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Temperature dependence of the fatigue and mechanical properties of lead zirconate titanate piezoelectric ceramics

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ABSTRACT

This paper presents research results on the temperature dependence of the fatigue and mechanical properties of piezoelectric ceramics. The material being examined is a lead zirconate titanate piezoelectric ceramic, PZT. The fatigue strength apparently increases with increasing sample temperature. The mean endurance limit at 10^5 cycles for the sample tested at 573 K is twice as high as that at 293 K. Similarly, the bending strength of the PZT increases with increasing sample temperature. A maximum bending strength is obtained at a sample temperature between 573 K and 773 K. The increment in the bending strength is attributed to the distorted lattice structure, in which a tetragonal lattice system is being changed to a cubic structure at 573 K, the Curie temperature. On the other hand, the reduction in the bending strength at temperatures greater than 773 K is caused by a reduction in the concentration of oxygen defects and high thermal energy, leading to dislocation movement. A wavy fracture surface with a mixture of transgranular and intergranular fractures is obtained in the samples fractured at temperatures between 573 K and 773 K due to the distorted lattice structure. In contrast, a flat face with transgranular fracture appears in tests at the room temperature and the high temperature (over 773 K). Details of the fracture mechanism are further discussed.

1. Introduction

In recent years, lead zirconate titanate ceramics (PZT) have been widely employed in a number of actuator applications, including precision positioning, vibration suppression equipment, power transducers and vibration sensors. This is because of the unique material characteristics of PZT ceramics [1]. A voltage difference is induced across two of the surfaces of the PZT ceramic as the shape of the ceramic is subjected to high alternating stresses. To use PZT ceramics in engineering applications over a long period of time, it is necessary to understand the material response to the electric field and the applied mechanical loading. Certain experimental results by other researchers provide an important background in this regard. In the study by Liu et al., the fracture behavior of a PZN-4.5%PT ceramic is examined, and it is found that the fatigue crack initiates in the ceramic substrate adjacent to the electrode coated on to the ceramic surface [2]. A fatigue crack is also generated from the electroplated surface of the PZT due to its rough surface [3]. Rattanachan et al. have reported that domain switching plays an important role on the toughness and fatigue properties of piezoelectric ceramics [4], and that poled PZT ceramics have a high fatigue strength compared with unpoled samples [5]. From their work, it is considered that the fatigue properties of PZT ceramics may be attributed to the material and piezoelectric properties.

Because of the good crystallinity of the perovskite structure, PZT ceramics such as ferroelectric lead–titanate films have recently been utilized in high temperature conditions, above 873 K [6]. Some papers have provided details on how to include the temperature-dependent behavior of the piezoelectric in constitutive relations using a thermodynamic approach since the electrostructive coefficients are independent of both composition and temperature [7,8]. Differences in the material strength at high temperature have also been reported. In the study by White et al., the fatigue behavior has been examined at various temperatures. In cases where the fatigue crack extension occurs in specimens at 473 K, the crack extension is minimal at 359 K [9]. Even though the temperature dependence of the material properties of PZT ceramics plays a significant role in the design of PZT ceramics for engineering applications [6,10–12], there appears to be little information available. In addition, the variation of the material strength as a function of sample temperature has not been systematically investigated. The main aim of the present paper is, therefore, to examine the influence of sample temperature on the fatigue and mechanical properties of PZT ceramics. In addition, an attempt is made to clarify the material characteristics at high temperatures to explain the variation of the material strength.

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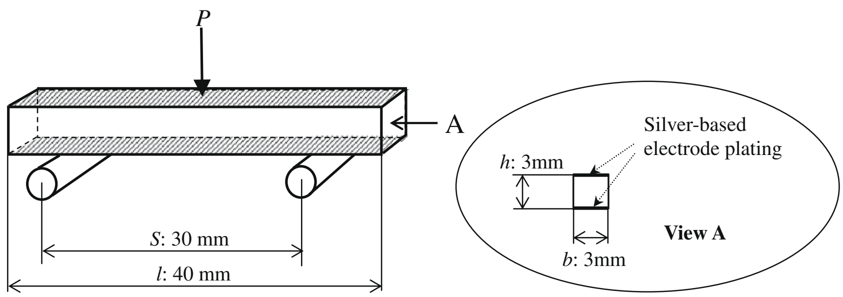

Fig. 1. Dimensions of three point bending specimen for the fatigue test.

