



Guidelines for Conducting Axial Load-Controlled Fatigue Testing of Neat, Filled, and Short Fiber Reinforced Thermoplastic Polymeric Materials

1 Introduction

Note: Nothing in this standard supercedes applicable laws and regulations.

Note: In the event of conflict between the English and domestic language, the English language shall take precedence.

1.1 Purpose. To provide a common, concise, accurate method of obtaining fatigue information for polymeric materials.

1.2 Applicability. This Fatigue Testing Procedure is applicable for all neat, filled, and short fiber thermoplastic reinforced polymeric materials.

1.3 Remarks. Most components and structures are subjected to cyclic loading; therefore, fatigue is a major consideration in their design and failure analysis. Several ASTM International (ASTM) and International Organization for Standardization (ISO), exist for characterizing fatigue behavior and determining fatigue properties of metallic materials. One such standard is ASTM E466 on conducting force controlled constant amplitude axial fatigue tests for metallic materials which has existed for 40 years.

Polymeric materials are increasingly used in many structural applications where they are often subjected to cyclic loadings. Fatigue behavior characterization and properties of polymeric materials are also of prime consideration in many of their applications. However, fatigue test standards for polymeric materials have not been available from major standard writing organizations such as ASTM and ISO until recently.

In 2012, a test standard was issued by ASTM as ASTM D7791-2012, Standard Test Method for Uniaxial Fatigue Properties of Plastics. This brief test standard lacks many details such as specimen geometry and cycling frequency selection. It is also limited to loading conditions for which stresses do not exceed the proportional limit of the material.

The guidelines in this procedure are intended to provide detailed axial load-controlled fatigue testing of polymeric material. This addresses testing equipment requirements, specimen geometry, testing procedures, data acquisition and analysis procedures, and material property determinations. Such guidelines can be used in support of activities such as research and development, process and quality control, and product performance and failure analysis.

2 References

Note: Only the latest approved standards are applicable unless otherwise specified.

2.1 External Standards/Specifications.

ASTM D7791	ASTM E739	SAE 2014-01-0901
ASTM E466	ASTM E1012	

2.2 GM Standards/Specifications.

GMW16652

2.3 Additional References.

- A. Fatemi, S. Mellot, A. Khosrovaneh, C. Buehler, "Tensile and Fatigue Behaviors of Two Thermoplastics Including Strain Rate, Temperature, and Mean Stress Effects", SAE 2014-01-0901, April 2014
- J. Crank, 1975, "The Mathematics of Diffusion, 2nd Ed". Clarendon Press, Oxford, UK.
- M. Eftekhari, A. Fatemi, 2016, "On the Strengthening Effect of Increasing Cycling Frequency on Fatigue Behavior of Some Polymers and Their Composites: Experiments and Modeling" Int. J. Fatigue. 87, 153-166.
- O. Krause, 2002, "Frequency Effects on Lifetime," Optimat Blades Project, DLR, doc. OB_TX_N003 rev. 1, Wieringerwerf, Netherlands.
- R. I. Stephens, A. Fatemi, R. R. Stephens, and H. O. Fuchs, 2000, Metal Fatigue in Engineering, 2nd Ed., John Wiley and Sons, New York, NY.
- S. Mortazavian, A. Fatemi, A. Khosrovaneh, 2015, "Effect of Water Absorption on Tensile and Fatigue Behaviors of Two Short Glass Fiber Reinforced Thermoplastics," SAE Int J Mater Manuf. 8(2), 435-443.
- S. Mortazavian, A. Fatemi, 2015, "Fatigue Behavior and Modeling of Short Fiber Reinforced Polymer Composites Including Anisotropy and Temperature Effects" Int. J. Fatigue. 77, 12-27.

3 Resources

3.1 Facilities.

3.1.1 Calibration. The test facilities and equipment shall be in good working order and shall have a valid calibration label.

