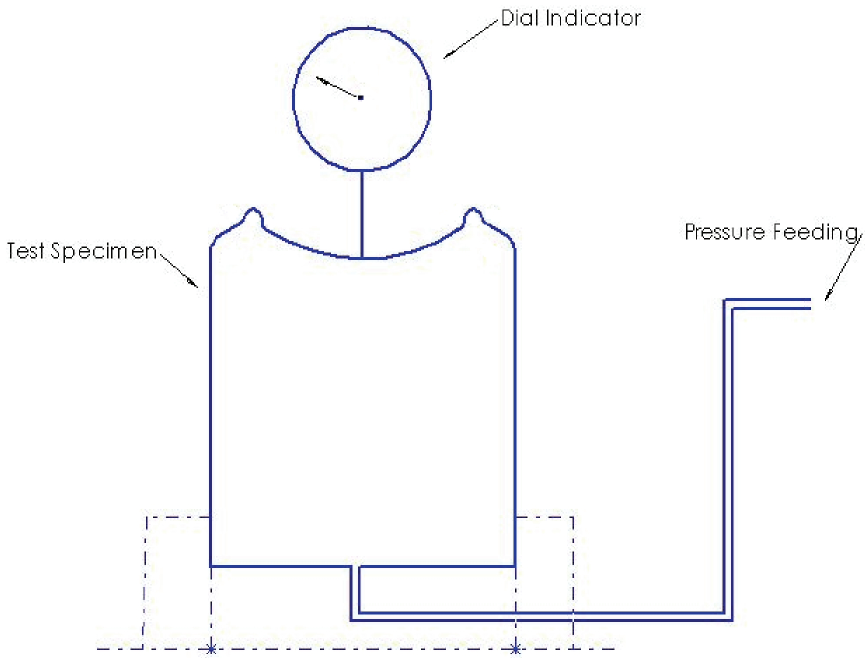

Figure 1a: Schematic of the experimental setup

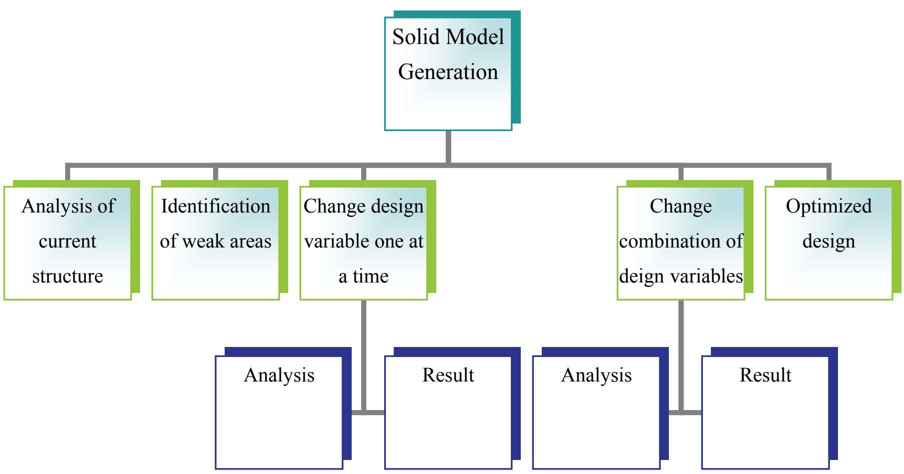

Figure 2: Process flow diagram

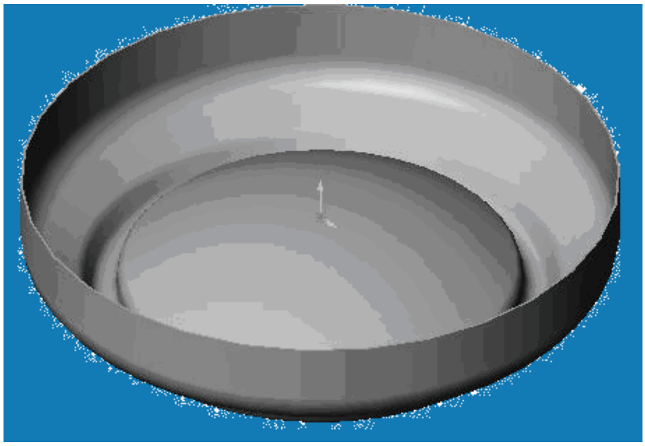

Figure 3: Aluminum beverage dome model

Table 1: Values of Pressure evaluation parameters obtained for selected specimens

Sr#	Pressure	Dome Growth	Pressure	Dome Growth	Pressure	Dome Growth
1	16.24	0.08	0	0	19.14	0.9
2	29.435	0.16	20.3	0.1	32.48	0.17
3	43.79	0.25	29.725	0.15	43.5	0.24
4	51.185	0.3	44.08	0.24	51.765	0.3
5	58	0.36	51.04	0.28	58.725	0.36
6	61.625	0.41	59.595	0.37	61.77	0.4
7	65.685	0.49	65.685	0.47	65.54	0.46
8	68.875	0.56	72.645	0.72	68.875	0.54
9	72.645	0.74	77.14	0.99	72.5	0.67
10	77.285	0.97	80.33	1.25	76.56	0.91
11	79.895	1.28	83.955	1.51	79.895	1.3
12	83.955	1.58	87.145	1.79	84.535	1.6

device and readings are taken after each consecutive pressure rise as in Table 1.

Container design analysis problem cannot be solved analytically because of the complexity of the part's shape and boundary conditions as in Figure 1. ANSYS, Cosmos Works and Solid Works were used to model the structural response of the container designs. The predictions from the models then verified against measured data (at least for the existing design).A simple flow diagram is shown in Figure 2 to show the process undertaken in this research work.

3 Analysis of Current Structure

Initially the current design used by the beverage industry is analyzed. The analysis is performed in Cosmos Works and ANSYS by gradually reducing the values of the current design variables to a minimum on each of the iteration step by step. The 3D Model (bottom only) is made using Solid Works as shown in the Figure 3. After making the solid model, in the Cosmos Works the Study (name) is defined and analysis is selected. Model is restrained from its sidewall and an internal pressure of 100 PSI (0.6897 N/mm^2) is applied normal to the each wall/plane. Material properties are defined (E = 69 GPa, υ = 0.33) and the model is then meshed by using a medium size mesh. The analysis is then run which after solving the problem gives us the results in the form of displacement, stress, and deformation graphs. The model is then analyzed using the data from those graphs and results are drawn from that analysis. The steps in the analysis are defined in Table 2. The obtained values assess the stress condition and displacement characteristics of the base of the container for a constant load condition with varying the current design variables as shown in Table 3.

Table 2: Solid Works/Cosmos& ANSYS Steps &Objective in modeling and simulation of Aluminum Container's dome

Model	3D
Study	Container
Analysis	Linear/Nonlinear
Restraint	Sidewall
Pressure	100PSI
Direction	Normal to wall/plane
Material properties	E=69GPa (Modulus of elasticity) V=0.33 (Poisson ratio)
Pressure range	90-100PSI
Design	890B
Manufacturer	Crown Cork and Seal Ltd UK
Material type	Aluminum (3003-3104)
Mesh Generation	Medium size
Analysis	Static/Dynamic
Results	Displacement, Stress, Strain
Hallucination	Matlab
Benchmarking	Experimental, Numerical

Table 3: Values of Maximum Displacement and Maximum Von Mises Stress obtained by Cosmos Works and ANSYS

Parameters	**Iterations 1-6**					
Maximum Displacement[mm] by COSMOS	0.6519	0.6347	0.6400	0.6698	0.7250	0. 8011
Maximum Von Mises Stress[N/mm^2] by COSMOS	675	652	654	675	719	766
Maximum Displacement[mm] by ANSYS	0.6519	0.6349	0.6402	0.6699	0.7253	0. 7984
Maximum Von Mises stress[N/mm^2] by ANSYS	658	635	633	653	698	774

