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Abstract

Appliance manufacturers have traditionally performed physical testing using prototypes to assess reliability and service integrity of new product designs. However, for white goods where service lives are measured in years or decades, the use of endurance testing to analyze long time reliability is uneconomical. As accelerated life testing (ALT) is more efficient and less costly than traditional reliability testing, the methodology is finding increased usage by appliance manufacturers. In the present study, a simulation-based ALT approach was used to predict the service life of a polyacetal hinge cam from a consumer refrigerator. A predictive life stress model based on cumulative surface wear under accelerated stress conditions was developed and used to predict time to failure under consumer use. Results show that the life stress model demonstrated good agreement with performance testing data and reasonably predicts hinge life.

Keywords: Cumulative damage model, Quantitative accelerated life test, Product reliability, Step-stress model, and Injection molding

1 Introduction

Long term reliability and durability of consumer appliances has traditionally been established using endurance tests conducted under normal operating conditions. However, such testing is problematic for white goods such as refrigerators which have service lives that can span years or even

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decades. Furthermore, globalization of the consumer appliance market has resulted in significant cost pressures and time constraints such that traditional reliability testing is increasingly unviable. In response to this, appliance manufacturers have begun to implement ALT as an integral part of new product development. While ALT has been demonstrated to be more efficient, the rapid pace of innovation in the appliance industry has further compressed available development time such that manufacturers are looking to achieve additional reductions.

Accelerated reliability test methods began to be actively used in the 1960's and the methodology has since come to be widely employed in the electronics and automotive industries. More recently ALT has begun to be employed in white goods manufacturing and case studies have been published by (Orlando et al., 2013) and (Jayatilleka & Okogbaa, 2006) who analyzed failure modes and causes in selected appliances. However, many applications of ALT are based on physical testing using actual prototypes such that material properties and physics of the failure are often not explicitly incorporated. As the ability to incorporate such information can lead to new design insights and provide a means to evaluate alternative materials, use of a physics-based ALT model can be beneficial. Furthermore, with the availability of robust simulation tools, mechanical-based failures such as wear can be implemented as part of a physics based ALT model and potentially reduce the cost of physical testing. Consequently, the use of numerical simulation in ALT represents a potential means to further improve testing efficiency and this was the basis for the methodology proposed by (Jeong, 2014).

In the present study, the durability of a door hinge from a new consumer refrigerator was analyzed using the simulation-based ALT methodology proposed by (Jeong, 2014). The intent was to demonstrate the methodology and confirm that a simulation-based approach could predict service life with acceptable accuracy. A flow diagram outlining the procedure is shown in Figure 1 and can be summarized as follows. As hinge failure was known to be based on wear, the governing stress factors were identified and an appropriate physics based failure model that could be incorporated in an FE simulation was selected. Because the commercial FE code DEFORM3D v10.2 has the capability to predict the wear profile for a surface, it was used in the study. Accelerated stress testing of the hinge cam was simulated in DEFORM3D using predetermined loads and times based on known use conditions. The next step was to develop a test response function which relates hinge wear in terms of the simulated step-stress test results. The final step consists of developing a life-stress function for the component that can be used to predict the service life under normal use conditions. Experimental testing was also performed to confirm the integrity of the methodology and validate the simulation results and these are also presented.
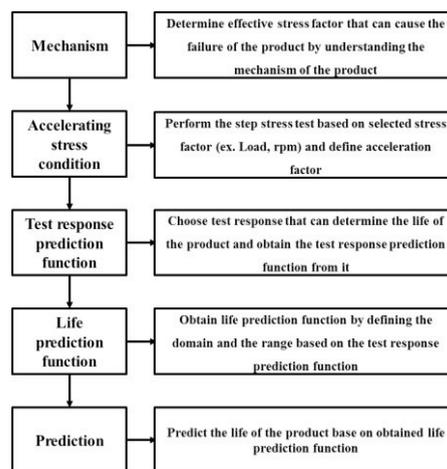

Figure 1: Flow chart showing process used to develop an ALT-based life cycle model for the door hinge analyzed in the study (Jeong, 2014).