3.1.2 Alternatives. Alternative test facilities and equipment may also be used. However, all measuring variables as specified in this standard shall be determined correctly with respect to their physical definition.

3.2 Equipment.

3.2.1 Testing Equipment and Verification. A variety of testing machines can be used to perform the tests. These include a variety of mechanical machines (such as power screw machines), hydraulic or electrohydraulic machines, and electromechanical or magnetically driven machines. Regardless of the type of machine used, the form and magnitude of the applied load signal should be closely controlled and monitored for the duration of the test. It is recommended that the load be maintained within 2% of the intended value for the duration of the test.

3.2.1.1 An effect to be most avoided is misalignment of the specimen and the load train components (i.e., load cell, grips, loading actuator, etc.) in the testing machine. Misalignment can significantly affect test results and cause large data scatter. It results from tilt and/or eccentricity of the test specimen in the loading machine from a variety of sources. These sources include lack of repeatability of the grips during gripping/un-gripping actions, misalignment of the load train, insufficient lateral stiffness of the load frame, and lateral movement of the loading actuator in the case of electrohydraulic machines during the cyclic loading process.

3.2.1.2 To achieve satisfactory alignment, it is recommended to use a stiff load frame (both in axial and lateral directions), a hydrostatic actuator to minimize lateral actuator movement, as short as possible of a load train length, and repeatable grips (typically hydraulic or pneumatic), in conjunction with an alignment fixture. An alignment fixture enables adjusting tilt in two (2) perpendicular orientations, as well as adjusting eccentricity in x-y plane perpendicular to the loading axis. An anti-rotation device may also be necessary to prevent twisting of the loading actuator, and turn the test specimen, during axial cyclic loading.

If measurement or monitoring of axial deformation during fatigue test is desirable (for example: to evaluate cyclic softening or cyclic creep or ratcheting during tensile mean stress tests), a Linear Variable Displacement Transducer (LVDT) or an extensometer (non-contact video or laser, or contact mechanical) can be used. An environmental chamber with an electronic heating element and a coolant system (such as liquid nitrogen) with flow circulation is typically used for testing at cold or at elevated temperatures. To monitor any temperature rise during fatigue tests due to self-heating at the applied load and testing frequency, a thermal imaging camera or a thermocouple can be used.

3.3 Test Vehicle/Test Piece. Not applicable.

3.4 Test Time. Reference material frequency dependence.

3.5 Test Required Information. See explanation via this document.

3.6 Personnel/Skills. Engineers and technicians should be familiar with testing equipment and behavior of polymers.

4 Procedure

4.1 Preparation.

4.1.1 Specimen Design, Fabrication and Storage. Test specimens can be machined from molded plaques (sheets or plates). The GM Materials Engineer will provide guidance for injection molded specimens. Machining specimens from plaques are recommended as the preferred method and should be followed. Note that the thickness of the plaques shall be similar to the thickness of the actual components. See Appendix A. A Computer Numerical Control (CNC) milling machine with an appropriate cutting tool can be used for machining the samples. Prior to specimen machining, the plaques should be stored under a controlled environment (i.e., temperature, humidity, ultraviolet light, etc.)

It is important to identify and record the orientation of the test specimen to be machined with respect to the plaque mold flow direction (for example, longitudinal versus transverse), as well as with respect to the plaque location (for example: edge versus middle). This is particularly important for fiber reinforced polymers, since fiber length and/or orientation distribution may not be uniform in different regions. For this reason, it is recommended not to use the beginning and the end of a molded plaque for specimen manufacturing (see GMW16652). An example of specimen identification method is shown in Figure 1.

