BASF Corporation

PLASTICS PART DESIGN: LOW CYCLE FATIGUE STRENGTH OF GLASS-FIBER REINFORCED POLYETHYLENE TEREPHTHALATE (PET)

Abstract

This paper summarizes our extensive investigation on the low cycle (up to $N_{f} = 5x10^4$, where N_f is the number of cycles to failure) fatigue behavior of short glass-fiber reinforced poly(ethylene, terephthalate), or PET, thermoplastic[1]. The modes of fatigue test include tension-tension, compression-compression, four-point bending (flexural) -- all at frequency f = 1-3 Hz, and flexural fatigue at f = 30 Hz (ASTM D-671). All tests were stress-controlled with stress ratio $R = S_{min}/S_{max} = 0.1$, except for flexural fatigue at f = 30 Hz where stress ratio R = -1. The fracture surfaces of tested specimens were analyzed using scanning electronic microscopy (SEM).

The results from this investigation provide comprehensive, up-to-date information and recommendations concerning methods for fatigue testing of injection molded specimens and models, prediction and optimization of low cycle fatigue properties that play a key role in determining a highly stressed plastic parts life and end-use performance, pre-selection of PET based plastic for various industrial applications.

Introduction

Much of the recent growth in fiber-glass reinforced PET has been found in various industrial applications such as automotive, appliances, furniture and so on, where PET made parts and structures are gradually replacing steels, light alloys, and in some case expensive plastics thermoplastics and thermosets. One of the critical factors in structural design of highly loaded plastic parts is the aspect of the part's fatigue endurance (at various numbers N_f of cycles to failure from 10^2 to 10^8 and above). Very often the fatigue endurance of thermoplastics must be tested and analyzed under various design versions, stress-strain and loads modes, frequency f, time-temperature *(t –T)*, and moisture (Figure 1).

The various topics of fracture and fatigue of glass-fiber reinforced polyamide (PA) and PET based plastics have been discussed in [1-8]. Largest portion of these investigations was oriented on fatigue performance of various polyamides (PA 6, PA 66, PA 46, etc.) and significantly less study were oriented on fatigue of PET [2-3, 7-8]. The number of published article on low cycle fatigue of plastics is very limited. In our previous report to ANTEC we discussed the influence of time-temperature [4], and fiber loading [5] on fatigue performance of short glass-fiber reinforced polyamide 6.

Resistance to low cycle fatigue has some specific [1, 8] related to method of testing, test frequency, geometry of the specimens, loading methods (tensile, compression, flexural, torsion, etc.), influence of hysteretic heating, microstructure, etc. The purposes of this paper is to investigate low cycle fatigue characteristics of injection-molded PET with the influence of:

- Loading modes (types) such as four-point bending (flexural) and flexural (ASTM D 671-93), tension-tension and compression-compression.
- Geometry and sizes of used specimens and models.

Low cycle fatigue resistance of short glass-fiber reinforced PET plastic is analyzed and compared. Important comprehensive information was provided for plastic pre-selection, optimized design, product development, and technical support.

Specific of test procedures and generated data

The typical flexural fatigue tests for plastics per ASTM D 671 are performed using well-known testers (SATEC SF-2U). The standard specimen is a cantilever beam with 3.2 mm in thickness and the width increasing linearly toward the beam root) is used for the test. The beam is subject to a symmetrical (stress ration $R = S_{min}/S_{max} = -1$, where S_{min} and S_{max} are the minimum and maximum stress levels respectively) cyclic loading under controlled stress amplitude" and at frequency f = 30 Hz. This test and used equipment are inexpensive and pro-

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[1] PET – thermoplastic polyester for injection molding.

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vides a basic data for comparison of different plastic materials. With some assumptions, developed fatigue data (S – N_f curves) is used for design of various plastic parts.