2 Hinge description and modeling

For a typical refrigerator, the service life of a door hinge is determined by the number of usage cycles (i.e. number of times a door is opened/closed) that result in a specified level of door deflection or sagging and is depicted in Figure 2a. Each door hinge consists of a steel mounting bracket and a polymer hinge cam. The function of the hinge cams are to hold the door in position and align it with the refrigerator opening when fully closed. A total of four hinges are used and these are normally mounted at the top and bottom of the refrigerator cabinet and door at the locations shown. Due to the combined effects of the door and content weight and sliding contact that occur between opposing hinge cams during each usage cycle (Figure 2b), the surfaces of the nose and ramps on the hinge cam are gradually worn down and this is depicted in Figure 3. As door sag is determined by the amount of cam wear, the change in hinge height was selected as the dependent variable for the analysis. To facilitate modeling and simplify the test set-ups needed, the brackets were neglected and only the hinge cams were considered with suitable loading conditions imposed for the door and content weight.

To determine the parameters and material properties needed to model the wear process, experimental and FE-based techniques were employed. The hinge cams are composed of Polyoxymethylene (POM) and are made by an injection molding process. POM, also known as polyacetal or polyformaldehyde, is an engineering thermoplastic which has low friction and good wear resistance and is widely used in gears, bearings, window guides, and furniture components.

To establish the mechanical properties of the POM material, testing was performed using prototype hinge cams to ensure that the results accurately reflected the part microstructure. An INSTRON 5882 (Figure 4) was used to perform tensile tests at constant cross-head velocities of 60 and 600 mm/min. The resulting load-stroke curves are shown in Figure 5 and indicate that deformation is relatively insensitive to strain rate over the range tested. This agrees with results reported by (Rae et al., 2007) and confirms that the mechanical properties of POM will not be affected by the accelerated conditions used during ALT.
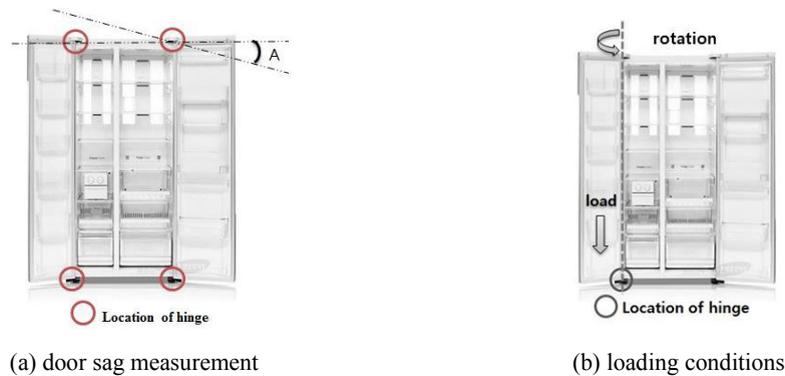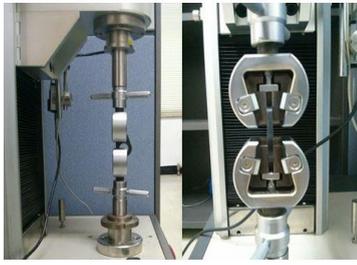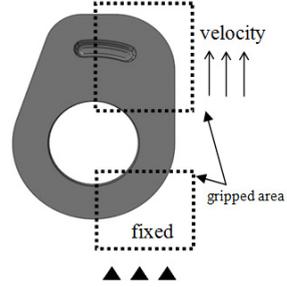

| (a) door sag measurement | (b) loading conditions |

Figure 2: Front view of a refrigerator showing (a) door sag measurement and (b) loading conditions acting on a hinge.

| (a) un-worn | (b) worn |

Figure 3: Representative surface profile of an (a) un-worn and (b) worn hinge cam.

(a) hinge component mounted in tensile tester   (b) analysis conditions used in the FE simulation

Figure 4: Photograph showing (a) hinge component mounted in tensile tester and (b) analysis conditions used in the FE simulation.
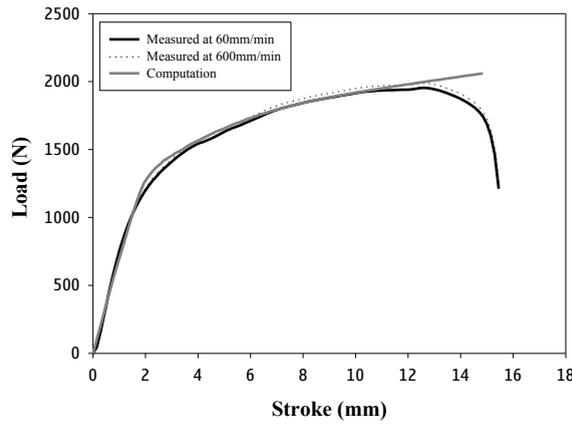

Figure 5: Load-stroke curves for POM hinge components obtained from tensile testing and FE simulation.

