Advanced Materials Research *Online: 2014-03-12*
ISSN: 1662-8985, Vols. 891-892, pp 1403-1409
doi:10.4028/www.scientific.net/AMR.891-892.1403

Notch Effects on Fatigue Behavior of Thermoplastics

Seyyedvahid Mortazavian[a] and Ali Fatemi[b]

Mechanical, Industrial and Manufacturing Engineering Department
The University of Toledo
2801 West Bancroft Street, Toledo, Ohio 43606, USA

[a]seyyedvahid.mortazavian@rockets.utoledo.edu, [b]afatemi@eng.utoledo.edu

Keywords: thermoplastic, short fiber composite, notch effect, fatigue life prediction

Abstract. An experimental study was conducted to evaluate notch effects on fatigue behavior of a neat polymer (PP impact co-polymer) and a composite made of 30 wt% short glass fibers in polybutylene terephthalate (PBT). A plate-type specimen geometry with a central circular hole was used. The experiments were conducted at room temperature in uniaxial tension-tension (R = 0.1) and tension-compression (R = -1) loading conditions. Some analytical methods including Neuber's rule and the method of critical distances were used in addition to FEA to predict fatigue life of notched specimens. Neuber's rule commonly used for metallic materials proved to be an accurate method for predicting the notched fatigue life of the thermoplastics considered.

Introduction

Neat and short glass fiber reinforced thermoplastics are being increasingly used in the automotive industry. Many components in such applications are under cyclic loading and contain geometrical discontinuities such as holes and other stress concentrators. Therefore, understanding fatigue behavior of such components is essential for their failure and life prediction analyses.

Notch effect on fatigue of unreinforced and short fiber reinforced thermoplastics has been the subject of a number of experimental studies. These include studies on the effect of stress concentration size and the influence of fiber length and orientation on fatigue behavior. Energy-based approaches and critical distance methods have been used to correlate fatigue lives for notched specimens with different types of stress concentrations or to estimate notch stresses.

Zhou and Mallick [1] studied notch sensitivity in a short glass fiber reinforced polyamide-6.6 using dog-bone shaped specimens with central circular notches of different radii. It was observed that fatigue strength based on the net area of notch specimens with different notch sizes fall on the same *S-N* curve. Sonsino and Moosbrugger [2] evaluated the effect of stress concentrations on fatigue behavior of a short glass fiber reinforced polyamide-6.6. Rectangular bars with central circular hole or sharp notches were used. By increasing the severity of the notch, a decrease in fatigue strength was observed at room temperature. At high temperatures, however, the effect of the notch nearly vanished due to the softening of the material.

Haldar and Senthilvelan [3] studied the effect of notch size on fatigue behavior of a short (average length of 0.44 mm) and a long (average length of 1.25 mm) glass fiber reinforced polypropylene. Central circular notch specimens were used for testing. Different behaviors in LCF and HCF were observed. In LCF, both short and long fiber reinforced composites indicated better fatigue performance with increase of the notch size. In HCF, short fiber reinforced materials indicated no effect of notch size, whereas the long fiber reinforced composite showed significant effect of notch size.

Cosmi and Bernasconi [4] conducted an experimental study on fatigue behavior of edge-notched specimens made of a short glass fiber polyamide-6. Specimens injected in the longitudinal direction indicated higher fatigue strength compared to the transverse specimens. This effect was attributed to variation of local apparent elastic properties, which in turn were related to the change in fiber

orientation. Meneghetti and Quaresimin [5] evaluated fatigue strength based on specific heat dissipation of rectangular bars containing either a circular or a slit notch in the center of specimens made of a short glass fiber reinforced polyamide-6.6. It was observed that the specific heat loss correlates the unnotched and central circular notch data well.

De Monte et al. [6] applied a strain energy-based method in order to predict the fatigue lives of central circular and slit notched short glass fiber reinforced polyamide-6.6 specimens. Fatigue data with different notch radii and load ratios were correlated by means of an average SED parameter over a control volume around the notch tip. Zago and Springer [7] studied variable amplitude fatigue behavior of flat specimens with a central hole made of a short glass fiber co-polyamide. Fatigue lives were estimated based on Miner's rule in conjunction with the results of mold flow simulation and FEA. A critical distance approach was used in order to estimate the notch stresses.

