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Dynamic Effect on Fatigue Strength of Brittle Materials

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Abstract

The bending fatigue of nuclear graphite and porcelain was investigated under static, dynamic and repeated impact load conditions to understand the effect of dynamic load on the fatigue degradation. It was found that a cyclic-dependent effect could be recognized for the fatigue behavior of porcelain as well as graphite, and the impact fatigue behavior was understandable as fatigue degradation under high frequency load. © 1997 Elsevier Science Limited.

1 Introduction

Ceramic materials have attractive properties, including corrosion resistance and high temperature strength, which may bring break-throughs in innovative energy technology. A thermochemical hydrogen production process, the Iodine-Sulfur (IS) process, has been studied at the Japan Atomic Research Institute (JAERI), which is expected to become a nuclear process heat utilization system to save energy in the future.[1] In the IS process, corrosion-resistant materials will be required as structural components under high temperature and thermally cycling conditions. Screening tests have suggested some candidate materials, such as ceramics against the sulfuric acid corrosion;[2] however, there are questions concerning the applicability of ceramic materials as structural components which must endure dynamic loads, including the impact loads occurring during an earthquake or induced mechanically in the system.

It has been proposed that the fatigue life of ceramic materials under cyclic and dynamic loading conditions can be evaluated by the static fatigue behavior associated with slow crack growth (SCG);[3] the rate of crack growth is known to depend on the corrosive environment.[4] Recently, however, the more profound comprehension of cyclic loading has been seen to require the characterization of the materials in terms of their cyclic-dependent and/or time-dependent behaviors.[5]

In this paper, the bending fatigue behavior of the brittle materials, nuclear-grade graphite and porcelain, under static, dynamic and cyclic loading conditions including impact is discussed to make clear the dynamic effect on the fatigue degradation. The fatigue tests covered a wide range of time to failure from 10^{-3} s to over 5×10^5 s and cycles to failure from a single impact to 2×10^5 cycles. Furthermore, the stress rate dependency of the fracture strength is discussed.

2 Experimental method

The impact fatigue and the impact strength tests were carried out at a room temperature by using a pendulum-type impact repeatedly bending machine.[6] The maximum impact velocity, energy and impact cycle frequency are $3\,\mathrm{m\,s^{-1}}$, 1 J and 0·5 Hz, respectively. The impact force acting on the specimen was measured from an instrumented strain gage at the contact surface; the radius of the contact surface is 5 mm. The specimen was supported simply at each end and subjected centrally to impact as shown in Fig. 1. The strain at the outer fiber of the specimen was measured by the

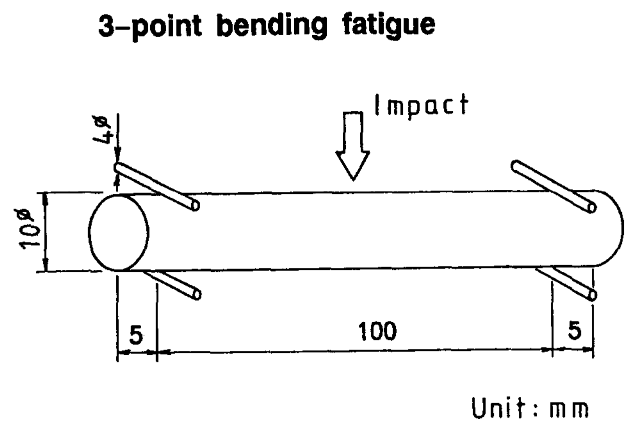

Fig. 1. Shape of specimen.

strain gage fixed on its center opposite the impact point. A conventional cyclic 3-point bending fatigue test was performed in the frequency range from 10^{-2} Hz to 50 Hz with sine wave form in unidirectional bending by using an electro-hydraulic testing machine. Figure 2 shows the examples of stress patterns in impact and conventional cyclic-fatigue.