As wear modeling requires knowledge of a material's constitutive behavior, yield stress was represented using the Swift equation (equation 1). In the Swift equation, three material constants; strength coefficient, K, strain hardening, n and initial strain, ε_0 have to be determined. Simulations were conducted using DEFORM3D v10.2 to obtain the strength coefficient and strain hardening exponent for the POM material and was determined by adjusting each value until satisfactory agreement was achieved between the predicted and experimental load stroke curves.

$$\sigma_y = 45.5(0.92 + \varepsilon)^{1.59} \ [\text{MPa}] \tag{1}$$

Because the Swift equation is only valid during uniform deformation, the Gurson-Tvergaard-Needleman (GTN) equation was used to describe necking and ductile fracture. The usual form for the GTN equation is shown in equations (2) and (3) and a total of nine constants must be defined for the material.

$$\Phi = \left(\frac{\sigma_e}{\sigma_y}\right)^2 + 2q_1 f^* \cosh\left(-q_2 \frac{3}{2} \frac{\sigma_m}{\sigma_y}\right) - \left(1 - q_3 f^{*2}\right) = 0 \tag{2}$$

$$f^* = \begin{cases} f & \text{if} \quad f \le f_c \\ f_c + \dfrac{\overline{f}_F - f_c}{f_f - f_c}(f - f_c) & \text{if} \quad f_c \le f \le f_f \\ \overline{f}_F & \text{if} \quad f_f \le f \end{cases} \tag{3}$$

The values for q_1, q_2, and q_3 were set to 1.5, 1, and 2.25 respectively based on published data (Choi et al., 2012) while the remaining constants were found using the test set-up described previously. As the procedures and calculations are available in the literature (Oh et al., 2005; Uthaisangsuk et al., 2008; Min et al., 2011), they will not be repeated here. Table 1 summarizes the values of the remaining 6 constants that were obtained. In Table 1, ε_n, s_n and f_n are the mean value, standard deviation, and volume fraction of void nucleation, respectively. A variation in the mean value leads to a horizontal shift in dependence to the effective plastic strain. Increasing the value of s_n leads to a smoother distribution of the void nucleation in dependence to plastic strain. f_n is related to the size of the normal distribution. f_0 is initial void volume fraction. f_c and f_f are critical void volume fraction and fracture void volume fraction when the material is fractured, respectively. Figure 6 shows the experimental and simulated load stroke curves and it can be seen that GTN equation and coefficients used satisfactorily model the post uniform deformation and fracture behavior of the POM material.

As the reduction in hinge cam height is based on surface wear, a modified Archard model (equation 4) was used to simulate the wear volume, W.
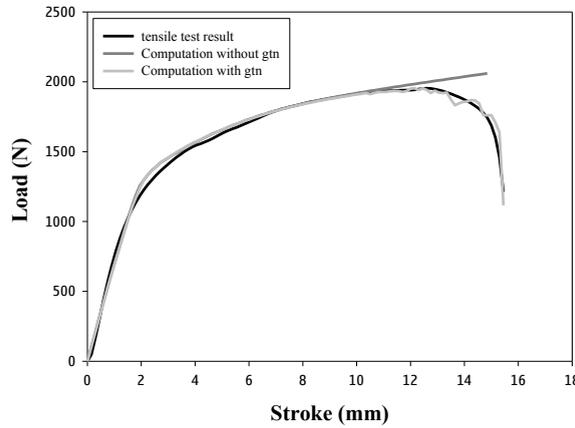
$$W = K \frac{P^a v^b}{H^c} t \tag{4}$$

Figure 6: Experimental and simulated load-stroke curves for POM obtained based on the Swift and GTN material models.

Parameter	ε_n	s_n	f_n	f_0	f_c	f_f
Value	0.7	0.3	0.008	0.003	0.04	0.08

Table 1: Experimentally determined GTN damage model parameters used for the POM door hinge.