Hoey and Taylor [8] investigated the effect of both central circular and hemisphere notches as well as double edge U-shape and V-shape notches on HCF strength of porous PMMA. The critical distance approach was used to predict the fatigue strength. Critical stress for these notches was found to be close to the fatigue strength of pore-free material.

The maximum stress at the notch root may not be appropriate for fatigue life prediction when the gradient of stress in the vicinity of the notch is high. Neuber proposed a microstructural critical distance length and averaged the stress along it to estimate the appropriate stress. Peterson used the stress at a specific distance from the notch root as the appropriate stress. More recently, the idea of Neuber and Peterson has been linked with LEFM as the theory of critical distances (TCD) for predicting fatigue strength [9,10].

In this paper, first the experimental program including the material, specimen geometry, and loading conditions is described. Then, the experimental results including unnotched and notched fatigue data are presented. Notched fatigue life predictions are evaluated next. Finally, conclusions from observed experimental results and performed analyses are presented.

Experimental Program

Two thermoplastics, one unreinforced and one reinforced, were chosen for this study including unreinforced (neat) PP impact co-polymer and polybutylene terephthalate with 30% wt. short glass fiber reinforcement (average fiber aspect ratio of about 26). Here they will be referred to as PP and PBT, respectively. These materials were chosen due to their common applications, particularly in the automotive industry.

An optimized specimen geometry was designed and machined from injection molded rectangular plaques (20 cm × 10 cm × 3.8 mm) [11]. PP was extracted in only transverse direction relative to the mold flow direction, but PBT specimens were provided in longitudinal and transverse directions due to considerable effect of mold flow observed in unnotched behavior. To study notched fatigue behavior, a central hole of 2 mm diameter was used (see Fig. 1) with an elastic stress concentration factor (K_t) of about 2.5. Tensile properties of the PBT in transverse direction are: tensile strength 60.5 MPa, strain at tensile strength 0.027 mm/mm, 0.2% offset yield strength 47.0 MPa, and ASTM D638 Young's modulus 5.73 GPa. In order to prevent the effect of moisture, PBT specimens were dried for 6 hours at 120 ºC prior to testing.

Load-controlled fatigue testing with a sinusoidal waveform was conducted at room temperature and in laboratory air condition on both unnotched and notch specimens using servo-hydraulic testing machines. Stress levels were selected in order to get fatigue lives between 10^3 and 10^6 cycles. Frequencies of 0.25 to 5 Hz were chosen, depending on the stress level, in order to avoid self-heating due to frequency which in unnotched specimens was measured to be less than 8 °C. Fatigue tests were conducted under tensile mean stresses (R = 0.1 for notched and 0.1 and 0.3 for unnotched specimens) in addition to the fully-reversed condition. In both unnotched and notched specimen tests, specimen fracture was defined as failure since the crack growth life was observed to be a small fraction of total life. Incremental step cyclic deformation tests at several stress levels in the range of

fatigue tests were also performed. These tests were conducted in load control while monitoring strain, in order to obtain a relationship between stress and strain amplitudes under cyclic loading.

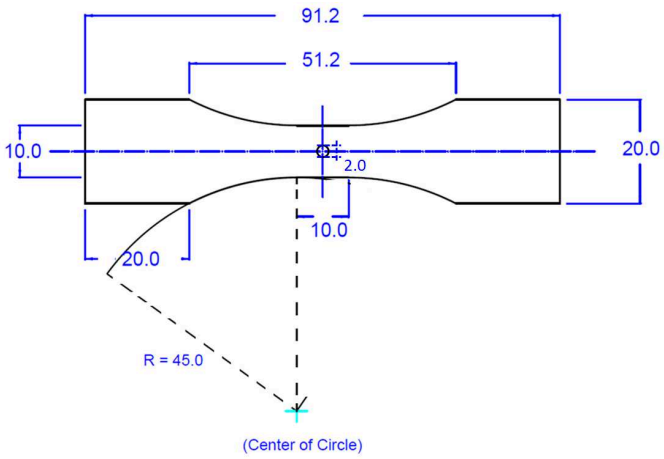

Fig. 1. Specimen geometry used for fatigue tests (dimensions in mm).