Table 4: Different parameters with upper and lower bounds ranges

Serial #	Symbol	Meaning	Upper and lower bounds(mm)
01	D1	Spherical Radius	20.8 < D1 < 22.5
02	D2	Dome countersink radius	0.55 < D2 < 1.8
03	D3	Stand rim radius	10 < D3 < 11.9
04	D5	Dome depth	0.762 < D5 < 1.8
05	D12	Doming die radius	37 < D12 < 40

4 Results and Discussions

This research aim is to minimize the buckling load factor. Initially the static analysis is performed on the initial design; the optimization analysis is done to find the optimum design of the beverage container bottom profile. The design variables D1, D2, D3, D5, and D12 shown in Figure 4 are not to exceed some upper and lower bounds. The upper and lower bounds imposed on the design variables are given in Table 4.

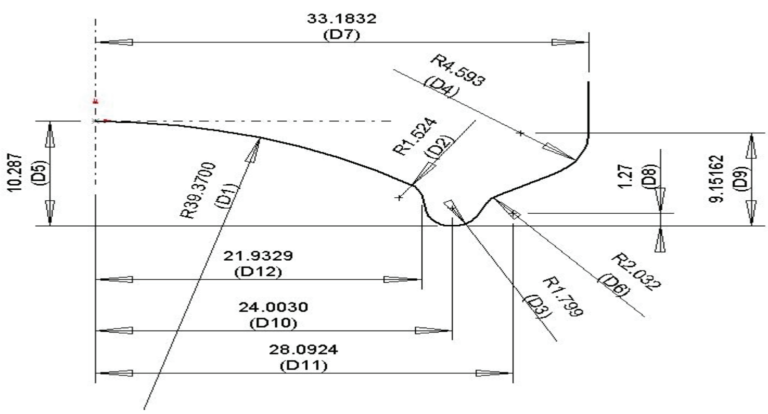

Figure 4: Beverage can Profile

Analysis of the three containers indicate that initially the beverage container bottom growth is axisymmetric and the dome nose radius profile seen to open first at the beginning of the dome growth. First the dome growth is less corresponding to the applied pressure and later on this growth increases while the pressure increments are constant. The dome growth trend can be seen in the Figure 5 as a result of Table 1.

