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On the strengthening effect of increasing cycling frequency on fatigue behavior of some polymers and their composites: Experiments and modeling

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Effect of cycling frequency on fatigue behavior of neat, talc filled, and short glass fiber reinforced injection molded polymer composites was investigated by conducting load-controlled fatigue tests at several stress ratios ($R = -1$, 0.1, and 0.3) and at several temperatures ($T = 23$, 85 and 120 °C). A beneficial or strengthening effect of increasing frequency was observed for some of the studied materials, before self-heating became dominant at higher frequencies. A reduction in loss tangent (viscoelastic damping factor), width of hysteresis loop, and displacement amplitude, measured in load-controlled fatigue tests, was observed by increasing frequency for frequency sensitive materials. Reduction in loss tangent was also observed for frequency sensitive materials in DMA tests. It was concluded that the fatigue behavior is also time-dependent for frequency sensitive materials. A Larson–Miller type parameter was used to correlate experimental fatigue data and relate stress amplitude, frequency, cycles to failure, and temperature together. An analytical fatigue life estimation model was also used to consider the strengthening effect of frequency in addition to mean stress, fiber orientation, and temperature effects on fatigue life.

1. Introduction

The usage of polymeric materials including neat, filled, and fiber reinforced composites is increasing rapidly in many applications, including in the auto industry. Ease of manufacturing complex geometries, light weight, cost effectiveness, and high production rate are some of the advantages of these materials compared to metallic materials. Fillers such as talc and reinforcements such as short glass fiber are widely used to improve mechanical properties of neat polymers. For example, tensile elastic modulus of polypropylene composite filled with 30% by weight (wt%) talc is 2.4 times higher than neat polypropylene, and fatigue endurance limit of polyamide-6.6 can be improved 100% by adding 30 wt% short glass fibers [1].

As structural components made of these materials are subjected to cyclic loading during their service life, fatigue performance is an important consideration in their design. Mortazavian and Fatemi [2] recently reviewed information from the literature on fatigue behavior of short fiber reinforced polymer composites, including microstructural aspects and effects related to loading condition and service environment. Another recent comprehensive literature review was conducted by Eftekhari and Fatemi [3] on mechanical behavior of short fiber reinforced thermoplastic composites, including their fatigue and creep-fatigue interaction, at elevated temperatures.

Generally, there is a stronger dependence of mechanical properties on time or frequency (in the frequency domain) in polymers and their composites, compared to metals, resulting from the viscoelastic nature of these materials. Their strain rate sensitivity and time-dependent failure under simple tension loading as well as their creep have been studied, for example in [4–8]. However, the effect of frequency on fatigue behavior of polymers and their composites has been studied far less, in spite of its important consequence in many applications.

Depending on the mode of loading, stress level, material characteristics, and the in-service temperature, frequency affects the cyclic behavior of polymeric materials to various degrees. Self-heating is the major effect of cycling frequency on fatigue behavior of polymers, resulting from viscous energy dissipation and frictional heating. Friction mechanisms between the polymer chains cause dissipation of a part of the total mechanical strain energy. A part of this dissipated energy is converted into heat. Due to low thermal conductivity of polymers, the cumulated heat from continuously applied cycles causes thermal damage, in addition to fatigue

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Nomenclature

A, B	parameters relating stress amplitude to Larson–Miller parameter
C_{LMP}	Larson–Miller parameter constant
E'	storage modulus
E''	loss modulus
f	frequency
LMP	Larson–Miller creep parameter
LMP_f	Larson–Miller type fatigue parameter
N_f	cycles to failure
R	stress ratio
S_a	stress amplitude
S_{max}	maximum stress
S_u	maximum tensile strength
t_f	time to failure in fatigue
t_R	time to rupture in creep
T	temperature
T_g	glass transition temperature
α, β, ζ	analytical fatigue model parameters
δ	phase lag between stress–time and strain–time signals
ΔS	stress range
ε_{max}	maximum strain
θ	fiber orientation angle

damage, which can reduce fatigue life dramatically. Different studies in the literature have evaluated self-heating effects on fatigue behavior of thermoplastics and their composites, including microstructural overview, modeling temperature rise and estimating cyclic life [9–20]. A critical frequency at which frequency results in unstable temperature rise has been obtained from experimental results and relationships have been suggested to estimate the critical frequency for a given stress level. Energy-based models based on hysteresis energy loss and steady state heat conduction have been utilized to calculate temperature rise and correlate experimental fatigue life data.

