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生物陶瓷材料的疲劳寿命预测

朱 平[1] 林忠钦[1] 陈关龙[1] 池田清彦[2]
(1. 上海交通大学 2. 日本宫崎大学)

摘 要 采用断裂力学中的四点弯曲试验法，研究并预测了氧化铝和氧化锆陶瓷材料在大气和水环境中的循环疲劳破坏特性. 结果表明，在相同的应力条件下，氧化铝和氧化锆陶瓷材料，尤其是氧化锆陶瓷，在水环境中的疲劳寿命比大气中的低. 通过将预测结果与实验结果比较和对人造股关节的应用，验证了这种疲劳寿命预测方法的有效性和适用性.

关键词 无机非金属材料，陶瓷材料，水环境，循环负荷，寿命预测
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Prediction of fatigue lifetime in bio–ceramics

ZHU Ping[1]* LIN Zhongqin[1] CHEN Guanlong[1] Ikeda Kiyohiko[2]
(*1.School of Mechanical and Power Engineering, Shanghai Jiao Tong University, Shanghai 200030*
2.Department of Mechanical Systems Engineering, Miyazaki University, Japan)

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* To whom correspondence should be addressed, Tel:(021)62932660–118,
E–mail: pzhu@sjtu.edu.cn

ABSTRACT The characteristics of cyclic fatigue fracture were studied by the crack growth tests using the four–point bending method in both environments of air and water for alumina and zirconia ceramics. The effect of water environment on the fatigue lifetime was investigated. The results showed that in the case of the same stress applied, the time to fracture in water is less than that in air, and it is more remarkable for zirconia. The fatigue lifetime predictions agree qualitatively with the experimental results for cyclic fatigue of alumina and zirconia in air and water environments, and the method of the fatigue lifetime prediction was applied to artificial hip joint.

KEY WORDS inorganic non–metallic materials, ceramics, water environment, cyclic loading, lifetime prediction

The applications of ceramics as biomaterial have been expected. Glass ceramics, alumina and zirconia are useful materials as bio–ceramics. Most of bio–ceramics are oxide ceramics which undergo fatigue by stress corrosion cracking. Furthermore, when such ceramics are used for implant materials such as artificial joints, they undergo cyclic loading for a fairly long period in corrosive environment. Thus, for practical use and to investigate the mechanism of fatigue fracture, it is important to know what fracture behavior is observed under cyclic loading in both environments of air and water, in particular the effect of water environment on the fatigue lifetime. Although many studies on fracture behavior of bio–ceramics have been carried out[1~5], the effect of water environment on the fatigue fracture and fatigue lifetime prediction almost have not been elucidated, in particular for zirconia[6,7].

In the present study, the crack growth tests were carried out under cyclic loading in both environments of air and water in order to investigate the effect of water environment on the fatigue lifetime for alumina and zirconia. In addition, the K_I–V characteristics[8] were used to predict the fatigue lifetimes under cyclic loading and the predictions were compared with the experimental results.

1 Experimental procedures

The materials chosen in this investigation are two kinds of commercially available alumina and zirconia. Their chemical compositions and mechanical properties are shown in Tables 1, 2 and 3. The average grain size obtained from the observation of fracture surface is about 3 μm to 5 μm in alumina, 0.5 μm to 1 μm in zirconia.

Table 1 Chemical composition in alumina (mass fraction, %)

Al_2O_3	MgO	SiO_2	Na_2O	Fe2O_3	TiO_2	CaO
99.7	0.087	0.062	0.032	0.012	0.003	0.042

Table 2 Chemical composition in zirconia (mass fraction, %)

ZrO_2+HfO_2	Y_2O_3	Al_2O_3	SiO_2	Na_2O	Fe_2O_3
94.33	5.38	0.25	0.019	0.021	0.004

Table 3 Mechanical properties in alumina and zirconia

Material	Density /g·cm^{-3}	Fracture toughness K_{IC} /MPa·m$^{-1/2}$	Bending strength /MPa	Hardness /HV10	Thermal conductivity /W·(m·K)$^{-1}$
Alumina	3.94	4.41	376	1640	32.6
Zirconia	6.07	5.00	1136	1300	3.11

The dimension of bending specimens is 40 mm×20 mm×3 mm. With Vickers indentation to introduce pre–cracks at the center of the specimens, where the load to mark the indentation is 196 N and the loading time is 30 s, the precracked specimens were obtained. The specimen was set on the four–point bending device and the pre–crack was on the tensile surface of the specimen. In cyclic loading the specimens were subjected to a sinusoidal cyclic stress with a stress ratio (minimum stress/maximum stress) of 0.1 and a frequency of 3 Hz. The crack growth tests were performed in both atmospheres of air with relative humidity from 40% to 60% and ion exchanged water, where the maximum testing time was limited to 5×10^5 s(∼139 h).