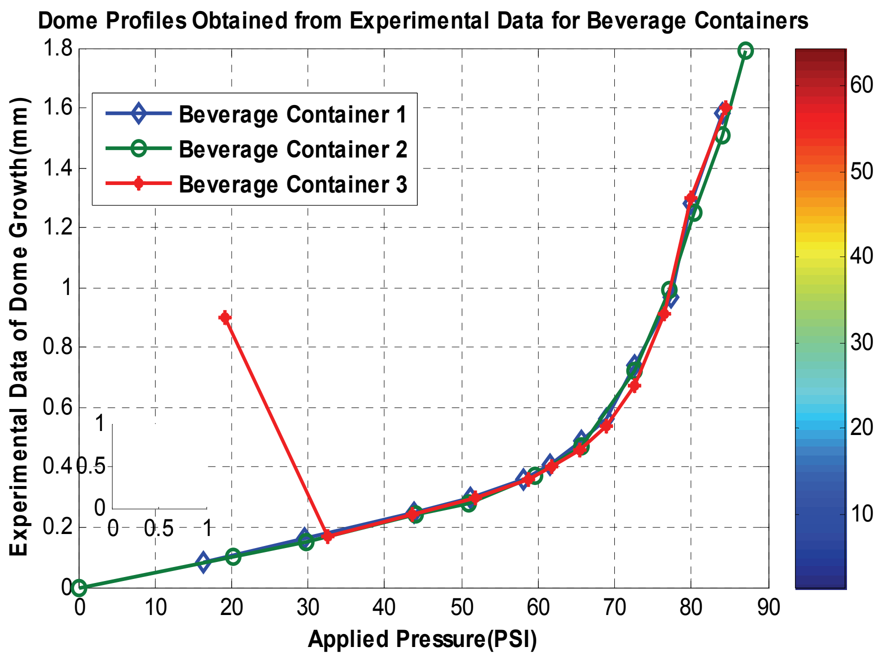

Figure 5: Dome growth profile obtained from experimental data

The buckling in the optimum design is less and the upper bound is set as 0.8 with in 20% tolerance. The buckling analysis is performed on the initial design and on the basis of the results of this analysis; the optimization analysis is carried out as according to the flow diagram as shown in Figure 6. Buckling analysis of the initial design was performed. The 2D model with a thickness of 0.275 mm is obtained. The material taken is Aluminum 3003. The constraints are applied. The part is fixed on the horizontal top face of the sidewall of the beverage container. The objective function and constraints are defined as in Table 7. The finally load of magnitude 0.6897 N/mm ^{2} is applied on all the inside curved or plane faces of the base profile of the Aluminum container. After meshing the model, the buckling analysis is run on the initial design which gives us the results in the form of deformation of the initial design.

The displacement plot gives us the displacement of the initial design in mm and the maximum displacement is 0.6421 mm. This displacement is very small as compared to the actual displacement as shown in Table 1. The displacement plots are shown in the Figures 6&7. It is obvious that the maximum displacement is at the dome of the beverage can and there is minimum or zero displacement at the

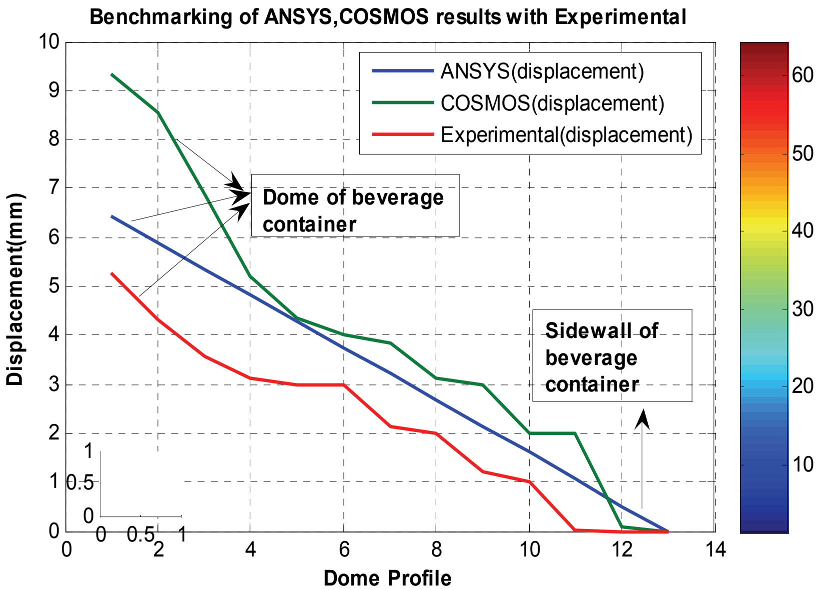

Figure 6: A comparison of displacement profile (of beverage container from side-wall to dome) obtained in ANSYS, Cosmos Works and experimental work