There are obvious limitations in the flexural fatigue data obtained using the ASTM D-671 procedure above, among them are:

- The data is obtained in a single flexural mode with stress ratio R = -1, whereas the real applications often encounter fatigue in tension-tension or compression-compression mode, or flexural mode with stress ratio R other than –1;
- The dimensions of thickness of actual plastic components, and thickness in particular, are often different from those of test specimens. As a result the different molding conditions experienced by the plastic parts and specimens may invoke different resistance to cyclic loading due to specifics in orientation and distribution of reinforcements, skin-core effects, etc.;
- The flexural loading mode in applications, as characterized by stress ratio R, and mean stress $S_m = 0$, is very different from the one in the laboratory flexural fatigue tests (ASTM D-671). The real stress ratio R is ~ 0 (or above) where in the flexural test R = -1. The mean stress $S_m > 0$ for tensile-tensile mode and $S_m < 0$ for compression-compression mode.
- The cyclic stress frequencies f in real applications are often substantially lower than the 30 Hz from the flexural ASTM tests;
- The shape of the cyclic loading function can also be very different from the sinusoidal used in the ASTM flexural fatigue test.
- The differences in fatigue cracks initiation and growth under variable loading modes (flexural, tension or compression, and multi-axial).

Although for some types of materials – metals in particular - the shape and frequency of the cyclic function may not have significant impact on the low cycle fatigue of the materials, this is not the case for thermoplastics. Due to the intrinsic viscoelastic behavior of thermoplastics, internal friction can easily cause heating in material samples at high frequency. This behavior results in lower fatigue resistance, especially when the often unmonitored and uncontrolled temperature goes above T_g, the glass transition temperature of the material [1, 4-5, 8].

Experimental

Material, Test Specimens and Models

45 wt.% short-glass-fiber reinforced PET thermoplastic colored in black (carbon black) was used for this study. This injection molding grade (Petra®[2] 140 BK-112) was developed for various applications where increased strength, stiffness, engineering property and dimensional stability performance is required. Typical mechanical properties are shown in Table 1. This data represent basic mechanical properties generated by ISO procedures for well-organized glass-fibers orientation in multi-purpose specimen only.

Test samples were molded into the following three types:

1. ISO multi-purpose tensile bars (ISO-3167) with 4 mm thickness that can be easily adapted for low cycle fatigue tests in three modes: tension, compression, and 4-point bending (flexural).
2. The “boss” (hollow cylinder, Figure 2).
3. Bars with cross-section 6.25 mm x 6.25 mm (Figure 3).

Mechanical Tests

The focus of our investigation was in the low-cycle fatigue N_f range from (2-3)x10^2 to (2-5)x10^4 cycles to failure. The low cycle fatigue tests were conducted using Instron-1361, a servo-hydraulic system. All tests were conducted in stress-controlled mode with a constant S_{max}, S_{min}, and stress ratio R. A frequency f of 3 Hz was selected for most of the low cycle fatigue tests except for four-point bending where f = 1 Hz was used. The stress ratio R = 0.1 was used for all low cycle fatigue tests, except the classical flexural fatigue (ASTM D671), where R = -1 at a frequency f = 30 Hz, as discussed before. Additionally we conducted short-term tensile (compressive) and flexural tests for strength data for every type of used specimens. Fatigue data (Figures 4-5) and short-term properties (Table 1, Figure 6) were developed at controlled laboratory conditions at 23 °C, air and 50% RH).

<u>Specific of Loading Modes, Specimens and Models</u>

The following four cyclic loading modes were used:

1. Tension-tension fatigue, conducted on injection molded ISO-3167 multi-purpose specimens with a thickness of 4 mm.
2. Compression-compression fatigue, conduced on three types of injection-molded specimens:

- Rectangular specimens modified from the ISO-3167 used for tension-tension fatigue. A 20-mm long prism was obtained from the center section where the two ends were carefully machined to make sure that they are even and parallel to each other.
- The “boss” (hollow cylinder) models were used as in applications (Figure 2 a, b).
- The same boss specimen with the 3-mm removed from the top. The top layer was suspected to have a molding imperfection (knit line) and fibers re-orientation that could be responsible for the reduced fatigue strength in many cases (Figures 2 and 7).