Where P is normal pressure, v is sliding velocity, H is surface hardness, and t is time. Values for a, b and c were obtained from the literature (Abbasi et al., 2011) and were specified as 1, 1 and 2 respectively. The wear coefficient, K, is a characteristic of the operating conditions and was determined using the following procedure. Opposing hinge cams were milled to generate specimens having flat surfaces at a 10 degree slant that was consistent with the original ramp geometry (Figure 7a). Both pieces were then mounted in a rotating die and placed in the test set-up shown in Figure 7b. Rotation of the lower specimen was limited to 20 RPM to prevent surface heating and a 48.7kgf load was applied as this represented the maximum load case for the door and contents. Tests were run for a total of 100,000 cycles under constant stress conditions with the combined height of the test pieces measured after every 10,000 cycles. The wear results were expressed in change of height for the combined test pieces and are shown in Figure 8. The straight line fit to the data confirms that wear rate is essentially linear with respect to time for a constant stress.

Fitting a least-squares curve to the data in Figure 8, the change in height due to wear can be expressed as a function of the number of rotations according to:
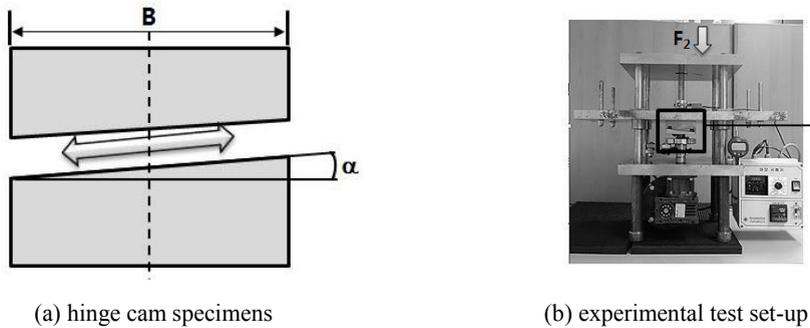
$$\Delta h = 0.3454N \ [\text{mm}] \tag{5}$$

(a) hinge cam specimens   (b) experimental test set-up

Figure 7: Schematic diagram of (a) hinge cam specimens and (b) experimental test set-up used to determine K.
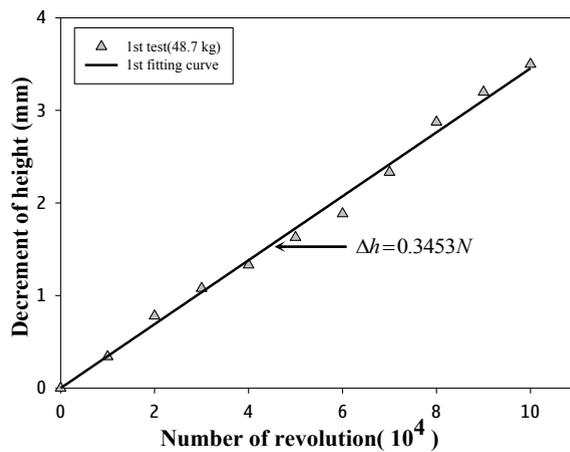

Figure 8: Change in height for the POM hinge cam specimens based on measurements obtained from the rotating test set-up.

Where N is the number of revolutions given in 10,000 cycle increments. By equating (4) and (5), it was possible to relate the wear coefficient and change in height as shown in equation (6) and develop an initial value of K for the Archard equation.

$$\Delta h = 795,431K - 0.2332 \text{ [mm]} \tag{6}$$

To calibrate the value of K, DEFORM3D was then used to simulate surface wear for the test pieces using different values of K. The resulting wear values obtained using equation (6) for the 48.7 kgf load and various K values are shown in Figure 9. To improve the precision of the value for K, a least-squares curve fit was applied to the wear predictions. After reducing the wear data to a per cycle basis, the value of K for the hinge cams was found to be equal to be 7.17 x10^{-7}. An additional simulation corresponding to 10,000 cycles was performed using DEFORM3D. The simulated and experimental change in height was found to be 0.346 and 0.345 mm respectively. The difference between the two values is less than 0.3% and validates the value of K that was obtained.
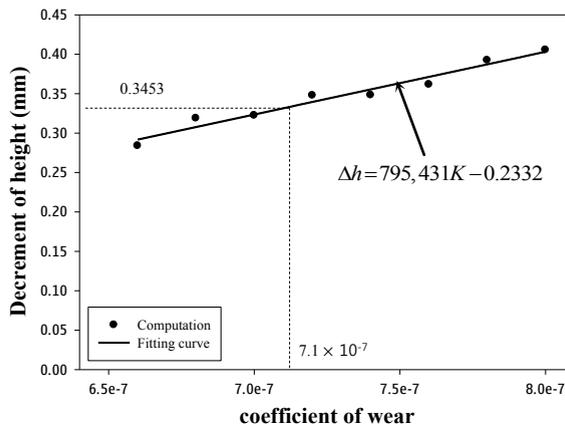