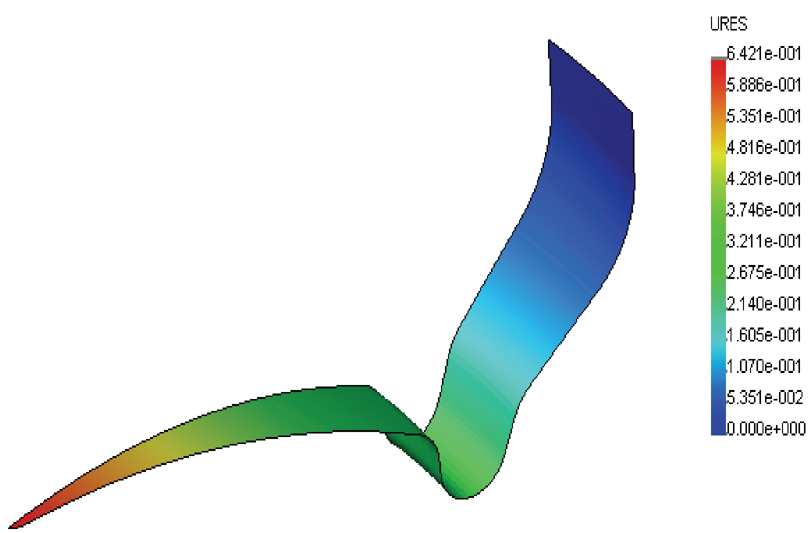

Figure 7: Displacement profile obtained in Solid Works integrated with Cosmos Works

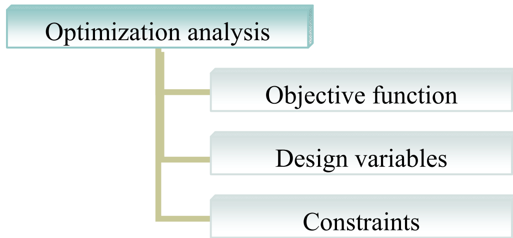

Figure 8: Flow pattern of optimization analysis based on FEM techniques

sidewall of the container. The two parameters displacement and deformation are obtained after buckling analysis. The displacement plot gives us the displacement of the initial design in mm and the maximum displacement is 0.6421 mm. It is obvious that the maximum displacement is at the dome of the beverage container and there is minimum or zero displacement at the sidewall of the container. The benchmarking of the beverage container dome profile is done using ANSYS and Cosmos Works and experimental data as shown in Figure 6.

Now after performing the buckling analysis, the optimization analysis was carried out using steps of Figure 8 and TableS 4, 5&6. A new study was defined and optimization is taken as analysis. The solid mesh is selected because mid surface shells before the buckling analysis were flipped manually after meshing but in optimization run, the meshing is done automatically after each iteration which does not allows to use mid surface shell mesh type. Minimum design cycles are 20 initially.

Table 5: Different parameters with upper and lower bounds ranges

Serial #	Symbol	Meaning	Upper and lower bounds(mm)
01	D1	Spherical Radius	20.8 < D1 < 22.5
02	D2	Dome countersink radius	0.55 < D2 < 1.8
03	D3	Stand rim radius	10 < D3 < 11.9
04	D5	Dome depth	0.762 < D5 < 1.8
05	D12	Doming die radius	37 < D12 < 40

The design variables are defined to minimize the buckling. The design variables with maximum and minimum values are given in Table 8. Finally the constraints are defined in Table 6, which is the buckling load factor quantity. In our case the buckling load factor was –0.16346. The analysis is done and it can be seen that the design variable changes in the design cycle until they reach their optimum values after the convergence achieved.

Table 6: Tolerance of lower and upper bounds for beverage container

Design variables	**Lower bounds(mm)**	**Upper bounds(mm)**	**Tolerance**
D1	37	40	10
D2	0.762	1.8	10
D3	0.55	2	10
D5	10	12	10
D12	20.8	22.5	10

Table 7: Objective function and constraints parameters

Objective function	
design goal	Minimize
Response quantity	Buckling
Mode shape	1
Convergence tolerance	5%
Constraints	
Response type	Buckling
Lower bound factor	-0.5
Upper bound factor	0.5

