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Evaluation of multiaxial fatigue life prediction criteria for PEEK

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ABSTRACT

Multiaxial fatigue test were conducted on PEEK under four loading paths and several criteria were used for life prediction. Predictions based on Fatemi–Socie criterion fall out of the factor-of-two line on the conservative side for proportional loading and non-proportional loading. The normal strain-based Smith–Watson–Topper criterion yield good prediction for proportional loading but non-conservative prediction for non-proportional loading. Taking the contribution from shear component into consideration, the Chen–Xu–Huang criterion achieve satisfactory results for both proportional loading and non-proportional loading, but with non-conservative prediction for pure torsion loading. To consider general cracking behavior, the modified SWT criterion is adopted and good agreement between experimental data and prediction values is achieved.

1. Introduction

Poly(ether-ether-ketone) (PEEK), is a semicrystalline polymer that is of great interest to the medical community for its several attractive properties: transparent to X-rays, no artifacts created in CT images, and excellent biocompatibility [1]. In practical use, these PEEK devices are inevitably experience cyclic loading or even multiaxial loading conditions, and fatigue failure will occur. Therefore, a better understanding of the fatigue behavior of PEEK, especially the multiaxial fatigue behavior, is of clinical interest.

Multiaxial fatigue life prediction of engineering materials has been a challenging task for over past decades and many fatigue criteria have been developed over these years. Overviews on multiaxial fatigue can be found in [2–5]. Generally speaking, the multiaxial fatigue theories could be classified as stress-based [6–14], strain-based [15–19] and energy based [20–26] according to the major physical quantity used in this model. In stress based, differences exist between stress invariant approaches and critical plane ones. For low-cycle fatigue, the critical plane approach, based on either maximum shear failure plane or maximum principal strain plane, has been widely used by researchers since it has a solid physical basis. As investigated by many researchers, cracks nucleate and grow on preferred plane rather than with random orientation [2]. Once cracks nucleate, they firstly grow along maximum shear planes and later along the maximum tensile plane. For materials showing shear fracture, Brown and Miller [19] proposed that parameters governing fatigue life are the maximum shear strain and tensile strain normal to the plane of maximum shear strain. However, this approach cannot account for additional cyclic hardening [27,28] caused by principal stress and strain axes rotating in out-of-phase or non-proportional loading as it only includes strain terms in the expression. While Fatemi and Socie (FS) [16] built their work on this model but proposed that the normal strain term should be replaced by normal stress so as to account for the effect of mean stress. This approach has been proven effective for a variety of materials [29–32]. For materials showing normal fracture, Smith et al. (SWT) [18] suggested that the maximum normal strain plane should be considered as the critical plane. Jiang and Sehitoglu [33] modified the SWT parameter to consider general cracking behavior and the modified criterion could predict different cracking behavior with a proper choice of value for the material constant [34–36]. With the ability of unifying microscopic and macroscopic data, energy-based model is based on the assumption that the cyclic plastic strain is related to the movement of dislocations, and the cyclic stress is related to the resistance to their motion. Thus, the plastic strain energy per cycle may be regarded as a composite measure of the amount of fatigue damage per cycle [23]. Based on the strain energy density per cycle, Ellyin [21] incorporated the positive elastic strain energy into the total strain energy as a way of introducing mean stress effect into an energy-based criterion. Liu et al. [25] proposed a virtual strain energy model for shear and tension fracture while Chu et al. [26] replaced the stress range in Liu's model with maximum stresses in an attempt to include mean stress effect. Chen et al. [24] proposed a combined energy density and critical plane approach to take into account of different mechanism for shear-type failure and tensile-type failure. Han et al. [31] evaluated six multiaxial fatigue

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Nomenclature

a	material constant in modified SWT criterion
b	axial fatigue strength exponent
b_γ	shear fatigue strength exponent
c	axial fatigue ductility coefficient
c_γ	shear fatigue ductility exponent
D, d	outer and inner diameters of the specimen, respectively
E	young's modulus
F	axial load
FP	fatigue parameter
G	shear modulus
l_0	gauge length
K	material constant in Fatemi–Socie criterion
N_f	number of cycles to failure
S_y	yield stress
T	torque
α	torsional angle
$\Delta\gamma$	shear strain range
$\Delta\gamma_1$	shear strain range on the maximum principal strain plane
$\Delta\gamma_{\max}$	maximum shear strain range
$\Delta\varepsilon$	axial strain range
$\Delta\varepsilon_1^{\max}$	maximum principal strain range
$\Delta\varepsilon_n$	normal strain range on the maximum shear strain plane
$\Delta\sigma$	axial stress range
$\Delta\sigma_1$	normal stress range on the maximum principal strain plane
$\Delta\sigma_n$	normal stress range on the maximum shear strain plane
$\Delta\tau$	shear stress range
$\Delta\tau_1$	shear stress range on the maximum principal strain plane
θ	angle between cross section of specimen and normal direction of an element
ν	poisson ratio
$\sigma_{\max}$	maximum stress in a loading cycle
$\sigma_{n\max}$	maximum normal stress on the maximum shear strain plane
$\sigma_1^{\max}$	maximum principal stress on the maximum principal strain plane
σ'_f	axial fatigue strength coefficient
ε'_f	axial fatigue ductility coefficient
τ'_f	shear fatigue strength coefficient
γ'_f	shear fatigue ductility coefficient