Specimens should be machined to a suitable geometry, such as that shown in Figure 2(a). The geometry shown in this figure has been designed as an optimum geometry considering several important factors. These considerations include:

- A large enough gage section volume sufficient to represent realistic fiber distribution in short glass fiber filled polymers.
- A sufficiently long gage section to represent uniform uniaxial stress condition, but short enough to avoid or minimize buckling during compression loading.
- A sufficiently wide gage section to accommodate stress concentrations, if testing to evaluate notch effects is desired. Typical notches include a central circular hole and a U notch or a V notch at the edge(s) of the gage section.
- A generous transition radius for the gage to the grip sections to minimize stress concentration. The geometry shown in Figure 2(a) has a stress concentration factor of 1.06.

4.1.1.2 Dimensional tolerances of about 0.025 mm are recommended. Of particular importance is symmetry of the machined specimens with respect to the specimen centerline. It is also important to avoid scratches during the machining process. After specimens are machined, any excess material and burrs should be removed, while maintaining the integrity of the specimen finish. Appendix A provides recommended guidelines on the specimen machining process.

4.1.1.3 Specimens should be tested dry-as-molded (DAM) unless otherwise indicated. Specimens should be stored in a controlled environment subsequent to machining. If moisture has an effect on test results, such as glass-filled polymers, dry conditioning should be obtained prior to testing. This is accomplished by heating the specimens at a specific temperature and for a specified duration per material supplier guidelines. (Any questions, contact GM Materials Engineer.) Note that the drying duration for complete moisture desorption can be varied significantly depending on the specimen thickness and amount of absorbed moisture. Figure 3 shows the effect of drying duration and type of chamber (regular or vacuum) on tensile stress-strain curve of 30 wt% short glass fiber reinforced Polyamide-66 with 0.75 wt% absorbed moisture after 14 months in the laboratory environment. Full desorption of water and full recovery of tensile properties were obtained by drying specimen in a vacuum chamber at 80 °C for 24 h.

Dried specimens should be stored in a desiccator with desiccant packs to avoid moisture exposure and absorption prior to testing. Specimens should also be stored away from ultraviolet (UV) exposure. Appendix B, Figure B1, contains additional information on moisture effect.

Visual inspection with unaided eyes or with low magnification should be used to note any obvious abnormalities such as fillet undercutting, cracks, or machining marks. Specimen dimensions including thickness and width should be measured using method(s) or instruments in a manner not to introduce any visible marks or scratches.

4.2 Conditions.

4.2.1 Environmental Conditions.

4.2.2 Test Conditions. Deviations from the requirements of this standard shall have been agreed upon. Such requirements shall be specified on component drawings, test certificates, reports, etc.

Note: GM Materials Engineering or GM Fatigue Focus Group Subject Matter Expert (SME), shall be consulted on any proposed deviation to this standard.

4.3 Instructions.

4.3.1 Specimen thickness and width should be measured to within 0.025 mm or smaller at several locations along the gage section. The minimum measurement should be used for the stress calculations.

The specimen should be positioned in the grips precisely to have good alignment consistently from specimen to specimen. Grip pressure producing the normal force on the specimen grip ends should be adequate to avoid slipping during cyclic loading, while not too high to cause visible deformation of the specimen grip ends. Tabs between the specimen surface and the grip faces may be necessary to reduce non-uniform grip force distribution and avoid grip end failures.

4.3.2 Alignment should be verified prior to starting the testing program. A common method for verifying alignment is using a strain gaged round or rectangular cross section bar with two (2) or three (3) series of four (4) strain gages positioned across from each other (left-right and front-back), and each series positioned at a constant axial position. ASTM E1012 provides guidelines for verification of test frame and specimen alignment under tensile and compressive axial loads. It is recommended that alignment be checked at loads similar in nature (tension and/or compression, static and cyclic) and in magnitude to those applied during the testing program. Bending stress measured from misalignment should typically be within 5% of the applied axial stress.

4.3.3 If the testing program includes tension compression cycling (as opposed to tension-tension cycling), it may be necessary to grip the specimen at a shorter length, (i.e., in the transition region between the specimen gage section and grip end) to avoid buckling during the compression part of the loading. For example, gripping the specimen geometry shown in Figure 2(a) at a width of about 15 mm, which is the average of the gage section and grip section widths, has proven successful without inducing grip end failures. Per 3.2.1.2, positioning the specimen precisely and consistently in the grips is essential for good alignment and validity of the test results.

