FEA performance comparisons of NNPB and BB refillable bottles

By identifying the difference in surface strength based on trade conditions and manufacture processes, strength criteria is established by Dr Wenke Hu, William G Slusser and Gary Smay. As an example, the performance of a 330ml refillable beer bottle design will be evaluated and discussed.

Glass bottles fracture when the magnitude of the tensile stress, created from applied loads such as internal pressure, impact or vertical load, equals or exceeds the glass strength at any given point on the surface of the container. Based on this general relationship, two variables will determine the overall performance of a bottle: The strength of the glass surface; and the magnitude of the tensile stress created in the glass by various applied loads. These two variables must be considered at the same location on the glass surface and at the same time, in order to determine the viability of the bottle.

Finite element computer stress analyses (FEA) were undertaken for refillable bottles made by the narrow neck press and blow (NNPB) process and by the blow-blow (BB) process when subjected to internal pressure, vertical load and impact forces(1, 2). Two models were considered in these analyses: Analysing bottles with the same minimum thickness for the two manufacturing processes; and analysing bottles with the same average thickness for the two manufacturing processes. The stress results for all three loads indicated that when the minimum thicknesses were the same, the overall glass weight for bottles manufactured by the NNPB process could be reduced by about 14% compared to the weight of bottles manufactured by the BB process while maintaining equivalent stress levels. When the average glass thicknesses were the same, the overall stress levels for bottles manufactured by the NNPB process were reduced compared to bottles manufactured by the BB process, even though the glass container weights were essentially the same.

Thus, it was concluded that the NNPB methodology might be advantageously used to manufacture refillable bottles. However, to fully understand the utility of using NNPB technology for refillable bottles, the stress levels in the previous studies need to be compared to expected strength values of glass surfaces and that will be discussed in the present study. By identifying the difference in surface strength based on trade conditions and manufacturing processes, strength criteria will be established against which a bottle can be judged for acceptable performance.

Previously(1, 2), four refillable bottles were analysed and the results were comparable for each of the examples. For brevity, only the results from a 330ml refillable beer bottle analyses will be discussed here (see figure 1).

STRENGTH SELECTION

Untouched, pristine glass surfaces formed in air under laboratory conditions and pulled directly from the melt, exhibit breaking strengths that typically range from 2060 MPa (300,000 psi) to more than 6865 MPa (1,000,000 psi(3). However, the actual strength of a moulded glass container surface is considerably less than these 'pristine' values because glass is susceptible to surface damage and static fatigue. Surface damage can be created, for example, during the manufacturing process, by mechanical contact during filing and by handling during transportation. Typical glass strengths of soda-lime glass containers are listed in table 1.

Figure 1: 3D Solidworks model for a 330ml bottle. The green coloured region represents the thickness distribution.

The severity of mechanical damage created during normal handling is related to the use of the bottle. For non-refillable bottles, the degree of damage is limited since the bottles only experience a single trip through a filling operation and by the presence of lubricious and scratch preventive surface coatings on the outside surface. For refillable bottles, more extensive handling damage is expected due to multiple trips through a filling line and abuse by the consumer. Typically, protective coatings are initially applied to the outside surface of newly formed refillable bottles. However, these coatings are removed and the surface protective properties are lost after five to 10 trips due to the chemical action of caustic washes during the cleansing operation in a filling line(4). Therefore, refillable bottles will receive more scuffing, resulting in lower surface strengths compared to non-refillable bottles.

In addition to the difference

Surface Condition	Impact < 1ms	3-seconds	ASTM 1-minute	20-minutes	Long Term Load
Pristine Inside	689.5	424.0	344.7	274.1	187.7
Pristine Molded	275.8	169.6	137.9	117.2	82.7
Mild/Moderate Abrasions	68.9	42.4	34.5	29.3	20.7
Moderately Severe Abrasions	46.2	28.4	23.1	19.7	15.5

Table 1: Typical surface strengths of soda-lime glass (MPa).