[2] Petra® is a registered trademark for BASF Corporation PET plastic products.

3. Four-point bend (flexural) fatigue test at a frequency f = 1 Hz, performed on 50 mm long specimens cut from the center section of ISO-3167. The bottom span was 38 mm, and the top span was 12.7 mm.

Results and Discussion

Figure 4 shows developed comprehensive data (S_a - N_f curves) for the stress amplitude S_a vs. cycles to failure N_f for the fatigue tests under various stress modes. In Figure 5, stress amplitude S_a under each loading condition is normalized with the corresponding static strength S_u (for used specimen, Figure 6). On the most basic level, all these diagrams may be anticipated to be the same. Some static strength of material theories, such as the Tresca-Guest (maximum shear stress) criterion or the specific energy of volume distortion are not sensitive to the sign (tension or compression) of the main (normal) stresses. Therefore, the tension and the compression could represent the same level of fatigue tolerance as soon as the maximum shear stress is the same. The same can be applied to flexural where the volumes subjected to the same absolute level of maximum tension and compression are present.

On a somewhat higher level and considering experience of measuring static strength of materials and comparing for tension and flexural one can anticipate a higher fatigue strength obtained in flexural test. Indeed, the following probability considerations are usually used to explain the phenomenon:

- The failure is correlated with the largest defect, and one can assume that the defects are uniformly distributed in the tested volume (the specimen). In flexural test, only the outer surface adjacent layers (volumes) of material are exposed to the maximum stress. The probability to find the largest defect in these areas is therefore lower then in tension where the whole volume is under maximum stress. The experience of observing higher static flexural strength then tensile one is rather consistent on different materials, and this theory seems reasonable.
- The same probability considerations can be used in explaining differences observed between larger and smaller samples (Figures 4-6). Indeed for the same reason the strength, especially, fatigue strength of a smaller specimen should be higher.

Figures 4-5 show also the classical flexural fatigue data (ASTM D-671). The difference between the conditions of the two flexural tests is:

- The specimen configuration, sizes (thickness);
- The loading frequency f;
- The loading method.

We already discussed the anticipated reduction of flexural fatigue strength on a larger specimen. The frequency f effect, if any, should lead to the opposite direction. The loading method should not lead to some substantial differences, because in both cases (the central section of the four-point flexural and ASTM test) the max stresses are constant through comparable areas of the surface. So what we can see from Figure 4 is that compressive fatigue strength is higher than both flexural and tensile fatigue strength. The $S_a – N_f$ curves are parallel within the same loading mode, but the slopes of the curves are steeper in the flexural and the tension modes, where they are parallel again within each mode. At the same time, Figure 5 shows that the differences within the compression mode become statistically negligible when the relative (with respect to the compressive static strength) values are considered (Table 1 and Figure 6). The differences between the tensile and the four-point flexural modes also disappear when looked at in the relative terms. These observations confirm the hypothesis that the major factor for the differences between the modes is the sign of the normal stress component in the max shear stress plane.

What is important is the observed substantial difference between the flexural modes of our four-point, where R = 0.1, and the flexural per ASTM D-671, where R = -1. If only the value of stress ratio R is considered, one would have expected a quite opposite picture to the one in Figures 4-5, namely, the stress amplitudes for R = 0.1 should have been higher then the ones for R = 0.1. Indeed, the maximum stress achieved during the cycle is higher for R = 0.1. This controversy can be explained by examining the effect of loading frequency f. Apparently, as mentioned before, the relatively high frequency f = 30Hz used in ASTM D-671 (as opposite to the f = 1 ~ 3 Hz used in other tests), can easily cause internal heating in the PET due to the viscoelastic nature of the material. The heat generated in the cyclic loading process cannot be dissipated quickly enough, causing rising temperature and softening of the material. The specimen, therefore, has been effectively tested at higher temperature when high frequency is applied. The reduced fatigue strength, as can be seen in the analysis, is caused more by the induced heat than the frequency itself. The flexural fatigue by ASTM D-671, therefore, will produce a $S_a – N_f$ curve lower than other types of curves generated at lower frequencies f when internal heating is not a problem.