criteria for SNCM630 steel under irregular axial–torsional loading and concluded that the energy-based parameters could achieve satisfactory results based on the maximum damage plane.

Many previous studies of the fatigue properties of PEEK were focused on the fatigue crack propagation behavior of PEEK [37,38] and stress-life (S-N) behavior. Tang et al. [39] investigated the HA/PEEK composites subjected to tension–tension fatigue under load-controlled load, they found that all of the specimen could withstand 50% ultimate tensile strength, which they attribute to the polymer chain re-orientation and stress-induced crystallization. The fatigue behavior of PEEK in the presence of a notch is studied by Sobieraj et al. [40,41] by examining both stress-life fatigue behavior and the fracture behavior. It is found that most of the lifetime was spent on initiation of cracks rather than propagation. To the authors' knowledge, very limited studies are available to date concerning the multiaxial fatigue life prediction of PEEK.

In this work, extensive fatigue tests were carried out under strain-controlled fully reversed uniaxial tension–compression, cyclic torsion, proportional loading and non-proportional axial–torsion loading. Several multiaxial criteria (the Fatemi–Socie criterion, the Smith–Watson–Topper criterion, the Chen–Xu–Huang criterion and the modified SWT criterion) were evaluated based on fatigue data in the tests.

2. Experimental procedure

PEEK micro-tubes with an outer diameter of 2.4 mm and a thickness of 0.2 mm are used in the current investigation. The mechanical properties of this material are shown in Table 1. The total length of the specimen is 40 mm and the gauge length is 20 mm. To reduce stress concentration at the grips of the machine, a layer of protection layer made of woven fabrics was wrapped around the ends of the specimens. All the tests are performed on a mini type tension–torsional material testing apparatus under the strain-controlled cyclic loading conditions. Resolution of displacement is 1 μm and resolution of rotation is 0.004°, which can meet the demand of tests. Fully reversed axial strain range and torsional strain range of triangular waves are used except for the circular path experiment with sinusoidal wave. The data are collected by an automatic data acquisition system. All the experiments are conducted at room temperature.

Four axial–torsion loading paths were used in the fatigue experiments, as shown in Fig. 1. The loading path is defined in $\varepsilon - \gamma/\sqrt{3}$ strain space: cyclic tension–compression (path I), cyclic torsion (path II), proportional axial–torsion (path III) and the non-proportional circular shaped axial–torsion (path IV). All the fatigue experiments are listed in Table 2. A 10% reduction from the stabilized or peak value, or a visible crack was found on the outer surface of the specimen, was chosen as the failure criterion. The cracking behavior under fully reversed tension–compression and cyclic torsional loadings were examined by Scanning Electron Microscopy (SEM).

Since the stiffness of the grips in the machine is much larger than that of the materials, displacement between the upper and lower grips is close to the actual displacement of the specimen. Accordingly, the axial and torsional shear strains could be obtained by converting the displacement and angle measured by sensors in the machine, which is also seen in [42]. To eliminate machine displacement, and at the same time to calibrate the measurement accuracy of the apparatus, a non-contact displacement detection system (NDDS) is used. The NDDS system is composed of a light source, a CCD camera, an image processing program and a data acquisition system. The monophonic lamp provides an environment that could guarantee a stable output signal of CCD camera. The minimum displacement that could be detected by this system

Table 1
Material mechanical properties of PEEK.

Elasticity modulus, E (GPa)	3.8
Shear elasticity modulus, G (GPa)	1.3 [48]
Poisson ratio, ν	0.4 [48]
Axial fatigue strength coefficient, σ'_f (MPa)	60.34
Axial fatigue ductility coefficient, ε'_f	0.00713
Axial fatigue strength exponent, b	−0.03314
Axial fatigue ductility exponent, c	−0.1528
Shear fatigue strength coefficient, τ'_f (MPa)	34.2
Shear fatigue ductility coefficient, γ'_f	0.0445
Shear fatigue strength exponent, b_γ	−0.0462
Shear fatigue ductility exponent, c_γ	−0.1537