A static fatigue test was performed to allow comparison with the cyclic tests of the fatigue behavior. Additionally, tests on the dynamic strength were carried out up to the range of stress rate greater than 10^6 MPa s^{-1}, by using the split-Hopkinson pressure-bar (SHPB) technique[7] and an electro-hydraulic testing machine. The porcelain includes a lot of glass components. As water is said to have a strong influence on the strength of glasses,[4] the dynamic fracture tests on the porcelain were performed using both dry and wet specimens

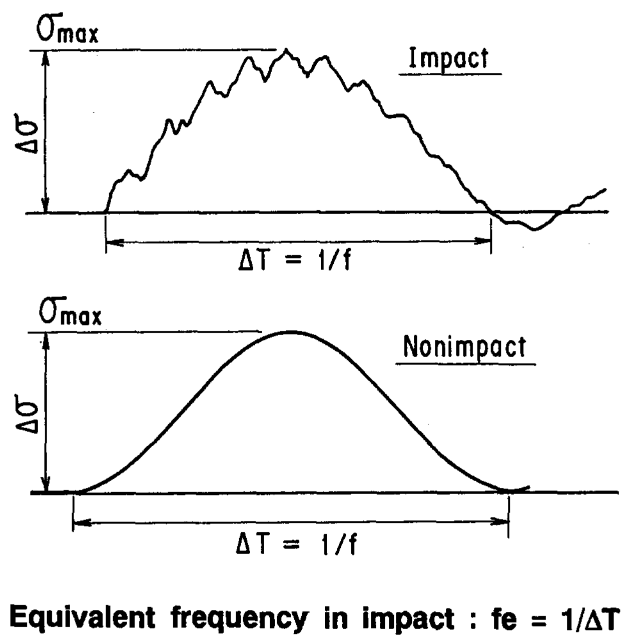

Fig. 2. Stress patterns in impact and non-impact cyclic fatigue.

Table 1. Main mechanical properties of porcelain and IG11 isotropic graphite

	Density ($kg\,m^{-3}$)	*Young's modulus (GPa)*	*Bending strength (MPa)*
Porcelain	$2{\cdot}4\times10^3$	65–80*	90–110*
IG11	$1{\cdot}8\times10^3$	10	43

*JIS C2141

to evaluate the effect on the dynamic strength. The dry specimen was stored in a desiccator for more than a week and the wet one was soaked in water for a day, just prior to performing the test. During the test on the wet specimens, water was supplied to the specimen using cotton cloth to maintain wet conditions on the surface. The main mechanical properties of the porcelain and the IG11 isotropic graphite are listed in Table 1.

3 Results and discussion

3.1 Dynamic and static fatigue behavior

Figure 3 shows for the porcelain material the relationship between the bending strength and the stress rate. Even in the absence of water, the fracture of the porcelain reveals clear rate- dependency at room temperature. In the case of the dry specimens, the bending strength increases with stress rate in the range from 0·5 MPa s^{-1} to 10^2 MPa s^{-1}, and then remains almost constant from 10^2 MPa s^{-1} to 10^5 MPa s^{-1}; over 10^5 MPa s^{-1}, the strength increases with the stress rate again. For the wet specimen, although a similar tendency was observed, the distinct influence of water on the strength was recognized in the range lower than 10^3 MPa s^{-1}; i.e. the strength of wet specimens is

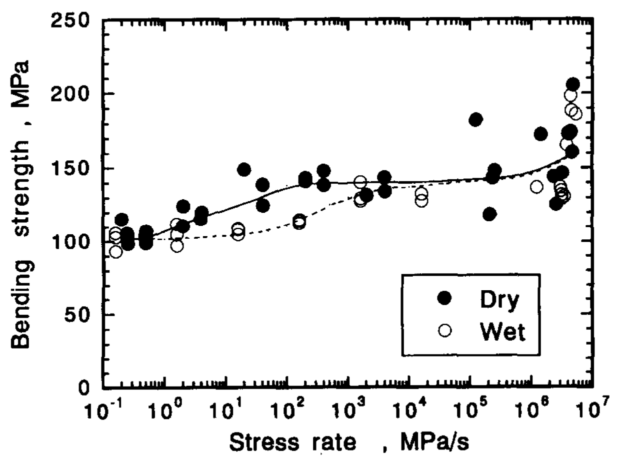

Fig. 3. Relationship between stress rate and bending strength in dry and wet conditions.

lower than that of dry ones and appears to be almost constant at about 100 MPa up to 10 MPa s^{-1}, independently of the stress rate. The influence of water can be sufficiently ignored over 10^3 MPa s^{-1}.