Summary and Conclusions

The results from this investigation will provide comprehensive, uniform, and up-to-date information and recommendations for design against fatigue in various molded parts, pre-selection of short glass-fiber reinforced PET thermoplastic for design, mechanical performance prediction and optimization.

Acknowledgment

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Property (in MPa)	**Strength**	**Modulus**
Tensile	190	12,700
Flexural	278	17,100
Compressive	191	8,087

Table 1. Typical mechanical properties of 45 wt.% GF PET colored in black at 23°C (multi-purpose test specimen ISO-3167).

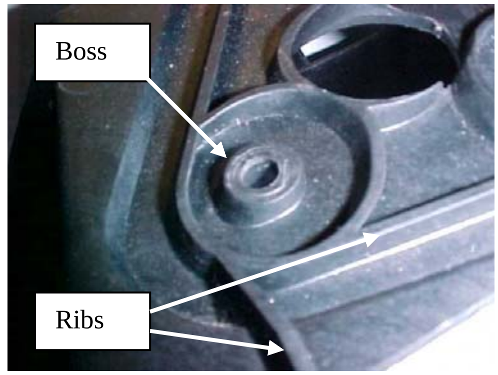

Figure 1. An example of injection molded load bearing thermoplastic part with various modes of local cyclic loading (boss – compressive, ribs – flexural).

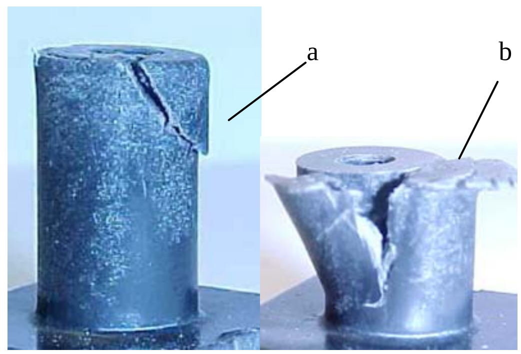

Figure 2. Fatigue failure mode for the boss at compression-compression loading. Agenda: a - shear cleavage along max shear stress plane; b - advanced stage of failure with the break along the knit line.

Figure 3. Fatigue failure mode for rectangular specimen at compression-compression loading (shear cleavage along max shear stress plane).

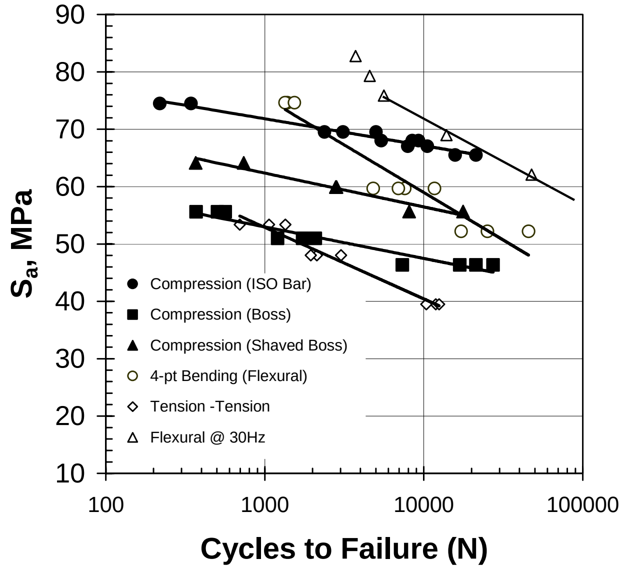

Figure 4. Comparison of Fatigue Properties of 45 wt.% short-glass-fiber reinforced PET. Agenda: S_a – is stress amplitude and N_f – number of cycles to failure.

