한국소성가공학회 2001년도 추계학술대회 논문집 pp.154~157

탄산음료용 PET병의 바닥면 크랙방지를 위한 Petaloid 디자인

신희철* · 류민영** · 김용환***

A Study on the Bottom Design of Petaloid Carbonated PET Bottle to Prevent Bottom Crack

H. C. Shin, M. Y. Lyu and Y. H. Kim

Abstract

Through this study we investigated the causes of bottom crack. We then redesigned petaloid bottom to prevent bottom crack. We examined the material property variations according to the stretch ratio of PET and analyzed stretches of bottom in blowing processes. We also performed crack test to observe a crack phenomena. The effective stress and maximum principal stress were examined by computer simulation. We concluded that the bottom crack occurs because of not only insufficient strength of material due to the insufficient stretch of PET but also coarse design of petaloid shape. The highest maximum principal stress occurred at valley in petaloid bottom of bottle and this strongly affected the crack in bottom. We redesigned petaloid shape to minimize maximum principal stress, and this result in increasing the crack resistance.

Key Words : PET, Carbonated Soft Drink, Bottle Blowing, Petaloid, Crack, Principal Stress

1. Introduction

The bottom shape of PET bottle for carbonated lsoft drink is petaloid in shape for self-standing. There has been crack problem in PET bottle at petaloid bottom. The published researches about the cracks in PET bottle were very limited. Most of published research papers were about the characteristics of fracture (1, 2) and crack (3-7) of PET material. The articles concerning the bottom cracks of PET bottle appeared in patents (8-10). And those patents were limited to the modifications of process and designs of preform. Most recently the cause of cracking at petaloid bottom was studied (11).

This paper presents the basic investigation of causes that invoke bottom crack in petaloid PET bottle. We examined the material properties, strength of bottom, crack phenomena and stress concentration in bottom of bottle. Subsequently we suggested design factors to prevent the bottom crack in carbonated PET bottle that has petaloid bottom. Finally we redesigned the petaloid shape and verified the increment of crack resistance.

---

* 삼양사 중앙연구소
** 서울산업대학교 금형설계학과
*** 충남대학교 기계설계학과

2. Experimental and Simulation

2.1 Bottle Blowing

The PET (TRIPET BI, Samyang co.) preforms that were used in blowing process were made by injection molding (XL 500 PET, Husky, 72 cavities). The blowing operations for 1.5ℓ and 350mℓ bottles were performed in Sidels (SBO 10/10) and Sipas (ECS 800) blowing machines respectively. As soon as the perform was heated by lamps up to 110℃, stretching rod stretched preform axially. Subsequently preform was blown by 4MPa pressure of air. The mold temperature was maintained at 10℃

2.2 Cracking Test

Citric acid and sodium bicarbonate were put into water contained PET bottle to make carbon dioxide gas. The contents of carbon dioxide gas were 8.45, 9.23 and 9.82 g/ℓ respectively. The bottom part of carbonated PET bottles was merged into water solution which contains 0.2wt% of NaOH to stimulate crack. Then we checked the time and location when bubble occurred through crack in the bottom of bottle.

2.3 Simulation of Carbonated Bottle

Stresses at the bottom of bottle were quantitatively examined by computer simulation using commerical software, Abaqus (Version 5.8-16).

We simulated a bottle for six different input data. We used same thickness in each simulation. The actual thickness in bottle was distributed unevenly. However, we used even thickness in simulation for simple modeling since the objective of this simulation was investigating the stress distribution that comes from the geometrical shape of petaloid bottom. The thicknesses were 0.35, 2.0 and 3.36 mm and corresponding modulli were 77.6, 173.1 and 173.1 kgf/mm2. Those thicknesses were average values of sidewall, bottom part and preform respectively. We applied two pressures, 0.04 and 0.06 kgf/mm2. Those were the pressures in bottle for 8.45 g/ℓ of carbon dioxide gas at 20 and 35 ℃ respectively.