The rate-dependency of the strength might be considered to be caused by two effects; the chemical corrosion rate[4,8] and the deformation rate associated with any viscous behavior caused by the presence of the glass component, e.g. at even room temperature the visco-elasticity in alumina ceramics was observed.[9,10] That is, the SCG is prompted by a stress-enhanced chemical reaction, in particular to the glass component, between the water and the highly stressed area near the outer fiber of the specimen. On the other hand, the viscous behavior could be dominant in the rate-dependency if the increasing rate of the strength against the stress rate were lower in the wet condition than in the dry one. In this experiment, for the rate-dependency of bending strength in the porcelain in the range lower than 10^3 MPa s^{-1}, the stress-enhanced chemical reaction is considered to be more significant than the viscous deformation effect since the increasing rate of the strength is higher in the wet condition than in the dry one. On the contrary, in the case of IG11 which is devoid of a glass component, the rate-dependent fracture hardly appeared at room temperature in the range of the stress rate from 10^{-1} to 10^5 MPa s^{-1} as reported so far.[11] The fracture mechanism pertinent to the stress rate, in particular for the range higher than 10^5 MPa s^{-1}, will be discussed later from the viewpoint of fractographic features.

The fact that the porcelain strength up to 0·5 MPa s^{-1} in the dry and 10 MPa s^{-1} in the wet hardly depends on the stress rate might mean an approach to the static fatigue limitation.[8,12] Assuming that the fatigue mechanism is dominated by a time-fatigue crack growth rate, the static fatigue life t_{fs} is given by:

$$t_{fs} = C_1 \sigma_f^{-n}, \qquad (1)$$

besides, using $\sigma(t) = \sigma t$ the dynamic fatigue life t_{fd} is given by

$$t_{fd} = C_2 \sigma_f^{-n}, \qquad (2)$$

where, C_1, C_2 are material constants, σ stress, σ_f strength, n fatigue parameter.[3] The dynamic and static fatigue, therefore, are proportional to the n-th power of σ_f.

Figure 4 shows the results for the dry specimens under 10^2 MPa s^{-1} in Fig. 3 after replotting them

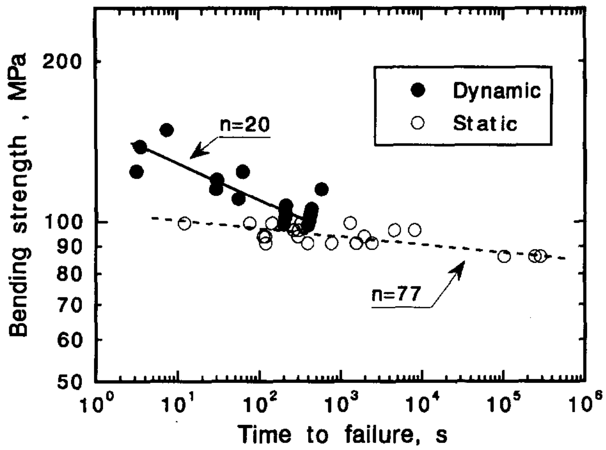

Fig. 4. Static and dynamic fatigue lives of porcelain.

to compare with the static fatigue data. There are distinct differences between the dynamic and static fatigue behaviors; i.e. the fatigue parameter n is 77 for static fatigue, but 20 for dynamic fatigue in the range of time lower than 200 s. The parameters were obtained by least squares fit to the experimental results. It is suggested from the results that the dynamic effect on the degradation of the fatigue strength cannot be ignored in particular for short period failure.