	Strength Indices	
Expected Loads	Outside Surface	Inside Surface
Internal Pressure (MPa/Bars)	3.23	5.81
Vertical Load (KPa/Kg_f)	62.60	----
Impact (NNPB) (MPa/cps)	0.77	4.60
Impact (B/B) (MPa/cps)	0.77	11.49

Table 2: Strength indices for assumed loading conditions.

Internal Pressure	Stress Indices (MPa/Bar)	
Key Bottle Regions	**NNPB**	**Blow and Blow**
Maximum Shoulder	2.25	2.16
Shoulder Contact	0.95	0.94
Maximum Sidewall	2.62	2.56
Heel Contact	1.06	1.05
Inside Knuckle	4.58	4.32
Bearing Surface	3.21	2.94
Maximum Bottom	3.15	2.98

Table 3: Internal pressure stress indices with same minimum thickness.

Internal Pressure	Stress Indices (MPa/Bar)	
Key Bottle Regions	**NNPB**	**Blow and Blow**
Maximum Shoulder	1.81	2.16
Shoulder Contact	0.81	0.94
Maximum Sidewall	2.08	2.56
Heel Contact	0.83	1.05
Inside Knuckle	4.24	4.32
Bearing Surface	2.69	2.94
Maximum Bottom	2.69	2.98

Table 4: Internal pressure stress indices with same average thickness.

Vertical Load	Stress Indices (KPa/Kg_f)	
Key Bottle Regions	**NNPB**	**Blow and Blow**
Maximum Shoulder	65.4	62.3
Shoulder Contact	41.0	39.5
Heel Contact	35.0	33.4
Maximum Heel	48.6	45.6

Table 5: Vertical load stress indices with same minimum thickness.

Vertical Load	Stress Indices (KPa/Kg_f)	
Key Bottle Regions	**NNPB**	**Blow and Blow**
Maximum Shoulder	51.7	62.3
Shoulder Contact	33.4	39.5
Heel Contact	28.9	33.4
Maximum Heel	38.0	45.6

Table 6: Vertical load stress indices with same average thickness.

Shoulder Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	**NNPB**	**Blow and Blow**
Flexure	3.80	3.76
In-Plane Hinge	0.46	0.44
Maximum Hinge	0.66	0.64
Stiffness x 10^3	6.2 kg_f/cm	6.2 kg_f/cm

Heel Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	**NNPB**	**Blow and Blow**
Flexure	4.55	4.50
In-Plane Hinge	0.52	0.49
Maximum Hinge	1.02	1.00
Bearing Surface Hinge	0.50	0.49
Stiffness x 103	6.6 kg_f/cm	6.6 kg_f/cm

Table 7: Impact stress indices with same minimum thickness.

in the severity of surface flaws for refillable and non-refillable bottles, the effect of static fatigue must also be considered. In the presence of tensile stresses and water (either liquid water or water vapour), the silica bonds at the tip of surface flaws will react chemically with moisture in the environment, leading to a slow increase in the depth of the flaws(5). This slow crack growth is typically referred to as static fatigue and is dependent on the water vapour concentration, temperature and the magnitude and duration of the tensile stresses created by various applied loads(6-9). For example, when flaws are subjected to tensile stresses for prolonged periods of time, such as bottles containing a carbonated product in a warehouse or during pasteurisation, there is enough time for the chemical reaction and subsequent crack growth to occur, resulting in a strength reduction. However, when flaws are subjected to impact forces, the duration of the tensile stress is extremely short (less than one millisecond) and neither the chemical reaction nor the associated static fatigue occurs(6-9).

An additional consideration is the strength of the inside glass surface of containers, which varies depending on the manufacturing process. For example, the strength of the inside surface of bottles made by the NNPB process is generally lower than the inside surface strength of bottles made by the BB process. The lower strength observed for NNPB ware is due to the presence of small foreign particles that can become embedded on the inside glass surface due to contact by the metal plunger used to create the parison. These particles are known as inside surface inclusions and act as stress concentrators that lower the strength of the glass. Conversely, the inside surface of bottles made by the BB process have only been contacted by compressed air and will typically exhibit higher strengths. Therefore, different strength values must be used in the evaluation of bottle performance, depending on the manufacturing process. This difference becomes most apparent when evaluating the performance of bottles for the flexure component of impact forces.