3. Results and Discussions

3.1 Investigation of the Bottom Crack

3.1.1 Physical Properties of Material

The tensile yield stresses of uniaxially stretched PET are shown in Fig. 1. The yield stresses remained at almost same value for low stretch ratios, between 1 and 2.3. However these increase as stretch ratio increases for high stretch ratios, higher than 2.3. During the stretching of PET at elevated temperature the increments of stresses were very small at low stretch ratios (11-13). As stretch ratios increase the molecules are arranged to the stretching direction. Subsequently after certain point of stretch ratio the stress increases drastically as stretch ratio increases. That is the strain hardening of material. Fig. 1 shows same physical behavior of strain hardening. Through this examination, we could see that the stretch ratio in bottle blowing should be higher than strain hardening point.

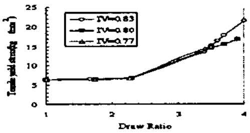


Fig. 1 Tensile yield stresses of stretched PET

3.1.2 Strength of Bottom in Bottle

The cross sections of blown bottle is shown in Fig. 2. We marked points in preform before blowing and than calculated the stretch ratios in thickness direction (thickness ratio of preform to bottle) in blown bottle. Fig. 3 shows the thickness and stretch ratio at foot and valley in petaloid bottom of bottle.

The stretch ratio in thickness direction increases after point 5. However, the material strength would not be improved by molecular orientation until point 6 because the stretch ratio was much lower than strain hardening point. The material strength increased after point 6 although the stretch ratio began to increase after point 5. Thus the material strength at bottom from point 1 to point 6 would be same. However the thickness of bottom decreased from point 5. Through this examination we can see the structurally weakness of bottom because of abrupt change of thickness between point 4 and 6 without increment of material strength.

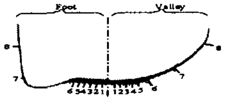


Fig. 2 **Cross-sections of blown bottle - 1.5 ℓ**

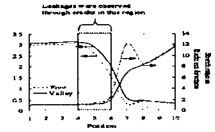


Fig. 3 **Variations of thicknesses and stretch ratios at foot and valley in bottom of bottle 1.5 ℓ**

3.1.3 Observations of Cracks in Bottle

The typical crack patterns in bottom of bottle are as shown in Fig. 4. There were two directions of cracks. One is the radial direction (Fig. 4a). In this case, cracks began bottom center and propagated to outside, radial direction. The other is the circumferential direction (Fig. 4b). The cracks were located in some distance from the bottom center and the direction was circumferential.

The most cracks that finally made leakage occurred at valley of the petaloid bottom and the directions of the cracks were circumferential as indicated by arrows in Fig. 4. The locations of these cracks were distributed between points 4 and 6 as indicated in Fig. 3. In these points the material strengths were weak because of insufficient stretching of material as discussed in the previous section.

Through the cracking experiments, we could also find some design factors (Fig. 5) which were related to the circumferential cracks at the valley that invoked leakages. Large clearance and foot length, and narrow valley width reduced the circumferential cracks at the valley.

(a) 350mℓ - Cracks in radial direction

(b) 1.5ℓ - Cracks in circumferential direction

Fig. 4 **Cracks in petaloid bottom of bottle**

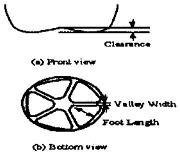


Fig. 5 **Design factors related to circumferential crack at valley**

3.1.4 Stresses in Carbonated Bottle

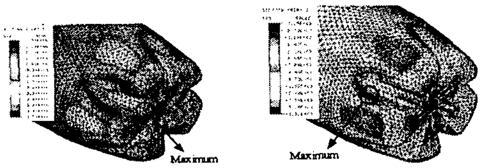
Fig. 6 shows the maximum principal stress in bottle. The crazing occurs in brittle materials such as amorphous and semi crystalline polymers under tensile stress. And the crazing contour is below the yield contour (14-16). The crazing is strongly related to tensile principal stress (16, 17). The maximum principal stresses of tensile occurred at valleys and the direction was radial. This radial direction was perpendicular to the crack direction that made a leakage in bottom as we observed in the previous section. Through these examinations we could see the maximum principal stress among the stresses does the major role in cracking the bottom of bottle.