Fatigue Test Results

Fig. 2 compares unnotched and notched nominal stress amplitude versus applied cycles to failure for PBT in the transverse direction. Nominal stress amplitude for notched specimens is obtained by dividing the applied loading amplitude by the net cross section area. Significant decreases in fatigue lives resulting from the notch effect are observed for both fully-reversed (Fig. 2(a)) and mean stress R = 0.1 (Fig. 2(b)) loading conditions. Similar behaviors were also observed for PBT in the longitudinal direction and for PP.

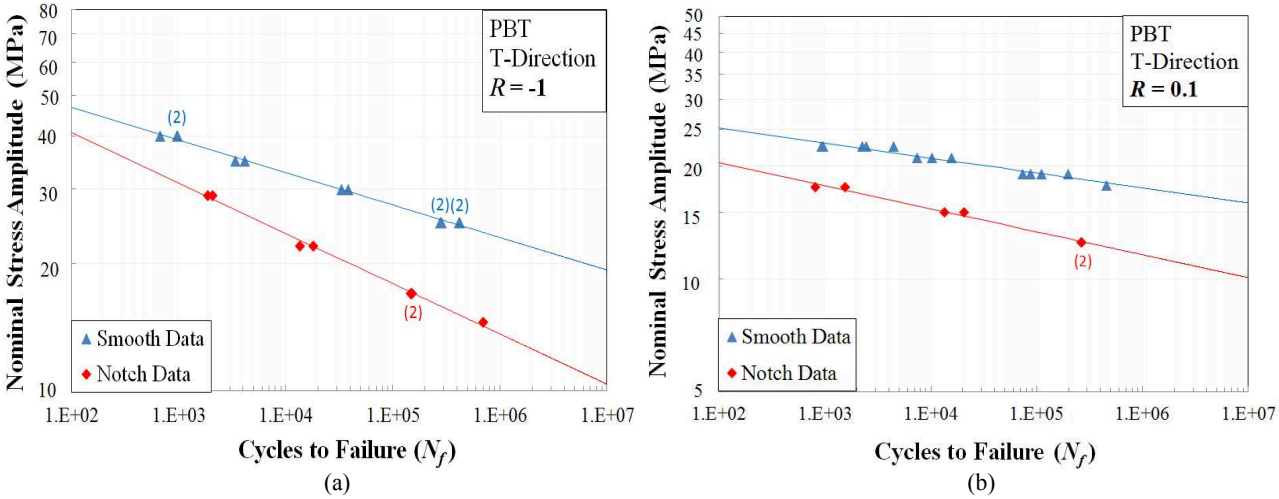

Fig. 2. Effect of notch on fatigue behavior for PBT in the transverse direction at (a) R = -1, and (b) R = 0.1. Numbers above or below the data in this figure and other figures to follow refer to the number of data points on top of each other.

Sensitivity of a material to a notch can be quantified by the fatigue notch factor given by:

$$q = \frac{K_f - 1}{K_t - 1}. \tag{1}$$

where K_t is the elastic stress concentration factor and K_f is the fatigue notch factor which is defined as unnotched fatigue strength divided by notched fatigue strength. Notch sensitivity factor which can take possible values between zero (for no notch sensitivity) and one (for full notch sensitivity) was calculated for the considered thermoplastics at 10^6 cycles. This value was 0.46 for PBT in the

transverse direction, 0.50 for PBT in the longitudinal direction, and 0.37 for PP. In LCF lower notch sensitivity was observed for both thermoplastics, so that unnotched and notch data line fits converged at one cycle, similar to that observed for ductile metallic materials [12].