Table 8: The initial and final values of the design variables

No.	**Design Variable**	**Initial Values** (mm)	**Final Values** (mm)
1	Doming Die Radius(D12)	21.933	23.4
2	Stand Rim Radius (D3)	1.799	0.60
3	Dome Depth (D5)	10.287	11.79
4	Dome Countersink Radius (D2)	1.524	0.77
5	Spherical Radius (D1)	39.37	40.87

After the optimization analysis, the improved values of the design variables are obtained. The initial and final values of the design variables can be seen in the table 6 for finite element analysis using Cosmos Works. Although the best results were for the design having radius 24mm but keeping the inner wall straight at 90 degree, we selected dome radius 23.4 mm. The final optimized design from our Cosmos analysis can be seen in the Figures 9,10 & 11. The results of this analysis indicate that the dome reversal initiation occurs when the dome edges puts pressure on the inside of the rim radius and starts opening it gradually. After a substantial amount of dome growth and reduction of the rim radius because of its opening, the dome bulges out slowly from one edge and then instantly pops out. These final values completely agree with the values concluded by the experimental results.

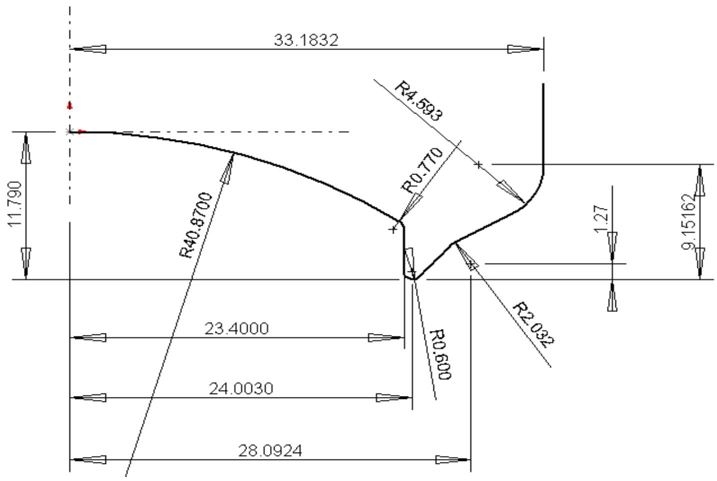

Figure 9: Final optimized design obtained by COSMOS and ANSYS

5 Conclusions

The overall optimization analysis gives us an idea about the insight of the real problem. Variation of design variables can minimize the dome reversal, under a typical inside pressure. The dome depth D5 and the rim radius D3 play a very important role in the whole analysis as shown in TableS 5& 6. Although there are constraints which do not allows us to change the design for further reducing the dome reversal but still there is much space for improvement. The optimization analysis indicates that the dome depth D5 is increased, rim radius D3 is decreased, dome shoulder radius D2 is decreased, and the inside wall of the rim radius D12 is decreased as well. The dome radius is increased slightly from its original value. These final values completely agree with the values concluded by the Utsunomiya and Nishimura (2000).

6 Recommendations

Experimental validation of the optimum design can be obtained by making prototypes models. One of the design variable dome radius (D1) can be used as a several blended radii. The manufacturing constraints fill volume, and stack-ability. The container analysis can be done including manufacturing constraints as shown

