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Uniaxial and biaxial ratcheting behavior of ultra-high molecular weight polyethylene

Hong Gao[a], Jianhai Wang[a], Fan Li[a], Lilan Gao[a,b,*], Zhe Zhang[a,**]

[a] School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, PR China
[b] School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300384, PR China

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ABSTRACT

Experimental studies were conducted to investigate the uniaxial and biaxial ratcheting behaviors of Ultra-high molecular weight polyethylene (UHMWPE). The effects of stress amplitude, stress rate and hydroxyapatite content on uniaxial ratcheting behavior were studied firstly. It is found that the ratcheting strain and its rate increase as stress amplitude increases. However, the ratcheting strain and its rate decrease with rising of stress rate. Meanwhile, it is found that the ratcheting strain decreases with increase of hydroxyapatite content. The ratcheting strain rates with different hydroxyapatite contents are not obviously different. The modified ratcheting strain accumulative model was constructed to predict the uniaxial ratcheting behavior of UHMWPE with different stress amplitudes, stress rates and hydroxyapatite contents. It is seen that the predictions agree with the experimental results very well. The effects of different loading paths on biaxial ratcheting behavior of UHMWPE were studied. Both ratcheting strain and ratcheting strain rate are strongly influenced by the loading path. It is found that the uniaxial loading path gives the highest ratcheting strain and its rate while the proportional loading path gives the lowest ratcheting strain and its rate.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) has been used as a bearing surface in total joint arthroplasty since the early 1960s. As the artificial joint liner, the wear resistance, oxidation resistance and resistance to mechanical fatigue damage are the main factors affecting the long term property of UHMWPE.

It has well been accomplished for the study on the oxidation resistance and abrasive wear resistance of UHMWPE. It was found that the cross-linking can increase the wear resistance of UHMWPE, but decrease the oxidation resistance [1,2]. The cross-linking was coupled with the subsequent remelting to neutralize the free radicals, which can improve the oxidation resistance of the material [3], but this treatment decreased its mechanical properties [4–7]. Recently, it has been replaced by incorporation of Vitamin E into UHMWPE to increase the oxidation resistance of UHMWPE [8]. In addition, some researchers made attempt to improve UHMWPE's tribological properties and increase the safety and biocompatibility in human implants by adding the hydroxyapatite (HA) [9,10].

UHMWPE bears the mechanical loadings, such as the tension, pressure, bending and shear stress, in the process of service, and these stresses are often cyclic and asymmetric. Under these loading conditions, the UHMWPE component may produce the ratcheting deformation, which accelerates its damage accumulation and shortens its service life. Therefore, it is necessary to study the ratcheting behavior of UHMWPE under cyclic loading. Ratcheting, being defined as the progressive accumulation of plastic deformation, can be found in materials subjected to stress-controlled cyclic loading with non-zero mean stress. As the number of cycle increases, the ratcheting deformation can accumulate continuously and it may not cease until fracture. It was noted that the ratcheting deformation affected the fatigue life of material in a negative manner [11–13]. There has been some research on the fatigue resistance property of UHMWPE. Ansari et al. and Pruitt et al. found that the clinical cross-linked UHMWPE had the lower fatigue fracture resistance properties [14,15]. Oral et al. found that the fatigue resistance of UHMWPE decreased with increase of radiation dose [6]. Ansari et al. found that the crystallinity of UHMWPE improved its fatigue resistance but the presence of fusion defects or oxidation reduced further fatigue resistance [16]. Recently, Ozgen Umit Colak and Kerem Asmaz [17] simulated the biaxial ratcheting behavior of UHMWPE by using the viscoplasticity theory. They proposed the kinematic hardening and tangent modulus to improve the strain ratcheting response of

* Correspondence to: L. Gao, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, PR China.
** Corresponding author.
E-mail addresses: gaolilan780921@163.com, hgao@tju.edu.cn (L. Gao), zhe.zhang@tju.edu.cn (Z. Zhang).

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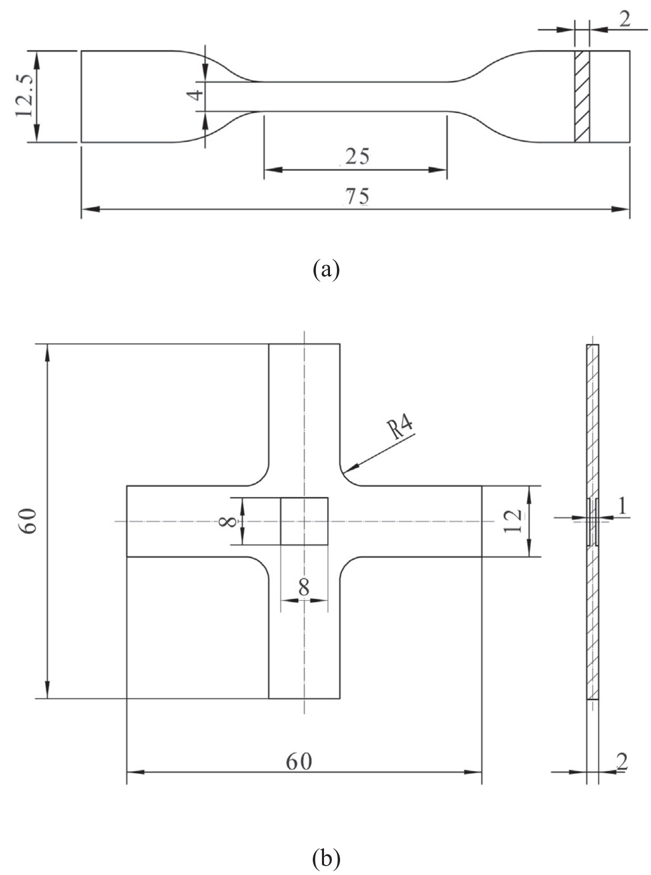

Fig. 1. Geometry and dimensions of specimens: (a) uniaxial specimen; (b) cruciform specimen.

