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Thermo-mechanical coupled in situ fatigue device driven by piezoelectric actuator

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ABSTRACT

This paper focuses on the design of a thermo-mechanical coupled in situ fatigue device driven by piezoelectric actuator. The structural resonances, transient response, grip design and thermal insulation performance of the device are discussed in detail. Micro-indentations are prepared on the specimen's surface as embedded defects, and the deformation behaviors of the indentation subjected to cyclic strain under temperature of 530 °C are investigated. Quantitative effects of the cross-sectional area of indentation, alternating displacement amplitude and temperature on the fatigue life of copper/aluminum composite specimens are obtained, respectively. The experimental results could serve as proofs to verify the feasibility of the proposed device. This paper shows a modular example that combines piezoelectric actuator and ceramic heating components to realize thermo-mechanical coupled in situ fatigue testing.

1. Introduction

In many industrial fields, structural failures are attributed to thermal fatigue failures frequently [1–3]. For instance, aviation engine blades occasionally fracture under the actions of high temperature and centrifugal force, and MEMS (Micro-electromechanical system) components malfunction when subjected to thermal cycling conditions. Studies of thermo-mechanical coupled behaviors of microstructures subjected to alternating stress could contribute to understand the mechanism of thermal fatigue failure [4]. Regarding polycrystalline metal materials, on one hand, high temperature helps the grain boundaries slip and affects the fatigue life [5], on the other hand, the initial defects of structure, such as micro void and crack, would significantly weaken the fatigue life of structures [6]. Furthermore, in situ fatigue testing under scanning electron microscope (SEM) or metallographic microscope is an effective tool to investigate the deformation behaviors of fatigue crack. Therefore, under high temperature conditions, the in situ fatigue testing is beneficial to understand the fatigue failure mechanism [7–10].

The design of fatigue devices integrating with heating function inside scanning electron microscopes or under optical microscopes faces a lot of challenges, such as the heating method, thermal insulation method, miniature size and high loading frequency. Regarding the commercial fatigue testing machines, due to the large sizes, they are difficult to be integrated with imaging instruments [8]. Also, limited by the rotation inertia of the transmission systems, such as motors and reducing mechanisms, existing miniature in situ tensile devices cannot realize high cycle fatigue testing [9,11,12]. In addition, to capture images of microstructures with high resolution, the image acquisition time of the imaging devices is relatively longer, it is difficult to realize the real-time observation of specimen subjected to cyclic stress with high frequency. Therefore, intermittent imaging method on basis of constant number of cycles is adopted to observe the deformation behavior of fatigue cracks [10,11]. Regarding the development of miniature in situ fatigue testing devices, [13,14], Park et al. [15] adopted voice coil motor as driven unit to carry out the high frequency fatigue testing of copper thin film. Shimadzu Co., Ltd. developed a hydraulic driven fatigue instrument compatible with SEM, the instrument could realize an effective amplitude of 10 mm and a maximum frequency of 10 Hz, the hydraulic unit and specimen clamping unit are mounted on the sealed door of SEM. Furthermore, piezoelectric components are also frequently used for the fatigue testing due to the properties of rapid response, high control precision and high reliability [16–23]. For instance, Tsuchiya et al. [22] adopted a commercial piezoelectric actuator (Physik Instrumente Co., Ltd.) to study the fatigue failure behavior of a monocrystalline silicon piece. However, the above researches seldom mentioned the design of miniature

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Table 1
Main functions of the device.

Specific dimensions/mm	Maximum load/N	Maximum displacement/μm
≤130 × 130 × 30	≥60	≥40
Maximum temperature of specimen/°C	Load resolution/N	Displacement resolution/μm
≥500	≤0.10	≤0.50
1st-order natural frequency/Hz	Maximum frequency/Hz	Fatigue life of hinge
≥500	≥100	≥10^7

in situ fatigue devices integrating with heating function. The effects of grip desgin, loading frequency and thermal insulation method on the testing accuracies of specimen's alternating stress and strain also need to be taken into account. Therefore, miniature fatigue devices that could be compatible with various imaging equipment integrating with heating function receive a lot of attentions.

This paper proposes an in situ fatigue device driven by piezoelectric actuator. Considering that the compatibility with optical microscopes or SEM, especially for optical microscopes or SEM with small stage or vacuum chamber, miniaturization is the main feature in designing the device, the specific dimensions of the device should be less than 130 × 130 × 30 mm. Also, in order to obtain relatively larger stress amplitude and strain amplitude of specimens during fatigue testing, the maximum load and displacement that the device could provide should be not less than 60 N and 40 μm, respectively. In addition, the maximum temperature, working frequency, first order natural frequency and fatigue life of the device should be not less than 500 °C, 100 Hz, 500 Hz and 10^7 cycles, respectively. Moreover, closed loop control mode and at least constant strain amplitude control mode should be provided. On basis of above requirements, main functions of the device are motivated as shown in Table 1.