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. A few studies have considered the beneficial effect of frequency on fatigue behavior of polymers and their composites in terms of crack initiation aspects by using un-notched specimens. These studies are reviewed in the next section. The present study investigates this beneficial or strengthening effect of frequency on fatigue behavior of injection molded neat, talc filled, and short glass fiber reinforced thermoplastics. Viscoelastic behavior was characterized from the results of temperature and frequency sweep dynamic mechanical analysis tests. Load-controlled fatigue tests were conducted at different frequencies at constant stress amplitude levels at different temperatures and stress ratios. Scanning electron microscopy was performed on specimen fracture surfaces to study the frequency effect at the microstructural level. Two different fatigue life estimation models that account for the effect of frequency were applied to the experimental data. To be able to apply the models to general cases, additional fatigue tests were conducted at different stress levels at each specific temperatures and stress ratio. The experimental program conducted, the results obtained, and the models applied are presented and discussed in the sections following the literature review.

2. Literature review on the beneficial effect of increased frequency on fatigue life

It has been observed that under certain conditions (including the loading type and level, polymer or polymer composite type, and the temperature), fatigue life increases and crack growth rate decreases with increasing frequency. Zhou and Mallick [21,22] observed the beneficial effect of frequency on fatigue life for 40 wt% talc filled polypropylene and 33 wt% short glass fiber reinforced polyamide-6.6 under stress ratio or R-ratio (ratio of minimum to maximum stress) of 0.1. For the talc filled polypropylene composite, the fatigue life increased with increasing frequency up to 2 Hz at maximum stress levels of 80% and 85% of tensile strength at room temperature. Above 2 Hz fatigue life decreased with increasing frequency because of self-heating but remained constant above 5 to 20 Hz. At high frequencies, the temperature rise was high enough to melt the samples. The same behavior was also observed for the polyamide-6.6 composite at maximum stress levels of 55% and 70% of tensile strength at room temperature. Fatigue life increased proportionally with frequency up to 2 Hz. Increasing frequency from 0.5 to 2 Hz caused about four times increase in fatigue life at both stress levels. Above 2 Hz, fatigue life decreased continuously up to 20 Hz, because of the self-heating effect and the rate of reduction decreased with increasing frequency.

Shrestha et al. [20] investigated fatigue behavior of polyther ether kerone (PEEK) using fully reversed strain-controlled fatigue tests at strain amplitudes ranging from 0.02 mm/mm to 0.04 mm/mm at several frequencies. The beneficial effect of frequency on fatigue life was observed at higher stain amplitudes, whereas at a lower strain amplitude of 0.02 mm/mm a minimal frequency effect was observed. For example, at strain amplitude of 0.03 increasing frequency from 0.5 Hz to 1 Hz caused increase in reversals to failure by factor of seven, although temperature rise on the surface of specimen increased from 37 to 66 °C.

In several studies, the beneficial effect of increasing frequency have been observed on fatigue crack propagation (FCP) behavior of polymers. It should be noted that the self-heating for notched or cracked specimens used for FCP investigations becomes less dominant than for un-notched specimens due to higher heat dissipation of the highly stressed material volume at the notch or at the crack tip. Hertzberg et al. [9,23–26] studied the beneficial effect of frequency on the FCP rate of different polymers in the frequency range of 0.1–100 Hz. It was observed that for poly(methyl methacrylate) (PMMA), polystyrene (PS) and poly(vinyl chloride) (PVC), the fatigue crack propagation (FCP) rate decreased and fatigue resistance significantly improved with increasing test frequency. On the other hand polycarbonate (PC), polysulfone (PSF), Nylon-6.6, and poly(vinylidene fluoride) (PVF_2) exhibited a slight worsening of FCP behavior with increasing test frequency. It was concluded that the frequency sensitivity is greatest in those polymers that show a high propensity for crazing. Also, the beneficial effect of higher frequency was related to competition between strain rate and creep effect, crack tip blunting because of hysteresis heating, and the role of beta transition in which bending and stretching of primary polymer bonds lead to increased toughness. The frequency sensitivity was stated to be maximum for polymers where the beta transition at test temperature occurs in the range of the experimental test frequency [24]. A higher frequency and, therefore, a higher strain rate causes an increase in modulus and strength. Localized heating due to increased frequency at the crack tip can blunt the crack tip and lower the effective intensity factor and, thus, decreases FCP rate.