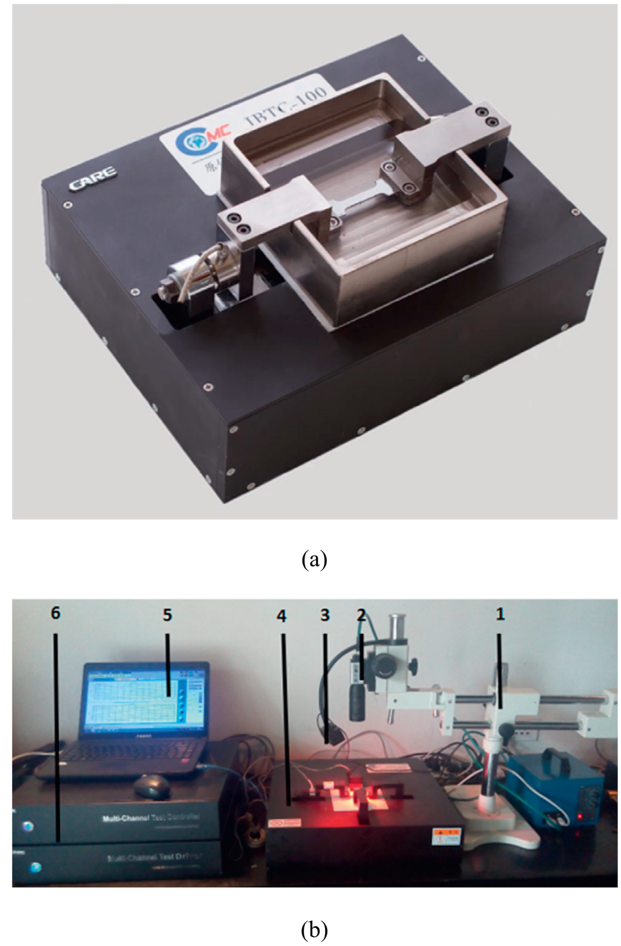

Fig. 2. Experimental system: (a) uniaxial in-situ fatigue testing machine; (b) biaxial cyclic testing system.

UHMWPE. However, it is necessary to study the uniaxial and biaxial ratcheting properties of UHMWPE systematically, especially for the ratcheting performance of modified UHMWPE. There is very little research on the uniaxial ratcheting behavior of UHMWPE at different additives contents. In addition, there is no research on the biaxial ratcheting behavior of UHMWPE under different loading paths.

In this study, the uniaxial ratcheting behaviors of UHMWPE were studied by cyclic tensile experiments and theoretical predictions. The factors, such as stress amplitude, stress rate and hydroxyapatite content were investigated. Subsequently, the biaxial ratcheting behaviors of UHMWPE were investigated by considering the influences of loading paths on ratcheting strain, which are studied for the first time.

2. Experimental descriptions

2.1. Materials and specimen design

UHMWPE granules of GUR 1020 were purchased from German Ticona company with an average molecular weight of 3.5×10^6 g/mol and density of 0.94 g/cm^3. The granules were compressed with hydroxyapatite particles of 0, 5, 10, 20 wt% at 200 °C and at a pressure of 15 MPa for 2 h in vacuum sintering furnace with vacuum degree of 5×10^{-1} Pa, and then cooled for 8 h to room temperature in the oven to obtain a sheet. The high-purity hydroxyapatite particles (99.99%) were purchased from Beijing Adecco company with average diameter of 20 nm and specific surface area of 50 m^2/g.

The specimens used in uniaxial tests were cut from the obtained four plates with different hydroxyapatite contents in accordance with standard DIN EN ISO 527-2 (Type 5A). The cruciform specimens used in biaxial tests were cut from the obtained pure UHMWPE plate. Their geometry and dimensions are shown in Fig. 1. For cruciform specimen, two aspects were considered to obtain the optimal value of maximum principal strain as well as ensure the uniformity of strain field in central region. Firstly, the four fillet type is necessary and should be enough curvature. Secondly, in the centre of the samples, the thickness was reduced to control the location of the initial strain localization.

2.2. Uniaxial and biaxial cyclic testing system

Uniaxial ratcheting experiments were carried out on a uniaxial in-situ fatigue testing machine (IBTC-100, CARE Measurement & Control Co., Ltd.), as shown in Fig. 2(a). The testing system is simple with maximum loading of 100 N, displacement stroke of 60 mm, loading precision of 0.3 N, displacement precision of 0.1 μm.

Biaxial ratcheting experiments were conducted on a biaxial in-situ fatigue testing system (IBTC-500, CARE Measurement & Control Co., Ltd.), which consisted of the following sections, as shown in Fig. 2(b):

Table 1
Loading conditions for uniaxial ratcheting tests.

HA含量 (%)	σ_m (MPa)	$\Delta\sigma/2$(MPa)	$d\sigma/dt$(MPa/s)
0	12	4	4
0	12	8	4
0	12	12	4
0	12	4	2
0	12	4	8
5	12	12	4
10	12	12	4
20	12	12	4