CONCEPT OF STRENGTH INDEX

In previous papers(1, 2), the principle of stress index was discussed. This index relates the magnitude of the stress that is developed in glass surfaces as a function of the load that is applied to the container and has the following form:

$$SI={}^{\sigma}/_{L} \qquad (1)$$

where SI is the stress index, σ is the stress and L is the load.

In a similar manner, a concept termed the strength index can be formulated as follows:

$$\sigma_C={}^{\sigma_s}/_{P} \qquad (2)$$

where σ_c is the strength index, σ_s is the surface strength (from table 1) and P is the expected maximum load magnitude. Strength values are selected on the basis of the manufacturing process, container usage conditions and load duration (to account for static fatigue) as determined by the nature of the product. The expected load magnitudes, such as internal pressure, vertical load and impact, can be determined from knowledge of the nature of the filled product, the conditions of the filling process and the time/temperature history concerning the >

Shoulder Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	3.55	3.76
In-Plane Hinge	0.38	0.44
Maximum Hinge	0.59	0.64
Stiffness x 10^3	8.0 kg_f/cm	6.2 kg_f/cm

Heel Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	4.30	4.50
In-Plane Hinge	0.45	0.49
Maximum Hinge	0.93	1.00
Bearing Surface Hinge	0.46	0.49
Stiffness x 103	8.9 kg_f/cm	6.6 kg_f/cm

Table 8: Impact stress indices with same average thickness.

storage of the filled ware.

By comparing the stress index to the expected strength index in various regions of the container, the overall bottle performance can be determined for different applied loads. If the stress indices from the FEA calculation for all regions of a bottle are less than the corresponding strength indices, the bottle is predicted to perform adequately for its intended purpose. However, if any of the stress indices exceed the corresponding strength indices, it is expected that the bottle might experience breakage problems. The solution to such an occurrence would require design changes and/or weight adjustments to the bottle in order to reduce the specific stress level. In this example, it is assumed that the strength index has been maximised through proper manufacturing practices, the bottle has been well coated and subsequently handled properly through the filling line and in the hands of the consumer.

DISCUSSION

For the 330ml, refillable beer bottle that was considered in this study, the maximum load magnitudes were:

- Internal pressure, 6.1 bars for 20 minutes, corresponding to a 2.5 volume product at a maximum pasteurisation temperature of 63°C;
- Vertical load, 454 kg_f for three seconds; and
- impact, 60cm/sec for less than one millisecond.

Based on these data, the strength indices were calculated from equation (2) and are summarised in table 2.

The stress indices for the 330ml refillable bottle were calculated and reported in previous papers[1, 2]. In these earlier studies, the specification for the minimum allowable glass thickness for a refillable beer bottle was used to calculate the overall bottle weight, assuming typical maximum-to-minimum thickness variations as observed historically for bottles produced by the NNPB and the BB processes (refer to the previous papers for a more detailed discussion of these principles). When considering the same minimum glass thicknesses, the bottle weights were 153 grams for the NNPB process and 177 grams for the BB process. When considering the same average glass thicknesses, the bottle weights were 177 grams for both the NNPB and BB processes. These values are less than the typical weight of these bottles, as they are currently manufactured in normal commercial practice. Thus, the bottle weights used in these analyses represent an aggressive degree of lightweighting that is hypothetically possible (termed ultra-lightweighting in this paper).

While the weights of these bottles may not match current commercial production, the comparison of these bottle weights in this study is instructional relative to the future feasibility of using the NNPB process for refillable bottles. Therefore, the stress indices from the earlier papers were compared to the strength indices as listed in table 2 to determine the suitability of this container for the three applied loads.