3.2 Cyclic fatigue behavior

Figure 5 shows the cyclic fatigue behavior of the porcelain under impact load and conventionally applied non-impact load at the frequency of 1 and 10 Hz. The cyclic fatigue strength is dependent on the cyclic frequency; i.e. the higher the frequency, the higher the strength. This is because the strength of the porcelain increases with the increase of the stress rate in the range up to 10^2 MPa s^{-1}, as shown in Fig. 3, i.e. in the range where the cyclic fatigue

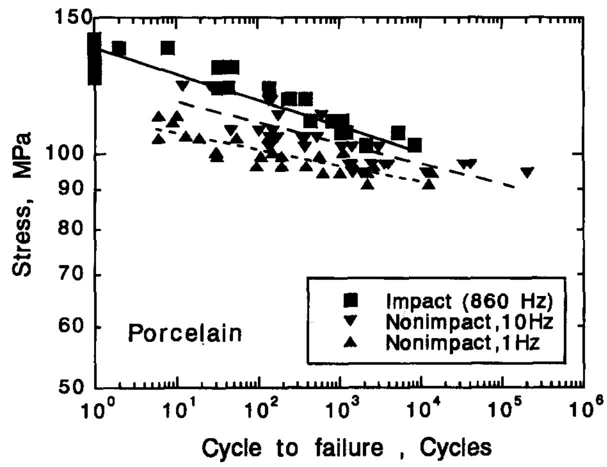

Fig. 5. Cyclic fatigue behavior of porcelain under impact load and under conventionally applied non-impact load.

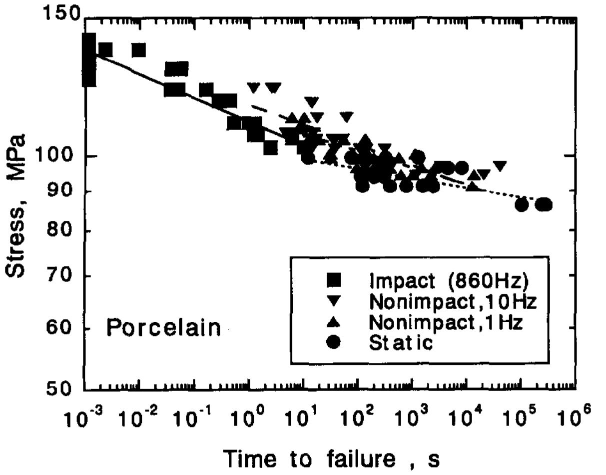

Fig. 6. Cyclic and static fatigue lives of porcelain.

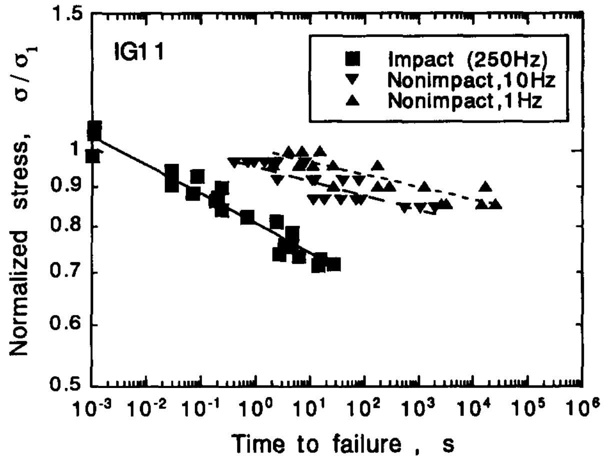

Fig. 8. Cyclic fatigue life of IG11 using normalized stress.

tests were carried out. The degradation of the fatigue strength with number of cycles is enhanced with an increase in the cyclic frequency.