Effect of stress ratio on fatigue behavior of PBT in the transverse direction is shown in Fig. 3. Mean stress resulted in a significant effect on fatigue lives and this effect was more pronounced at the low cycle regime. The reason may be attributed to increased dependency of fatigue behavior in this regime to the maximum stress, in addition to the stress amplitude. At positive *R*-ratios the maximum stresses are much higher than maximum stresses in of fully-reversed loading and close to or above the yield strength of the material. Therefore, different failure mechanisms may be dominant in different regions. For example, at high stresses (LCF) for $R = 0.1$ tests, matrix yielding plays a dominant role in fatigue failure, whereas at low stresses (HCF) crazing can play a dominant role. This behavior with regards to a decrease in *S-N* line slope with a tensile mean stress was also observed in other studies including unreinforced and short fiber reinforced thermoplastics [11,13].

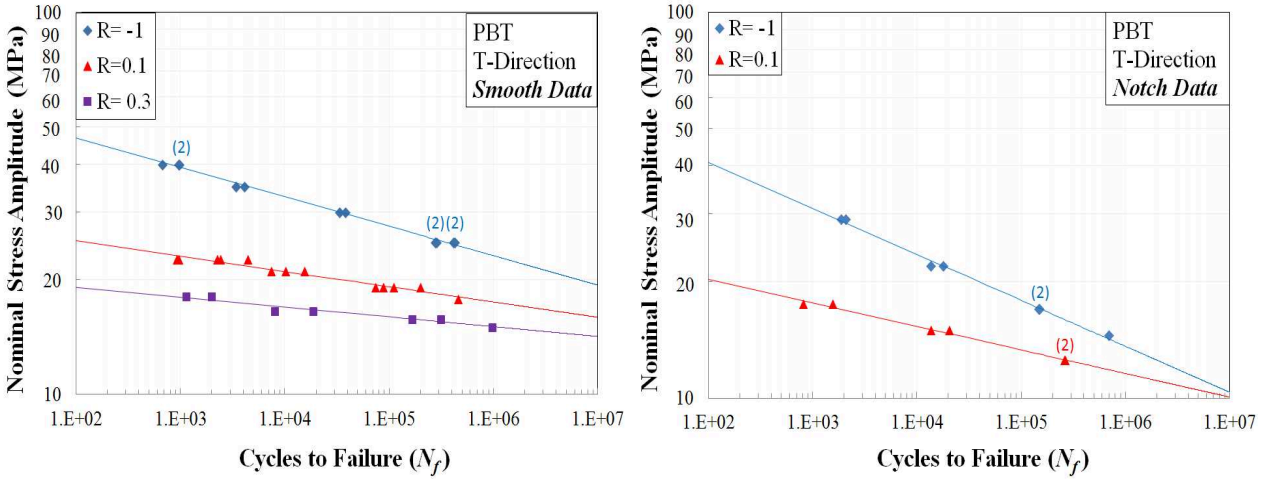

Fig. 3. Effect of mean stress or *R*-ratio for PBT in the transverse direction for (a) unnotched behavior, and (b) notched behavior.

Fatigue Life Predictions

Incremental step test data in the range of fatigue tests were used to obtain the Ramberg-Osgood equation representing the cyclic stress-strain curve [12]:

$$\varepsilon_a = \frac{\sigma_a}{E'} + \left(\frac{\sigma_a}{K'}\right)^{1/n'}. \tag{2}$$

where E', K', and n' are cyclic elastic modulus, cyclic strength coefficient, and cyclic strain hardening exponent, respectively. Neuber's rule was then applied to estimate notch root stress for fatigue life prediction of notched specimens. This rule can be expressed as:

$$\sigma_a \varepsilon_a = K_f^{\,2} \frac{S_a^{\,2}}{E'}. \tag{3}$$

where S_a is the nominal stress amplitude (i.e. load divided by net cross section area). Using this rule along with the cyclic stress-strain curve (Eq. 2), the local stress (σ_a) at the notch root was calculated. It should be noted that K_f rather than K_t is used in Neuber's rule (Eq. 2), since this results in typically much better estimation of fatigue lives, as compared to using K_t. The difference between K_t and K_f is believed to be due to the stress gradient effect at the notch root [12]. Therefore, by using K_f this effect is taken into account, although empirically. Correlations of notched and unnotched

specimens fatigue data at both *R*-ratios based on Neuber's rule are shown in Fig. 4. As can be seen, reasonably good correlations are obtained.