2 Effect of water environment on the fatigue lifetime

The results of the cyclic fatigue tests are shown in Fig.1. It shows the $\log\sigma_{\max}$–$\log t_{fc}$ relationship for alumina and zirconia in both air and water environments. The time to fracture decreases with increasing the applied stress. In the case of the same stress applied, the time to fracture in water is less than that in air, and it is more remarkable for zirconia. Therefore, it is considered that the fracture in alumina occurs mainly at grain boundaries where SiO_2 bonds exist, while the fracture in zirconia occurs at both grain boundaries and the interior of the grain due to stress corrosion cracking with principal components of ZrO_2 and SiO_2.

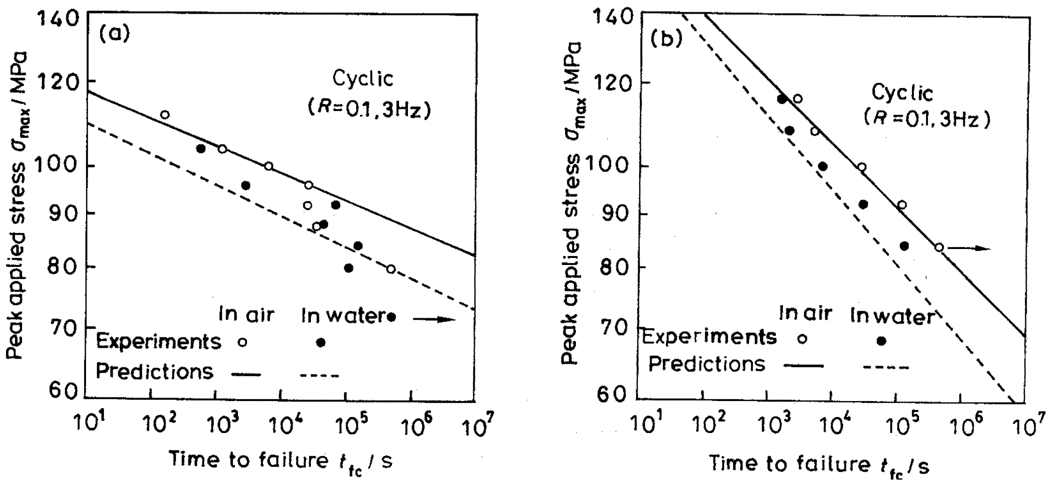

Fig.1 Cyclic fatigue experimental results and lifetime predictions (a) Alumina, (b) Zirconia

3 Fatigue lifetime predictions

3.1 Time–to–failure predictions

It is commonly found that the crack velocity V can be expressed as a power function of the applied stress intensity factor K_I [9]

$$V = \frac{da}{dt} = AK_I^n = V_c\left(\frac{K_C}{K_{IC}}\right)^n \tag{1}$$

where A and n are the crack propagation parameters, V_c is a crack velocity at the critical stress intensity factor K_{IC}.

Pre–cracks at the center of the specimens were produced with Vickers indentation when the fatigue tests were carried out. The residual stress was produced in the region of pre–cracks. So the stress intensity factor K_I includes two parts, one is the tensile stress intensity factor K_{ap}, and the other is the residual stress intensity factor K_{res}[10]

$$K_I = K_{app} + K_{res} = Y\sigma_a a^{1/2} + \chi P/a^{3/2} \tag{2}$$

where Y is the shape factor whose value is $2\sqrt{\pi}$, σ_a is the applied stress and χ is the material factor which is calculated as shown in the following equation[11]

$$\chi = \frac{27K_{IC}^4}{256PY^3\sigma_f^3} \tag{3}$$

where σ_f is the fracture stress.

The time–to–failure t_s for static fatigue is given by integrating Eq.(1) from an initial crack size a_i to a critical size a_c.

$$t_s = \frac{K_{IC}^n}{V_c} \int_{a_i}^{a_c} \frac{da}{K_I^n} \tag{4}$$

For cyclic fatigue that a sinusoidal stress $\sigma = \sigma_{max}\sin\omega t$ is applied, the time–to–failure t_c should be written as[12]

$$t_c = \frac{t_s}{g(n, R)} \tag{5}$$

where R is the stress ratio ($\sigma_{min}/\sigma_{max}$), $g(n, R)$ is the Evans's converting factor.