The time to failure t_{fc}, defined by eqn 3, in cyclic and static fatigue is plotted in Fig. 6 to investigate the cyclic dependency of the fatigue,

$$t_{fc} = N_f f^{-1} \tag{3}$$

where N_f is the number of cycles to failure and f the cyclic frequency. In the case of the impact fatigue, the equivalent frequency, which is derived by assuming that the contacting time between contact surface and specimen measured from the impact wave profile, as illustrated in Fig. 2, is equal to a period of the frequency, is used to estimate the t_{fc} and becomes about 860 Hz. The fatigue degradation with time appears to be dependent on the cyclic frequency. Moreover, in order to make clear the frequency effect on the fatigue, the ordinate in Fig. 6 for the porcelain material can be replaced with the normalized stress, σ/σ_1, as shown in Fig. 7; i.e. the maximum imposed stress is divided by the failure stress at the first cycle, σ_1. Figure 8 shows the cyclic fatigue life for the graphite material IG11, which does not exhibit the rate-dependent fracture strength.[11] It is clearly noticed from Figs 7 and 8 that the cyclic fatigue degradation of the materials increases with the frequency; the cyclic-dependent effect should be taken into account for the fatigue behavior of both materials.

Figures 9 and 10 show the time-dependent and cyclic-dependent effects of both materials in terms of the frequency versus the inverse of time to failure. In the figures, the results should fall on a line with an angle of 45° if the cyclic-dependent effect is dominant on the fatigue behavior, and parallel to the X-axis if the time-dependent effect is dominant.[5] Although the fatigue behavior of the IG11

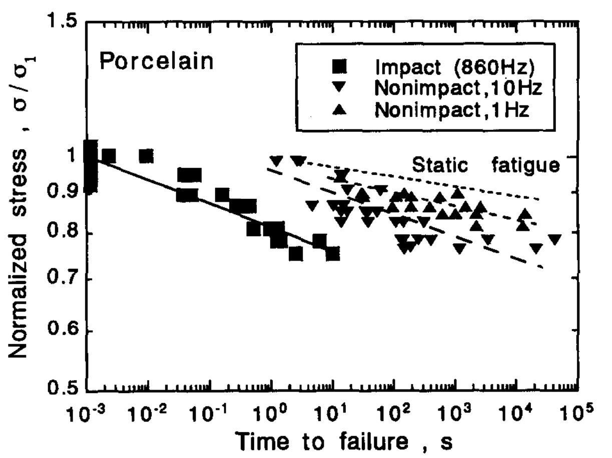

Fig. 7. Cyclic fatigue life of porcelain using normalized stress.

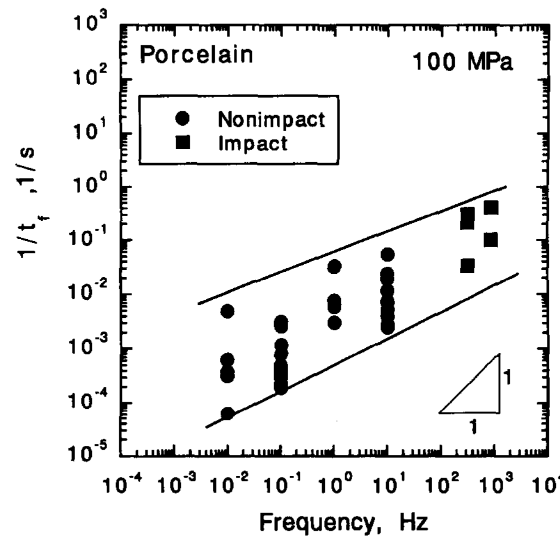

Fig. 9. Cyclic frequency effect on fatigue life of porcelain.