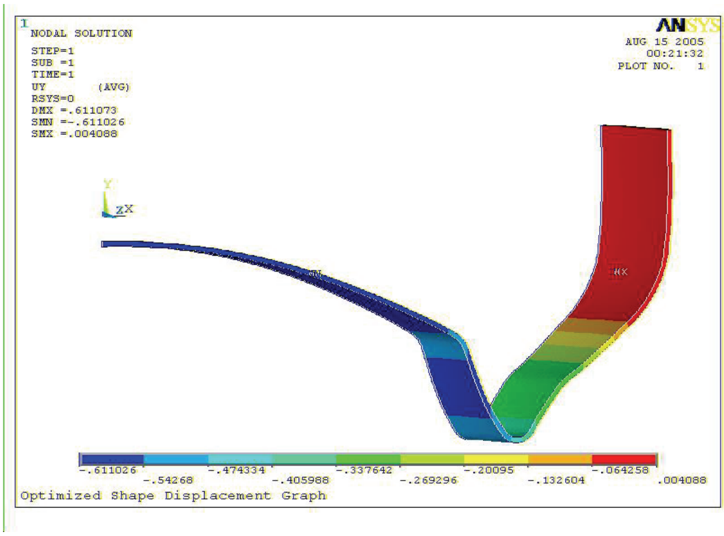

Figure 10: Optimized dome displacement graph obtained in ANSYS

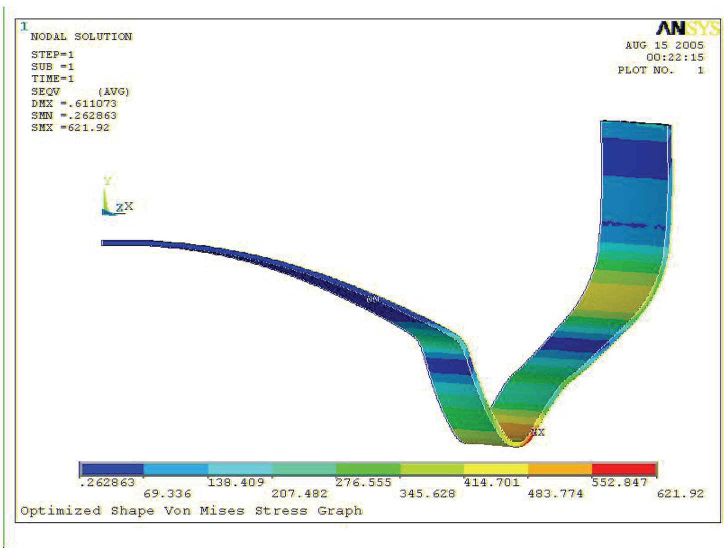

Figure 11: Optimized stress plot obtained in ANSYS using von Mises criterion

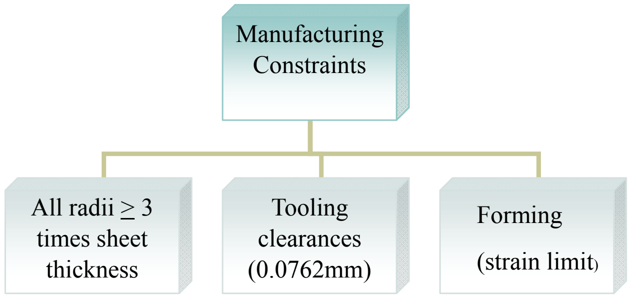

Figure 12: Manufacturing constraints

in Figure 12. The minimum radii limit, the tool clearances and the formability requires additional analysis and the strain limits must be checked for the optimum design. The fill volume can be adjusted by changing the length of thin wall. The stack-ability is not easy to quantify but can be used in the evaluation of the optimal design. In actuality, the outside nose angle must be matched (inline) with the neck of the beverage container in order to stack properly. Geometrical constraints must be obeyed to have a continuity that needs the lower and upper bounds of the design variables to be close enough in order to be solvable as well as to cover the entire design space.

The beverage container must also withstand an axial column load of 136 kg and a static drop pressure of at least 11.15 MPa during forming, filling and shipping operations. The optimized design must be tested against the above constraints in order to fulfill the stackability requirement and accidental drop impact. Changing the asymmetric buckling mode to axisymmetric buckling mode can also help in improving the dome reversal pressure. The axisymmetric buckling mode can stop the buckling in initial stages which was observed in the asymmetric buckling mode but to achieve this would need perfect geometry of the dome after the manufacturing process.

Autofrettage is an effective technique for increasing the fatigue life and bearing capacity of thick-walled structures but it can be adopted for thin-walled structures and research work is in progress as the methodology is termed as inverse autofrettage.

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