4.3.4 Prior to testing, the temperature and humidity should be recorded. For other than room temperature testing, the specimen should be stabilized at the testing temperature for a pre-determined duration in the environmental chamber prior to testing to ensure the specimen temperature is the same as the temperature in the chamber.

4.3.5 The loading to be used can be specified by load amplitude P_a and R ratio (ratio of minimum load P_{min} to maximum load P_{max}) or mean load P_m , or by specifying the maximum and minimum loads. The following relations exist between these quantities:

$$R = P_{min}/P_{max} \quad \text{Equation (1)}$$

$$P_{max} = P_m + P_a = P_a [2/(1-R)] \quad \text{Equation (2)}$$

$$P_{min} = P_m - P_a \quad \text{Equation (3)}$$

$$P_a = (P_{max} - P_{min})/2 \quad \text{Equation (4)}$$

$$P_m = (P_{max} + P_{min})/2 \quad \text{Equation (5)}$$

The R ratio of -1 indicates fully reversed loading and a zero R ratio indicates pulsating tension loading. The most commonly used R ratio for fatigue testing of polymers is 0.1. The load amplitude has a primary effect on fatigue life, while the mean load has a secondary but still significant effect. Stress values corresponding to the aforementioned load quantities are calculated by dividing the loads by the initial measured cross sectional area. The required R ratio value for the fatigue testing will be provided by GM Materials Engineer or GM Fatigue Focus Group SME.

4.3.5.1 The testing machine can be programmed to follow a variety of dynamic load waveforms (sinusoidal, triangular, square, etc.) Unless otherwise specified, it is recommended to use a sinusoidal waveform. Test data may be recorded at specified intervals during each fatigue test using an automated data acquisition system. This data may include cycle number, load amplitude, mean load and, if desired, deformation amplitude and mean. An appropriate data recording scheme should be used to record the data at selected cycles. Examples of such recording schemes include data acquisition at 2^n cycles (i.e., cycles 1, 2, 4, 8, 16, 32, etc.) or at cycles 1, 5, 10, 50, 100, 500, etc. Such schemes allow for more data collection at earlier stages of the test since more changes to the material behavior resulting from load cycling typically occur early in the fatigue life.

4.3.5.2 Specimen fracture is typically used as definition of failure. Once a test has ended, the specimen failure location should be noted. A failure in the 10 mm uniform gage section length, or within 3 mm away from this section for the specimen geometry in Figure 2(a) can be considered valid. These regions are shown in Figure 2(b) as IGIT and OGIT (see 7.1 Glossary for definitions), respectively. Failure in the OGIT section can be considered valid since the width at 3 mm away from the uniform gage section is 10.2 mm. This corresponds to 2% larger width than the 10 mm uniform width. The stress at this location, as confirmed by finite element analysis, is only 4% higher than that in the uniform test section, which is less than the stress concentration factor of 1.06. Specimens which do not fail at a prescribed number of cycles are designated as runouts.

The number of duplicate tests to conduct at each load or stress level depends on the objective(s) of the testing program, as well as the extent of the observed fatigue life data scatter. Unless otherwise specified, three (3) replicate tests at four (4) stress levels resulting in fatigue lives between about 10^3 and 10^6 cycles are recommended. A runout test (2×10^6) is also required.

4.3.6 Testing Frequency. A very important consideration for the application of cyclic loading is the selection of an appropriate test frequency. Too high a frequency results in significant self-heating which will not only affect the test results considerably, but also changes the failure mode. Too low of a test frequency is not practical for high cycle fatigue, since test durations will be too long. Therefore, an appropriate test frequency should be selected which can vary with the material as well as the load amplitude and mean. An allowable temperature rise limit, resulting from self-heating deemed not to affect the fatigue behavior for a given material, should be selected prior to starting a fatigue testing program. Stable specimen temperature in the gage section should be monitored and recorded in each fatigue test to ensure the temperature rise does not exceed the predetermined allowable limit.