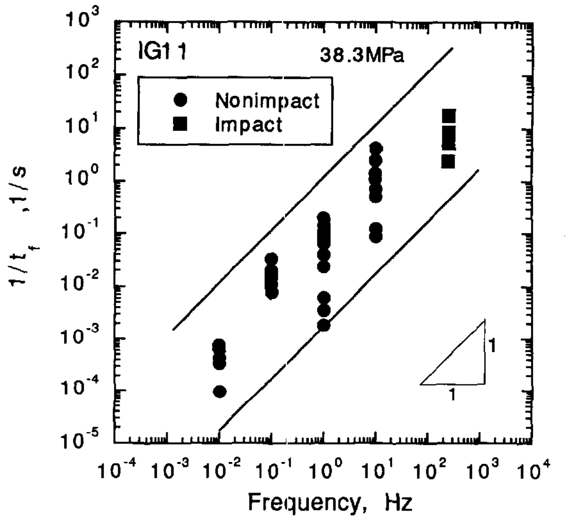

Fig. 10. Cyclic frequency effect on fatigue life of IG11.

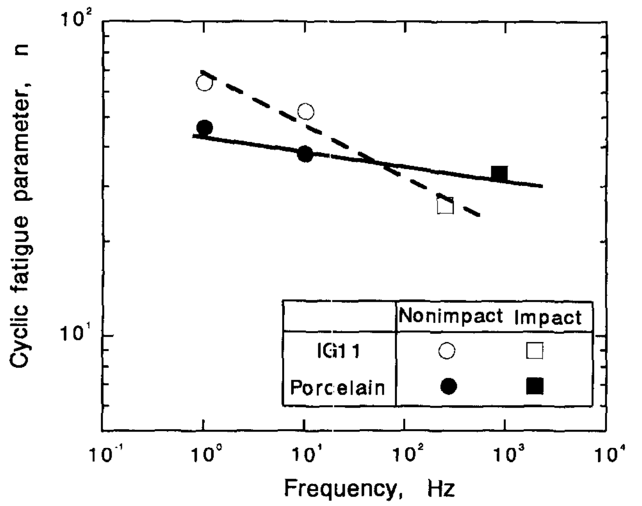

Fig. 11. Dependency of cyclic-fatigue parameter.

appears to be almost controlled by the cyclic-dependent effect, the porcelain material indicates the combined effect of time dependency and cycle dependency as shown in Fig. 9. Additionally, Figs 9 and 10 emphasize that the impact fatigue behavior can be understood as fatigue degradation under high frequency load.

Now we can postulate the relationship between applied stress σ_a and time to failure t_f for cyclic fatigue similar to eqn 1 but with the different exponent n_c as follows:

$$t_f = C_c \sigma_a^{-n_c} \tag{4}$$

where C_c is a material constant. The cyclic-fatigue parameters n_c for each frequency in Figs 7 and 8 are shown in Fig. 11. The frequency dependency of the cyclic-fatigue parameter n_c decreases with increase of the cyclic frequency irrespective of material. The decreasing rate of the IG11 is larger than that of the porcelain, indicating the remarkable effect of the cyclic dependency on the IG11. It is confirmed from Fig. 11 that the cyclic-dependent effect exists in the fatigue behavior of porcelain and graphite, and that the magnitude of the degradation due to cyclic frequency depends on the type of material.

3.3 Fractographic features

Figure 12 shows the fracture surfaces of the porcelain photographed by an SEM. The intergranular fracture with relatively rough surfaces is more predominantly observed in the static fatigue than in