Nonlinear finite element analysis (FEA) utilizing the cyclic stress-strain behavior of the material and isotropic hardening law was also performed as an alternative life prediction method. Eight node hexagonal elements were used with refined element size of 0.04 mm at the notch. Fig. 4 also shows correlations of notched and unnotched specimens fatigue data based on FEA notch root stress values. As can be observed, the FEA notch stress values are high, resulting in overly conservative (by several orders of magnitude) life predictions. This is because while the FEA-obtained maximum stress at the notch root is used for fatigue life predictions, this stress is not most appropriate to use due to the high stress gradient in the vicinity of the notch, as mentioned previously.

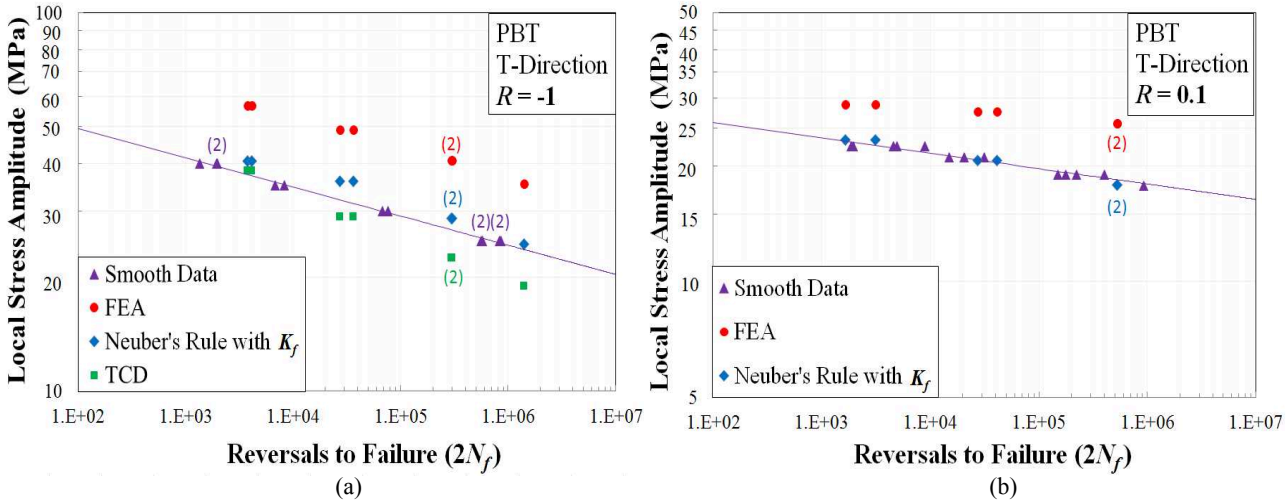

Fig. 4. Correlation of unnotched and notched specimen fatigue data using Neuber's rule, FEA notch root stress, and TCD method for PBT in the transverse direction at (a) R = -1, and (b) R = 0.1.

Using FEA results, a better approach than using notch root stress is the method of TCD, where the notch root stress gradient is accounted for. In this method, first a critical distance from the tip of the notch is calculated as a function of material properties from:

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta \sigma_0}\right)^2 . \tag{4}$$

where L is the critical distance length, ΔK_{th} is the material threshold stress intensity factor range, and $\Delta\sigma_0$ is the fatigue limit range for unnotched behavior. Then the stress at this critical distance is obtained from FEA. Variations of this method can be used as the point method or the line method [9]. In the point method the stress value obtained from FEA is the stress at a distance of $L/2$ from the notch tip. In the line method the stress value obtained from FEA is the average stress over a distance of $2L$ from the notch tip. Using a ΔK_{th} value of 2.5 MPa$\sqrt{m}$ from [14] for 25% glass-reinforced PBT in the transverse direction and a $\Delta\sigma_0$ value of 45.6 MPa from unnotched specimen fatigue curve at 10^6 cycles in the current study, the value of L is computed to be 0.96 mm for PBT in the transverse direction. Using the point method, the results for the fully-reversed condition are shown in Fig. 4(a). As can be seen, the predictions are much better than those based on notch root stress. Improvements of predictions based on the TCD method may be obtained by using the line method, or by defining the distance L as a function of fatigue life [15].