2. In situ fatigue device and testing system

2.1. Functional design

Considering that the piezoelectric stack could provide a smooth motion and a very fast response, a horizontal piezoelectric actuator is designed as the driven unit of the fatigue device. Fig. 1 shows the mechanical structure to explain the topology of the proposed device. Four piezoelectric stacks (10 × 10 × 40 mm, Suzhou Pant Piezoelectric Tech Co., Ltd.) are symmetrically surrounded by an annular closed flexure hinge [24]. On one hand, the tandem distribution of piezoelectric stacks is adopted to improve the strain and stress amplitudes of the specimen, on the other hand, the annular closed design would contribute to improve the dynamic stiffness of the flexure hinge. In addition, 1065 manganese steel (according to the international standard of ASTM A 29/A 29M-04 [25]) with allowable tensile strength of 432 MPa and fatigue limit σ_{-1} of 430 MPa is adopted to machine the hinge, and circular arc transitional type is adopted to weaken the influences of stress concentration. As shown in Fig. 1, the rigid part of the flexure hinge and fixed wedge block are assembled on the base of the device, which is rigidly fixed on the stage of microscope. The fixed wedge block maintains line contact rather than surface contact with the mobile wedge block all the time, the contact mode would weaken the influences of surface roughness of wedge blocks on the positioning accuracy of piezoelectric stacks. Furthermore, a long hole and a pair of grooves are machined on the fixed wedge block. Grooves are designed to put the position of a pair of SiN ceramic heating

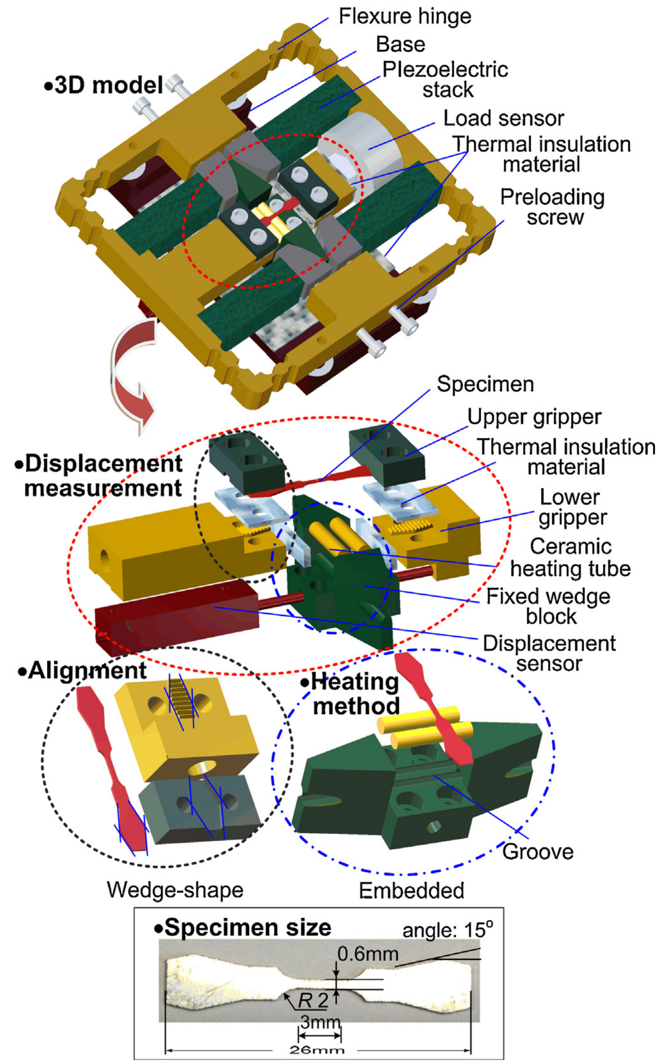

Fig. 1. Schematic describing the mechanical structure to explain the topology of the proposed device, including the displacement measurement method, the distribution of thermal insulation materials, the grip design to achieve the alignment, the heating method realized by a couple of ceramic heating tubes and the specific size of specimen.

tubes, which are symmetrically distributed under the specimen's gage part, and the heating method is thermal radiation, the distance between the upper edge of the heating tubes and the lower surface of specimen is 0.20 mm. The displacement sensor (Sakae Co., Ltd.), which is distributed under the specimen, directly measures the relative linear displacement between the two lower grippers. The probe of the displacement sensor maintains elastic contact with a lower gripper through the long hole of the fixed wedge block, the fixed part of the displacement sensor is rigidly assembled on the other lower gripper. Four pieces of TDD vacuum multi-layer insulation materials with thickness of 2 mm and thermal conductivity of 0.28×10^{-2} W/(m K) are respectively glued between the upper gripper, lower grippers and the heating tubes. The connection part between the load sensor (SM609A, Sewhacnm Co., Ltd.) and the lower gripper is filled with TDD insulation material, the upper surface of the device's base is also glued on TDD material to weaken the thermal deformation of the base. Schematic of the grip design is also shown in Fig. 1, sawtooth structures are machined on the upper and lower grippers to enhance the stability of clamping. Regarding the alignment issue, the location relation between the upper and lower grippers is realized by a pair of boss and groove [10]. The gripping part of the specimen, the groove and boss present uniform wedged