Figure 9: Predicted decrease in height as a function of the wear coefficient (K) for the hinge cam specimens.

3   Accelerated life testing

3.1   Acceleration Factor and Step-Stress Testing

To extrapolate the time to failure at the higher stress levels used in ALT to predict service life under normal operating conditions, a multiplier or acceleration factor (AF) can be used (Elsayed, 1996). Because the change in height of the hinge cam is known to be proportional to the number of cycles and the applied load, the AF between two different levels was defined as:

$$AF = (N \times F)/10,000 \tag{7}$$

Where N represents the number of cycles and F is the applied load on the hinge cam. As loading conditions on a hinge typically vary and are time dependent, it was also necessary to specify an accelerated test strategy. Several workers have investigated the efficiency of time varying stress strategies used in ALT (Lam et al., 2007; Shaked & Singpurwalla, 1983; Srivastava & Jain, 2011) and

the step stress model proposed by (Nelson, 1980) has gained broad acceptance. A step-stress test was then simulated in DEFORM3D using the geometry and conditions depicted in Figure 10a. Test conditions corresponding to a reference weight of 43.7kgf that was increased in 2.8 kgf increments after every 20,000 cycles for a total of 100,000 cycles. A total of 10 simulations were performed to predict the change in height and resulting surface profile at 10,000 cycle increments. To validate the simulated step stress test, a pair of hinge cams were also tested experimentally using the test set-up shown in Figure 7b. Measurements were taken at the location indicated in Figure 10b and the change in height was measured after every 10,000 cycles. The simulated and experimental wear results are shown in Figure 11 and it can be seen that the relative difference is small and confirms that the computational model is able to predict the change in height of the hinge cam under time varying stress conditions.
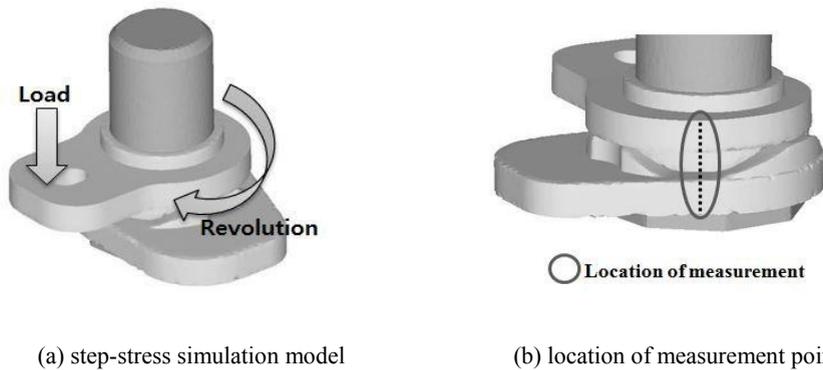

| (a) step-stress simulation model | (b) location of measurement point |

Figure 10: Schematic representation of (a) step-stress simulation model and (b) location of measurement point used to determine change in height for the hinge cam.
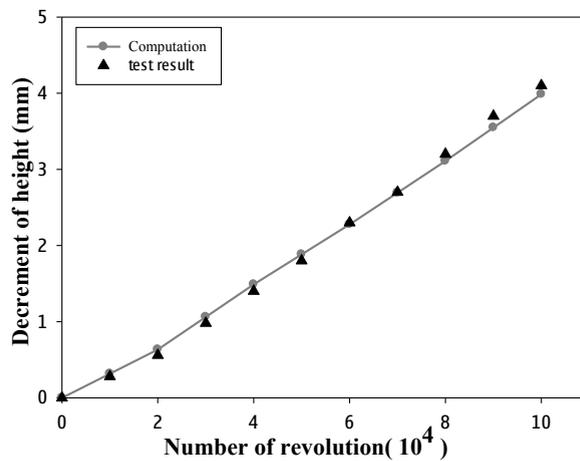

Figure 11: Comparison between test result and computation result.