2. Material and experimental procedures

The material selected in the present work was a commercial bulk lead zirconium titanium oxide (PZT) ceramic, Pb(Zr, Ti)O_3. The nominal grain size of this ceramic was about 5 μm in diameter. Silver-based 10 μm thick electrodes were plated on to the specimen surfaces. After the electrode attachment, the sample was polarized between the two electroplates. Fig. 1 shows a schematic illustration of the specimen material, a rectangular rod with dimensions 3 mm × 3 mm × 40 mm. The fatigue and static bending tests were conducted using a screw driven universal testing machine with 10 kN capacity. A muffle furnace with an accuracy of better than 0.1 K was used for the high temperature fatigue and bending tests. The furnace was designed originally to be fitted into the testing machine. At any time during the test, the actual temperature in the specimens was controlled. A R ratio of 0.05 with a frequency of 0.05 Hz was set for this fatigue test [3], and the maximum cyclic load, P_{max}, was determined on the basis of the bending strength (P_B) of this PZT ceramic, e.g., P_{max} is to be less than 90% of P_B [13,14]. The bending tests at room and elevated temperatures were carried out in accordance with the Japanese Industrial Standard (JIS). In this study, the electrical properties of this ceramic, for example the electromechanical coupling factor, were also examined using an impedance analyzer as a function of the sample temperature. The change of the lattice structure in the ceramics was investigated by in situ high temperature X-ray diffractometry using Cu $K\alpha$ incident radiation.

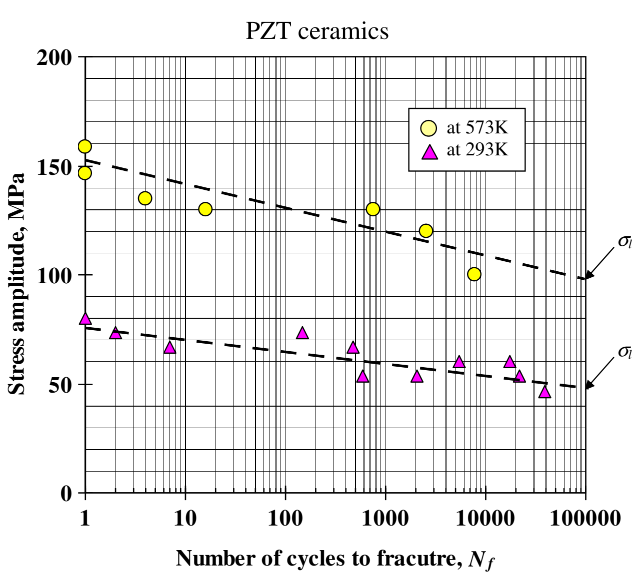

Fig. 2. Stress amplitude vs. cycles to failure in the PZT ceramics tested at 293 K and 573 K.

3. Results and discussion

3.1. Fatigue and mechanical properties

Fig. 2 shows the relationship between the stress amplitude and number of cycles to fracture (S–N relations) for the PZT ceramics

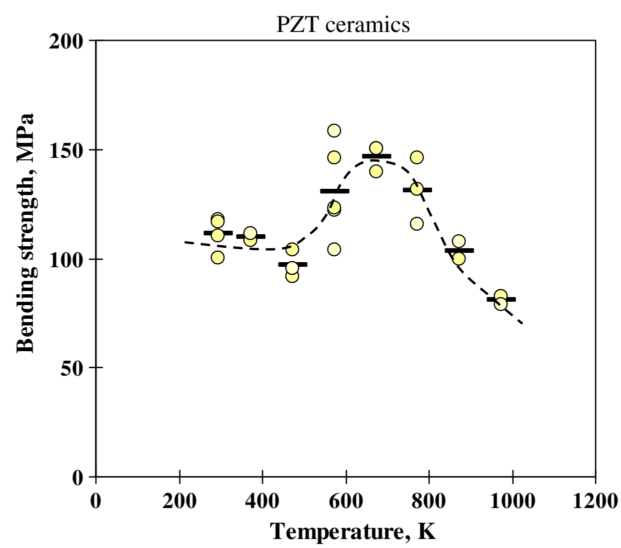

Fig. 3. Variation of bending strength as a function of the sample temperature in the PZT ceramics.

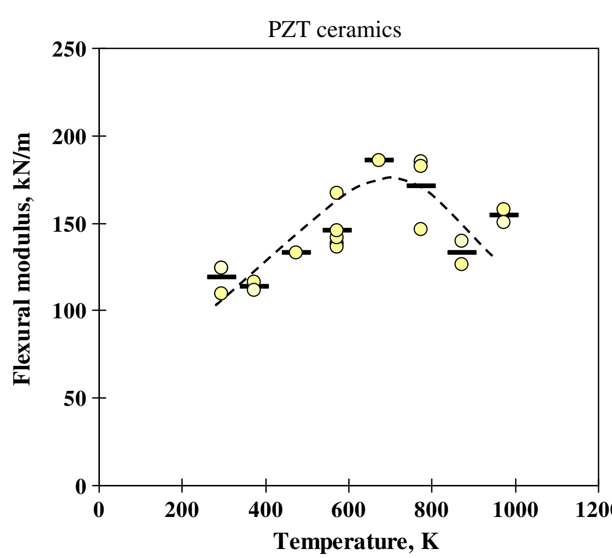

Fig. 4. Variation of flexural modulus as a function of the sample temperature in the PZT ceramics.