To select appropriate test frequencies to be used in fatigue testing for a given material, preliminary incremental step tests with a predetermined number of applied cycles at each test frequency can be performed. Each incremental step test can be performed at a given load amplitude level and R ratio, where the test starts with a low frequency. After reaching and recording a stable temperature rise, the test frequency is increased and each step is repeated, until the temperature increase no longer stabilizes and keeps increasing. Typical data of stable temperature rise versus test frequency at several stress amplitude levels for a neat polymer tested at R ratio of 0.1 is shown in Figure 4(a). The stress amplitude and R ratios used in such tests should be the same or similar to those to be used in the fatigue testing program.

A constant energy parameter ($\sigma_a \epsilon_a f$) (see 2.3, "Frequency Effects on Lifetime" by O. Krause) which is a function of the testing frequency f , stress amplitude σ_a , and strain amplitude ϵ_a can be used to correlate the data from such incremental tests. This correlation for the data presented in Figure 4(a) is presented in Figure 4(b) and is given by:

$$\Delta T = C \sigma_a \epsilon_a f^2 \quad \text{Equation (6)}$$

Where:

The constant C is found from the fit shown in Figure 4(b). It should be noted that strain amplitudes can be found from the cyclic stress-strain curve obtained from incremental step tests (reference Metal Fatigue in Engineering, 2nd Edition.) This relation can be used to determine the test frequency at a given load level and for an allowable temperature rise ΔT due to self-heating (see 2.3, "Tensile and Fatigue Behaviors of Two Thermoplastics Including Strain Rate, Temperature, and Mean Stress Effects", SAE 2014-01-0901).

4.3.6.1 Another effect of frequency on fatigue behavior of some polymers other than the self-heating effect is known as the beneficial or strengthening effect of frequency (see 2.3, "On the Strengthening Effect of Increasing Cycling Frequency on Fatigue Behavior of Some Polymers and Their Composites: Experiments and Modeling", Int. J. Fatigue. 87, 153-166). For these polymeric materials, fatigue life increases with increasing frequency up to a certain limit, then decreases. At higher frequencies self-heating due to hysteresis heating overtakes the beneficial effect of frequency and decreases the fatigue life. An example of this effect is shown in Figure 5 for neat and short glass fiber reinforced polypropylene. Fatigue tests at a given stress level and temperature with different cycling frequency should be conducted to see if the material has the strengthening effect of frequency.

Viscoelasticity plays the main role for this beneficial effect. When the viscoelastic damping reduces with increasing frequency, fatigue life increases. The damping can be related to the area of hysteresis loops and $\tan \delta$ values. The phase lag (δ), is the phase lag between stress and strain signals under cyclic loading. Instead of conducting fatigue tests at different frequencies to investigate the beneficial effect of increased frequency, frequency sweep dynamic mechanical analysis (DMA) tests can be used to obtain the variation of $\tan \delta$ with frequency, as shown in Figure 6. For the materials for which the beneficial effect of increased frequency on fatigue life is dominant, $\tan \delta$ value decreases with increasing cycling frequency.

4.3.6.2 The beneficial effect of increased frequency on fatigue behavior directly relates to the polymer matrix and not the fiber reinforcement or the filler of the composite materials. For the materials for which the beneficial effect of increased frequency on fatigue life is dominant, the fatigue behavior is more related to the time rather than cycles, provided that fatigue life is not considerably influenced by self-heating. Therefore, for these materials fatigue damage in addition to being cycle dependent is also a time-dependent phenomenon.

4.3.7 Temperature Effects. Polymeric materials show a strong dependence on the temperature due to their viscoelastic nature. Appendix C provides additional detail on temperature effects.