Summary

This study evaluated notched fatigue behavior of one neat and one glass fiber-reinforced thermoplastic with or without mean stress. Analytical methods including Neuber's rule and the method of critical distances were used in addition to the finite element analysis to estimate notch

stresses for use in fatigue life prediction of notched specimens. Based on the experimental results and the analyses conducted, the following conclusions can be made:

1) Effect of a circular notch under both fully-reversed and mean stress loading conditions was found to be significant, with several orders of magnitude life reduction in HCF.
2) A lower notch sensitivity was observed in LCF, as compared to HCF, similar to that observed for ductile behaving metallic materials.
3) A tensile mean stress decreased fatigue strength of both unnotched and notched specimens and this effect was more pronounced in LCF than in HCF regime.
4) Both Neuber's rule with use of the K_f and the method of TCD estimated notched fatigue strength reasonably well.
5) Using notch root stress from FEA for life predictions results in overly conservative predictions. This is attributed to the fact that the notch stress gradient also plays a key role in notched fatigue behavior.

Acknowledgements

This project was funded by General Motors. Technical assistance of Dr. A.K. Khosrovaneh and Mr. Charles Buehler at GM is appreciated.

References

[1] Y. Zhou and P. Mallick, Fatigue performance of an injection-molded short E-glass fiber-reinforced polyamide 6, 6. I. Effects of orientation, holes, and weld line, J. Poly. Comp. 27 (2006) 230-237.

[2] C.M. Sonsino and E. Moosbrugger, Fatigue design of highly loaded short-glass-fiber reinforced polyamide parts in engine compartments, Int. J. Fat. 30 (2008) 1279-1288.

[3] A.K. Haldar and S. Senthilvelan, Notch effect on discontinuous fiber reinforced thermoplastic composites, Key Eng. Mat. 471 (2011) 173-178.

[4] F. Cosmi and A. Bernasconi, Fatigue behavior short fiber reinforced polyamide: morphological and numerical analysis of fiber orientation effects, Giornata IGF Forni di Sopra UD (2010).

[5] G. Meneghetti and M. Quaresimin, Fatigue strength assessment of a short fiber composite based on the specific heat dissipation, Comp. Part B: Engineering 42 (2011) 217-225.

[6] M. De Monte, M. Quaresimin and P. Lazzarin, Modeling of fatigue strength data for a short fiber reinforced polyamide 6.6 based on local strain energy density, Proc. of 16th Int. Conf. on Comp. Mat. ICCM16, Kyoto, Japan (2007).

[7] A. Zago and G.S. Springer, Fatigue lives of short fiber reinforced thermoplastics parts, J. Reinf. Plast. and Comp. 20 (2001) 606-620.

[8] D. Hoey and D. Taylor, Fatigue in porous PMMA: the effect of stress concentrations, Int. J. Fat. 30 (2008) 989-995.

[9] D. Taylor, Analysis of fatigue failures in components using the theory of critical distances, Eng. Fail. Analy. 12 (2005) 906-914.

[10] L. Susmel and D. Taylor, A novel formulation of the theory of critical distances to estimate lifetime of notched components in the medium-cycle fatigue regime, Fat. & Frac. of Eng. Mats. & Structs. 30 (2007) 567-581.

[11] S.R. Mellott and A. Fatemi, Fatigue behavior and modeling of thermoplastics including temperature and mean stress effects, Poly. Eng. & Sci. DOI: 10.1002/pen.23591.

[12] R.I. Stephens, A. Fatemi, R.R. Stephens, and H.O. Fuchs, Metal Fatigue in Engineering, 2nd ed., New York, 2000.

[13] P.K. Mallick and Y. Zhou, Effect of mean stress on the stress-controlled fatigue of a short E-glass fiber reinforced polyamide-6,6, Int. J. Fat. 26 (2004) 941-946.

[14] H. Voss and J. Karger-Kocsis, Fatigue crack propagation in glass-fiber and glass-sphere filled PBT composites, Int. J. Fat. 10 (1988) 3-11.

[15] L. Susmel, The theory of critical distances: a review of its applications in fatigue, Eng. Frac. Mech. 75 (2008) 1706-1724.