Fig. 6 **Maximum principal stress distribution and direction - 350mℓ**

3.2 Redesign of Petaloid Bottom

To modify the petaloid shape we considered the three design factors, clearance, foot length and valley width that were found in cracking test. Optimal petaloid shape for reducing the maximum principal stress was decided by computer simulation. The clearance of bottom was increased by 50 % and the foot length was also increased by 5 % with same dimension of valley width compared with existing bottle.

The performance of redesigned petaloid shape was examined by computer simulation and cracking test. Fig. 7 shows the maximum principal stresses at petaloid bottom before and after modification. The highest value of maximum principal stress was decreased by 21 %. The location of the highest maximum principal stress was moved to near sidewall from valley near the center where the leakage occurred by crack. We examined the cracking resistance of redesigned petaloid shape through cracking test. Fig. 8 shows the leakage occurrence times at the bottom before and after modification. The leakage occurrence time of the redesigned bottle was increased by about 70%.



Unit : kgf/㎟ **Unit : kgf/㎟**

(a) Before modificaton **(b) After modification**

Fig. 7 Comparison of maximum principal stress distribution before and after modification - 1.5 ℓ

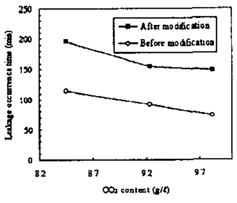


Fig. 8 Comparison of leak occurrence time before and after modification

4. Conclusions

The crack that made leakage of carbonated liquids in PET bottle was circumferential direction at the valleys in petaloid bottom because of structurally weak material strength and concentration of high maximum principal stress.

The maximum principal stress occurred at the valley. The direction of this stress was radial direction and this caused a crack circumferentially through crazing. The maximum tensile principal stress should be lowered or minimized at valley of petaloid bottom in PET bottle to prevent bottom crack by carbonated liquid.

There were three design factors, clearance, foot length and valley width that affect the crack in petaloid bottom of bottle. The crack resistance of bottom of carbonated bottle can be improved by the modification of the petaloid shape considering the design factors. Through these modifications, maximum principal stress was reduced and the location was moved to the safe region, near sidewall. The improvement of crack resistance of new designed petaloid shape was verified by cracking test.

References

(1) Foot, J.S., Ward, I.M., 1972, J. Mat. Sci., 7, p. 367.
(2) Tanrattanakul, V., Perkins, W.G., Massey, F.L., Moet, A., Hiltner, A., Baer, E., 1997, J. Mat. Sci., 32, p. 4749.
(3) Kastelic, J.R., Baer, E., 1973, J. Macromol. Sci.-Phys., B7(4), p. 679.
(4) Marom, G., Konieczny, N., Mushtakel, M., 1979, Polymer, 20, p. 1054.
(5) Kambour, R.P., 1984, Polymer Communications, 25, p. 130.
(6) Jabarin, S.A., Lofgren E.A., 1992, Polym. Eng. Sci., 32, p. 146.
(7) Moskala, E.J., 1998, Polymer, 39, p. 675.
(8) Wider, M., 1991, US Patent 5 009 801.
(9) Tekkanat, B., Kovacich, A.A., McKinney, B.L., and Tiedemann, W.H., 1991, US Patent 5 001 935.
(10) Rossio, C.E., and Anderson, T.E., 1991, US Patent 5 073 280.
(11) M.-Y. Lyu, H.C. Kim, J.S. Lee, H.C. Shin, and Y. Pae, 2001, Intern. Polym. Proc., 16, p. 72
(12) Jabarin, S.A., 1992, Polym. Eng. Sci., 32, p. 1341.
(13) Rietsch, F., 1990, Eur. Polym. J., 26, p. 1077.
(14) Osswald, T.A. and Menges, G., 1996, "Materials Science of Polymers for Engineers", Hanser, NY.
(15) Donald, A.M. and Kramer, E.J., 1982, J. Mat. Sci., 17, p. 1871.
(16) McCrun, N.G., Buckley, C.P., and Bucknall, C.B., 1997, "Principles of Polymer Enginnering", 2nd Ed., Oxford University Press, NY.
(17) Sternstein, S.S., Ongchin, L., and Silverman, A., 1968, Applied Polymer Symposia, No. 7, p. 175.