INTERNAL PRESSURE

The FEA results for internal pressure applied to bottles made by the NNPB process and BB processes with the same minimum thicknesses and for the same average thicknesses are listed in tables 3 and 4 respectively. As shown by these data, internal pressure stress indices for the 330ml bottle design were all at or below the strength indices. Thus, this hypothetical ultra-lightweight refillable bottle is predicted to perform well with regard to the anticipated maximum internal pressure load.

VERTICAL LOAD

The FEA results for a vertical load applied to bottles made by the NNPB process and BB process with the same minimum thicknesses and for the same average thicknesses are listed in tables 5 and 6 respectively.

Shoulder Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	3.55	3.76
In-Plane Hinge	0.38	0.44
Maximum Hinge	0.59	0.64
Stiffness x 10^3	8.0 kg_f/cm	6.2 kg_f/cm

Heel Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	4.30	4.50
In-Plane Hinge	0.45	0.49
Maximum Hinge	0.93	1.00
Bearing Surface Hinge	0.46	0.49
Stiffness x 103	8.9 kg_f/cm	6.6 kg_f/cm

Table 9: Impact stress indices with same minimum thickness.

Heel Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	2.27	2.58
In-Plane Hinge	0.17	0.21
Maximum Hinge	0.61	0.71
Bearing Surface Hinge	0.21	0.24
Stiffness x 10^3	65.3 kg_f/cm	48.9 kg_f/cm

Table 10: Impact stress indices with same average thickness.

Bottle Size	Identical Minimum Thickness		Identical Average Thickness	
	NNPB	Blow and Blow	NNPB	Blow and Blow
330 ml	214	245	245	245

Table 11: Adjusted glass weights (gram).

As shown by the single red value in table 5, the maximum shoulder stress index for the NNPB process was slightly (4.4%) higher than the strength index. The stress index for this location should be reduced by either minor design modifications or by moving glass from other acceptable regions of the bottle to the shoulder area (any alterations in glass thickness distribution must not deleteriously affect the performance of the bottles with regard to internal pressure). Thus, with a slight modification, the vertical load performance of refillable bottles made by the NNPB process for this FEA model is viable.

As shown in table 6, all of the stress indices for both the NNPB and the BB processes are less than the corresponding strength indices. Thus, the vertical load performance of refillable bottles made by the NNPB process for this FEA model is viable.

IMPACT

The FEA results for impact forces applied to bottles made by the NNPB process and BB process with the same minimum thicknesses and for the same average thicknesses are listed in tables 7 and 8 respectively.

As shown in tables 7 and 8 for bottles made by both the NNPB and BB processes, the maximum hinge stress indices for the heel impact site are greater than the corresponding strength indices. Modest design modifications or increasing the glass thickness at the heel region would be necessary in order to reduce the stress indices to acceptable values.

CORRECTIVE ACTION

As discussed in the previous section, both the NNPB and BB ultra-lightweight bottles exhibited shortcomings for impact loads. Therefore, an iterative FEA process was used in which the weights and subsequent glass thicknesses were incrementally increased to determine the minimum bottle weight that would result in acceptable performance for heel hinge stresses. The final results of these iterations are summarised in tables 9 and 10 for the same minimum and average thicknesses respectively. As shown by these data, all of the impact stress indices are now less than the corresponding strength indices. It is obvious that both the pressure and vertical load stress indices will also decrease as the weights of the bottles are increased. Thus, the acceptable results discussed earlier for these two loads will be even further enhanced.

The corresponding new adjusted weights for the NNPB and BB bottles are shown in table 11. While these weights are greater than the starting weights in these analyses, they are still less than typically observed for similar capacity refillable bottles currently being manufactured.

CONCLUSION

In this paper, the various factors that affect glass surface strength and the concept of strength index were presented. The performance of a hypothetical ultra-lightweight version of a 330ml refillable beer bottle was analysed to show the difference between the NNPB and BB process for internal pressure, vertical load and impact forces. The results of these analyses show:

- Refillable bottles made by the NNPB process are viable.
- In one FEA model (identical minimum glass thicknesses) the glass weight of refillable bottles made by the NNPB process can be reduced compared to bottles made by the BB process, while retaining acceptable performance. ■

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