Further confirmation of model accuracy can be seen in Figure 12 where the wear distributions and surface profiles for the hinge cam are shown at increasing usage cycles during the step-stress test. Comparing the simulated geometries shown in Figure 12, it is evident that the predicted and actual wear distribution and profiles show good agreement and that the change in height is proportional to the number of cycles.

As it was desired to represent the reduction in hinge height under different consumer use conditions using a single equation, the number of cycles and the applied load were expressed as a unified parameter based on the *AF* defined in equation (7). This was accomplished by re-plotting the change in height data obtained from step-stress testing as a function of *AF* and is shown in Figure 13. The wear results closely follow a straight line and using a least-square fit, the test response function describing the change in height for the hinge cam is given by equation (8).
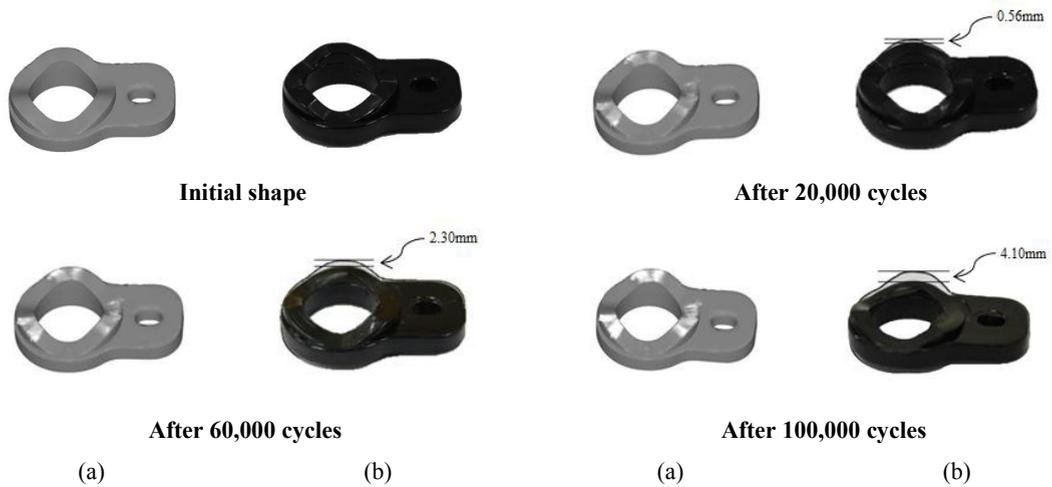
$$\Delta h = 7.4986 \times 10^{-4}\, AF + 0.0511 \qquad\qquad (8)$$

Initial shape

After 20,000 cycles

After 60,000 cycles

After 100,000 cycles

(a) (b) (a) (b)

Figure 12: Hinge cam surface profile and wear height obtained by (a) FE simulation and (b) experimental step-stress testing.

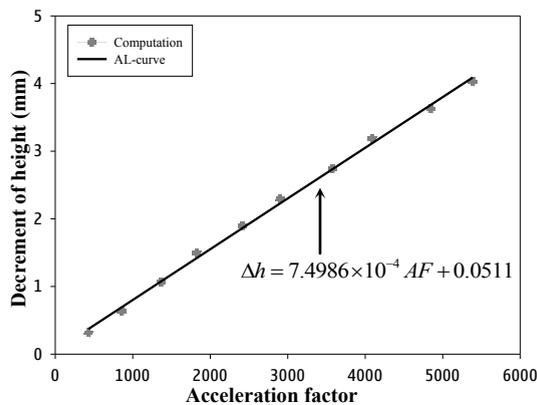$$\Delta h = 7.4986 \times 10^{-4}\, AF + 0.0511$$

Figure 13: Simulated decrease in height as a function of acceleration factor.