3.2 Comparison with experimental results

The crack propagation parameter n and the material factor χ are summarized in Table 4. Thus, using the crack propagation parameter n determined by the crack growth test[8], the material factor χ, the factor $g(n, R)$, and the time–to–failure under cyclic fatigue conditions can be predicted.

Table 4 Material parameters in alumina and zirconia

Material	Environment	Loading condition	n	χ
Alumina	air	static	51.5	0.0516
	air	cyclic	44.3	0.0516
	water	static	43.1	0.0440
	water	cyclic	34.2	0.0440
Zirconia	air	static	21.8	0.0203
	air	cyclic	17.6	0.0203
	water	static	21.5	0.0232
	water	cyclic	15.2	0.0232

Fig.1 shows the comparison between the predictions for the fatigue lifetime and the experimental results for cyclic fatigue of alumina and zirconia in air and water environments. The predictions agree qualitatively with the experimental results.

Fig.2 shows the femoral shaft replaced by artificial hip joint, which is added by the abductor force, femoral head force and ground–to–foot reaction. The bending moment applied to the femoral shaft is seen to be 0.8 $W(a+x)$. For the femoral shaft itself, assuming that the inner and outer diameter are 16 mm and 27 mm and the body weight is taken to be 700 N, the maximum stress due to bending is 41.3 MPa. For artificial hip joint, the introduction of a femoral stem will result in a sharing of the bending moment in the ratio of the bending stiffness. When the bone–cement–stem composite is subjected to bending in the frontal plane, the maximum tensile stress on the lateral sides of the femoral shaft can be expressed as follows

$$\sigma_{max} = \frac{ME_sI_s}{(E_sI_s + E_BI_B)} \cdot \frac{d}{2} \cdot \frac{1}{I_s} \tag{6}$$

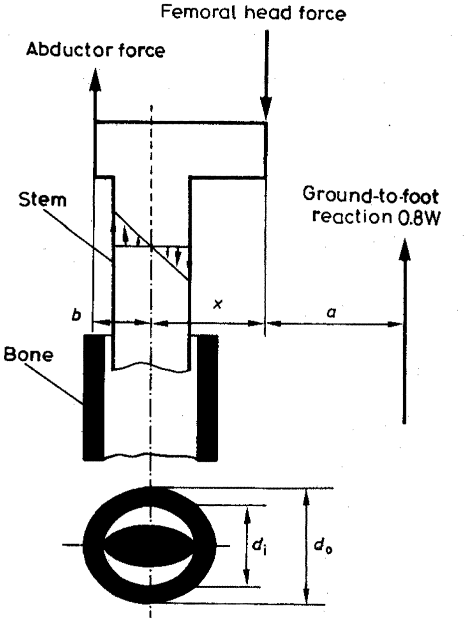

Fig.2 Femoral shaft replaced by artificial stem

where I_s and I_B are second moments of area of the section for stem and bone respectively, E_s and E_B are modulus of elasticity for stem and bone respectively, d is the diameter of stem. The maximum stress calculated for three kinds of stem materials of cobalt alloy ($E_s = 210$ GPa), alumina ($E_s = 364$ GPa) and zirconia ($E_s = 140\sim200$ GPa) are 221 MPa, 314 MPa and 157~207 MPa, respectively. It is found that zirconia is the best material among those materials from the standpoint of strength of materials. Furthermore, when femoral stem of zirconia that has a semicircular crack with initial crack size of 100 μm is subjected to static and cyclic loading of 700 N under water environment, the predicted lifetime is obtained (Table 5). It shows that lifetime abruptly decreases with increasing the applied stress and adding cyclic stress in zirconia.

Table 5 An example of lifetime predictions in artificial hip joint using zirconia as femoral stem

σ_a/MPa	Lifetime(static loading)/d	Lifetime(cyclic loading)/d
157	4377	13
207	12	5

4 Conclusions

1. In the case of the same stress applied, the time to fracture obtained from the cyclic fatigue tests in water decreases more than that in air for alumina and zirconia, and it is more remarkable for zirconia.

2. The fatigue lifetime predictions agree qualitatively with the experimental results for cyclic fatigue of alumina and zirconia in air and water environments, and the method of the fatigue lifetime prediction was applied to artificial hip joint.

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