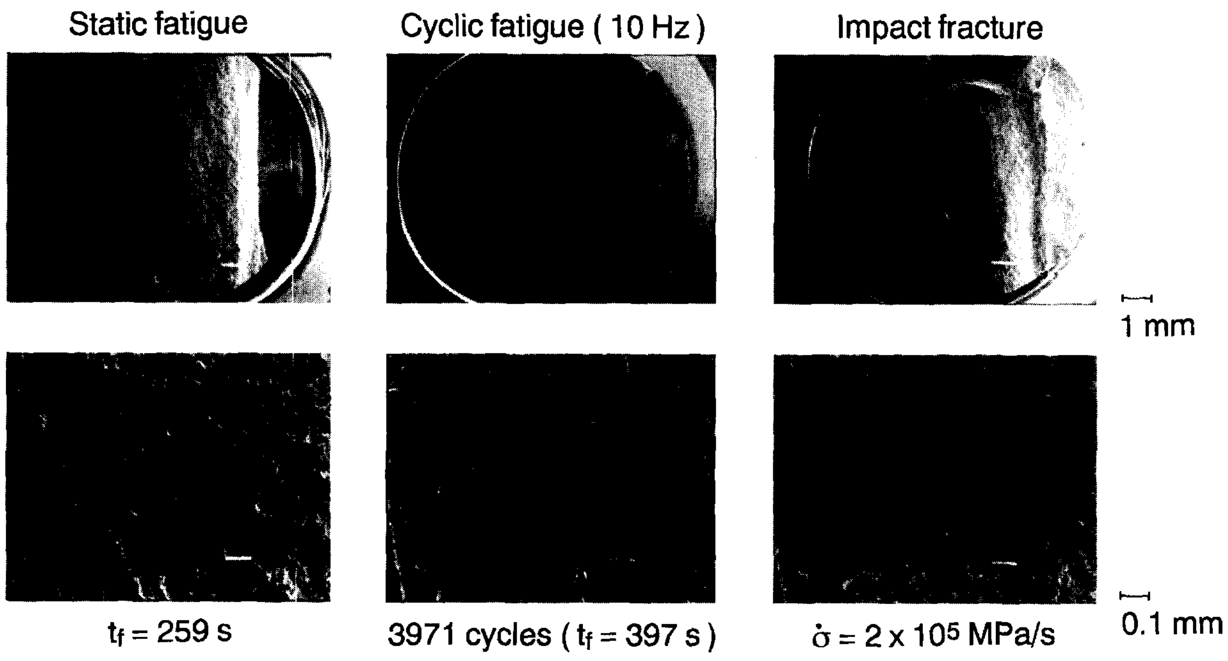

Fig. 12. SEM photographs of fracture surface in porcelain.

cyclic fatigue and impact fracture. In particular, in the impact fracture, although an undulating surface including a considerable number of ridges appears on the fracture surface of low magnification photographs, a flat surface owing to transgranular fracture is clearly observed around the area of fracture onset. The transition from intergranular slow crack growth to transgranular rapid crack growth[13] is indicated in the porcelain, which might be associated with the increase of the strength with loading rate.

The kinetic energy due to impact loading, the part of which will be transformed into the fracture energy, is radiated more broadly into the specimen by both the inertia effect and the complicated stress-wave propagation path, i.e. dynamic effect, than occurs under quasi-static loading. In static fatigue, a preferential fracture crack is likely to propagate steadily from a limited origin along the fracture surface. In impact fracture, plural cracks are initiated as simultaneous events from certain positions, such as pores, impurities or second phases, because of perturbations due to the dynamic effect; the instantaneous crack fronts then develop in various directions. As a result, the undulating fracture surface with ridges appears more readily under a high loading rate or impact than under a low loading rate or static loading.

It is difficult to distinguish features owing to the cyclic frequency. It seems, however, that the fracture surface under static fatigue is rough compared with that of cyclic fatigue at 10 Hz. It may imply that a transgranular failure region broadens at increasing cyclic frequency.

4 Conclusions

The bending fatigue of porcelain and nuclear grade graphite IG11 was investigated under static, dynamic and cyclic loading condition including impact to understand the effect of dynamic load on the fatigue degradation. The following conclusions can be drawn:

(1) A stress rate dependency of bending strength of the porcelain appears in the range from $1\,\mathrm{MPa\,s^{-1}}$ to $10^3\,\mathrm{MPa\,s^{-1}}$ and is influenced by the presence of water in the environment.
(2) The porcelain material shows the combined effects of time-dependency and cycle dependency, while the fatigue behavior of the IG11 is almost fully dominated by the cyclic-dependent effect.
(3) The impact fatigue behavior can be understood as fatigue degradation under high frequency loading.
(4) A transgranular failure region is developed with increasing loading rate.

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