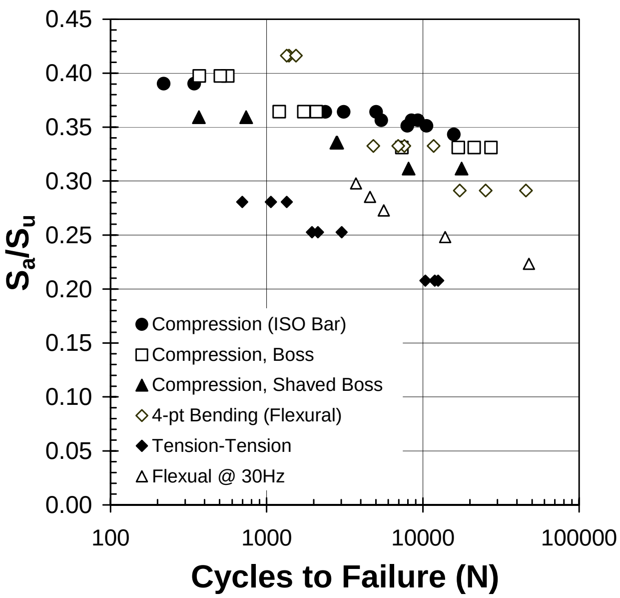

Figure 5. Master S_a/S_u – N_f Curve for All Fatigue Tests. Agenda: where S_a is stress amplitude; S_u is static strength of plastic/used specimen, and N_f is number of cycles to failure.

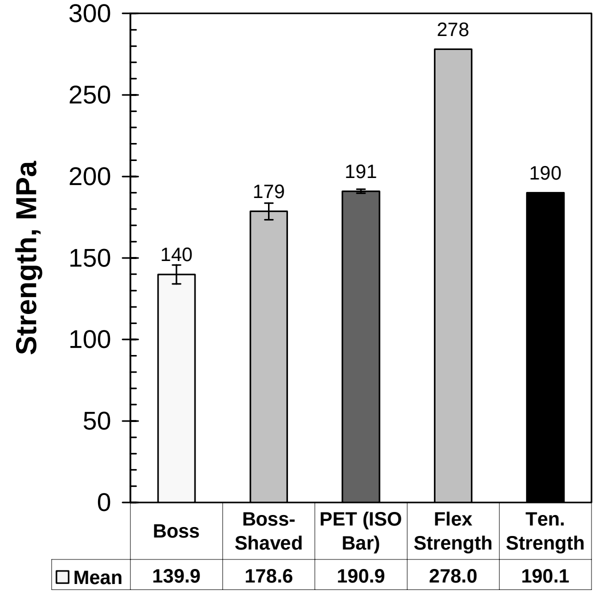

Figure 6. Mechanical Properties of 45 wt.% short-glass-fiber reinforced PET plastic.

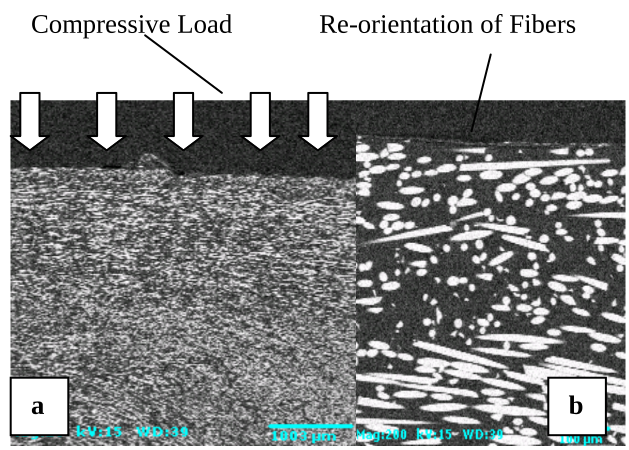

Figure 7. Specific of glass-fiber orientation for hollow boss (top layer content fibers oriented perpendicular to stress direction). Agenda: a – morphology of hollow boss; b – glass-fiber orientation and distribution at top layer, which was removed).

Keywords

Poly(ethylene terephthalate), PET, fiberglass, reinforced, orientation, low cycle, fatigue, strength, mechanical performance, tensile, flexural, compressive.

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