177

3.2   Life prediction of the hinge cam

After the test response prediction function had been developed, it was then possible to formulate a life prediction function and quantify hinge life based on expected door loads and frequency of use. Based on OEM specifications for maximum door deflection, Δh was set to 1 mm for the analysis. The average number of times that a consumer opens/closes a refrigerator door each day (i.e. usage cycles), x, was estimated by the manufacturer to be 40 such that an annual yearly usage cycle can be determined. Consequently the life prediction function can be expressed as number of usage cycles to failure at a given load divided by the yearly usage cycle. Product life in years can then be expressed as:

$$product\ life[in\ year] = \frac{number\ of\ cycles\ to\ failure\ criterion}{x \times 365} \qquad (9)$$

By using a range of loads, equations (8) and (9) can be used to calculate the predicted service life in years and the resulting product life curve based on a maximum deflection of 1 mm is shown in Figure 14a. In an actual consumer refrigerator door, the hinge components do not physically make contact until a threshold load of 38 kgf is exceeded. By assuming a maximum load of 44kgf (including the door weight), the actual force that will act on the door hinge will be 6 kgf. Under these conditions the life of the refrigerator door hinge is predicted to be 14.01 years as shown in Figure 14b.

To validate the prediction obtained from the product life curve, an experimental test stand was built and an endurance test conducted. The set-up incorporated a prototype refrigerator, automatic opening/closing mechanism, velocity controller, and cycle counter as shown in Figure 15. As nominal door weight is 11.6 kgf, six 5.4 kgf weights were placed in the inner shelves of the door during the endurance test to represent the maximum load condition of 44 kgf.
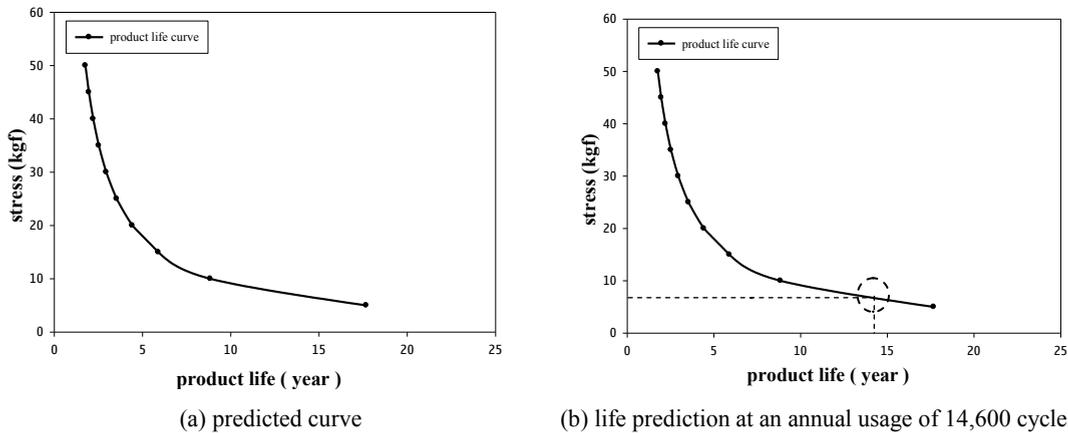

| (a) predicted curve | (b) life prediction at an annual usage of 14,600 cycles |

Figure 14: Product life of the POM hinge cam showing (a) predicted curve and (b) life prediction at an annual usage of 14,600 cycles.

(a) refrigerator door cycling mechanism   (b) experimental test set-up
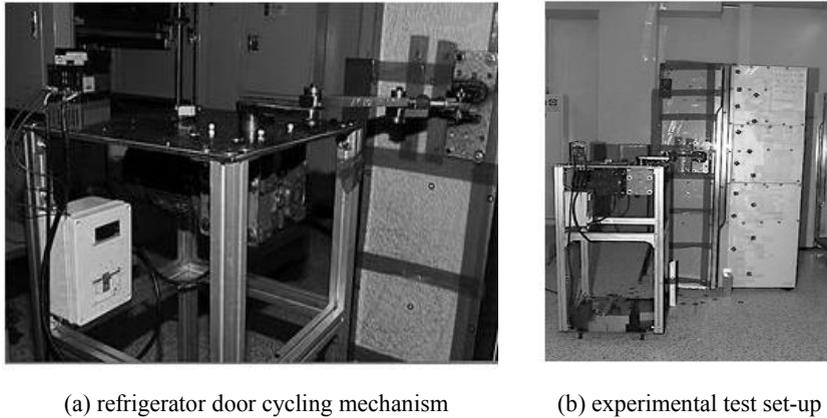
Figure 15: Photographs showing (a) refrigerator door cycling mechanism and (b) experimental test set-up.

A total of 204,604 cycles resulted in a 1 mm door sag on the experimental set-up and this corresponds to an equivalent service life of 14.78 years. This compares favorably to the predicted life of 14.01 years and the difference is less than 4.9%. Consequently the simulated accelerated life test and life prediction function can be considered to be sufficiently reliable. The advantage of the simulation-based method is that the step stress testing required a total of 85 hours to perform. In comparison, the total CPU time required to simulate the step-stress test was 30 hours which represents a 65% reduction and could be further reduced if sufficient computational resource are available to run concurrent simulations.

4   Conclusions

In the present study, an accelerated life test based on simulation modeling was performed to predict the service life of an injection molded polycetal hinge cam used on a consumer refrigerator. As the failure mode was known to be based on wear, an FE model of the hinge cam was developed in DEFORM3D and used to simulate component wear using a modified Archard equation and constitutive behavior based on the Swift and GTN material models. A combination of experimental and numerical simulation was used to establish and calibrate the coefficients used for wear modeling. DEFORM3D was used to simulate the step-stress testing and a test response function was developed for the hinge cam. The final step consisted of formulating a life prediction function which enabled service life to be predicted based on expected consumer usage. In order to validate the life prediction, endurance testing was performed and the results showed good agreement with computational based predictions under a maximum load case. Based on the results obtained, it can be concluded that simulation-based ALT can be used to incorporate failure physics and predict service life for wear-based mechanical failures.

References

Orlando, B., Tucci, M., De Carlo, F., Fanciullacci, N. (2013). Accelerated life tests for new product qualification: A case study in the household appliance. *Proc. of the 11th IFAC Workshop on Intelligent Manufacturing Systems*, Sao Paulo, Brazil.

Jayatilleka, S., Okogbaa O. G. (2006). Accelerated life testing for speedier product development: Problems and strategies. *Proc. of RAMS'06*, Newport beach, California.

Jeong, H. (2014). A study on the accelerated-life test coupled with analysis for life prediction of product according to wear and damage. *Master's Thesis*, Sogang University, Seoul, Korea.

Rae, P. J., Brown, E. N., Orler, E. B. (2007). The mechanical properties of poly(ether-ether-ketone) (PEEK) with emphasis on the large compressive strain response. *Polymer*, 48(2), 598-615.

Choi, J. H., Choi, S. H., Park, D., Park, C. H., Rhee, B. O., Choi, D. H. (2012). Design optimization of an injection mold for minimizing temperature deviation. *International Journal of Automotive Technology*, 13(2), 273-277.

Oh, C. K., Kim, Y. J., Park, J. M., Kim W. S., Baek, J. H. (2005). Development of stress-modified fracture strain criterion for ductile fracture of API X65 steel. *Transactions of the Korean Society of Mechanical Engineers – A*, 29(12), 1621-1628.

Uthaisangsuk, V., Prahl, U., Münstermann, S., Bleck, W. (2008). Experimental and numerical failure criterion for formability prediction in sheet metal forming. *Computational Materials Science*, 43(1), 43-50.

Min, H. E., Fuguo, L., Zhigang, W. A. N. G. (2011). Forming limit stress diagram prediction of aluminum alloy 5052 based on GTN model parameters determined by in situ tensile test. *Chinese Journal of Aeronautics*, 24(3), 378-386.

Abbasi, M., Ketabchi, M., Izadkhah, H., Fatmehsaria, D. H., Aghbash, A. N. (2011). Identification of GTN model parameters by application of response surface methodology. *Procedia* Engineering, 10, 415-420.

Elsayed, E. A. (1996). Reliability Engineering. Massachusetts: Addison Wesley Longman.

Lam, C. F. Guo, H., Larson, L. (2007). Time-varying multi-stress ALT for modeling life of outdoor optical products. *Proc. of RAMS'07*, Orlando, Florida.

Shaked, M., Singpurwalla, N. D. (1983). Inference for step-stress accelerated life tests. *Journal of Statistical Planning and Inference*, 7(4), 295-306.

Srivastava, P. W., Jain, N. (2011). Optimum ramp-stress accelerated life test for m identical repairable systems. *Applied Mathematical Modelling*, 35(12), 5786-5793.

Nelson, W. (1980). Accelerated life testing-step-stress models and data analyses. *Reliability*, *IEEE Transactions on*, 29(2), 103-108.