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Fatigue of micromachined stainless steel structural materials for vibrational energy harvesting

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Fatigue of micromachined stainless steel structural materials for vibrational energy harvesting

Y Shimizu, L Van Minh, H Kitayoshi and H Kuwano

Graduate School of Engineering, Tohoku University, Sendai, Japan

y.shimizu@nanosys.mech.tohoku.ac.jp

Abstract. This work presents fatigue measurement for micromachined stainless steel (SUS304) structural substrate using resonant bending mode. Micromachined specimens for fatigue test had a cantilever structure with a proof mass. They were fabricated by $FeCl_3$ wet etching and wire-discharged cutting. The SUS specimens had Young's modulus of 198 GPa on average. The endurance limit of micromachined specimens was 213 MPa on average after 10^8 cycles under our fracture definition. The large SUS specimens had the endurance limit of 229 MPa after 10^7 cycles.

1. Introduction

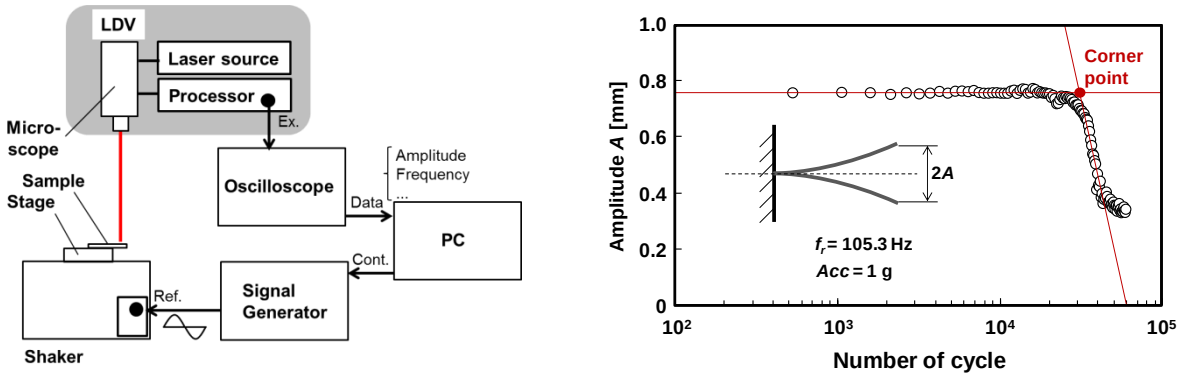
Development of wireless sensor nodes for internet of things (IoTs) has needed miniaturize power source that is capable of converting on-site ambient energy resources into electricity. From a point of view of energy capacity and microfabrication compatibility, piezoelectric vibrational energy harvesters are promising for practical applications. To improve the further performance, previous researchers focused on developing piezoelectric materials for energy harvesting [1-4]. Minh *et al.* developed lead-free piezoelectric energy harvesters in which piezoelectric thin films were grown on silicon wafers [1,2]. The KNN-based harvester was able to provide the normalized power density of 1.98 $mW.g^{-2}.cm^{-3}$ [1]. Recently, Minh *et al.* provided the (Mg,Zr)-doped AlN based micro-energy harvesters at level of 4 $mW.g^{-2}.cm^{-3}$[2]. Although they provided high power density, those energy harvesters fabricated from Si structural materials are likely to be suitable for ambient vibrations with frequency above 200 Hz. Low fracture toughness and low elastic strain limit prevent silicon to be applied in the case of heavy weight and low frequency resonance. Therefore, there is a desire of seeking a new structural material for substituting silicon in those low frequency applications. Cao *et al.* had used the stainless steel substrate for fabricating piezoelectric macro-energy harvesters [3,4]. However, there is likely to have no research to consider the mechanical and fatigue properties of stainless steel substrate at micro scale. In this work, we aim at studying the mechanical and fatigue properties of micromachined stainless steel that might provide the important data for guiding a design of energy harvesters.

2. Experimental procedure

2.1. Resonant-vibration fatigue measurement

Fatigue test technique of micro-scale structural substrates for micro-energy harvesters is not matured, although it is a prerequisite for devices' design [5-7]. Most fatigue tests have been performed under

tension-tension loading by using low frequency (tens of Hz) cyclic fatigue system [5]. For reducing time consumption of fatigue test and being compatible with both macro- and micro-scale fatigue specimens, resonant bending mode is preferable [6]. Therefore, in this work, we applied resonant bending mode to measure endurance limit of micromachined SUS304 specimens. We prepared both of large and microscale cantilever-like fatigue specimens. In our fatigue measurement, fatigue specimens were vibrated at their resonant frequencies. Displacement amplitudes were measured by a laser vibrometer (Onosokki LV-1710) and controlled by a shaker controller (Asahi Seisakusho G-Master 05) (Figure 1(a)). The endurance limit was determined by the corner point at which the displacement amplitude decreased 20% because of initial occurrence of the micro-fracture as shown in Figure 1(b). Applied stress values were deduced from the experimental displacement amplitudes by using FEM simulation (ANSYS 16) with SOLID186 element.



(a) (b)

Figure 1. The fatigue measurement set-up (a) and illustration of defined endurance limit (b) for both of large and micro SUS304 cantilevers.

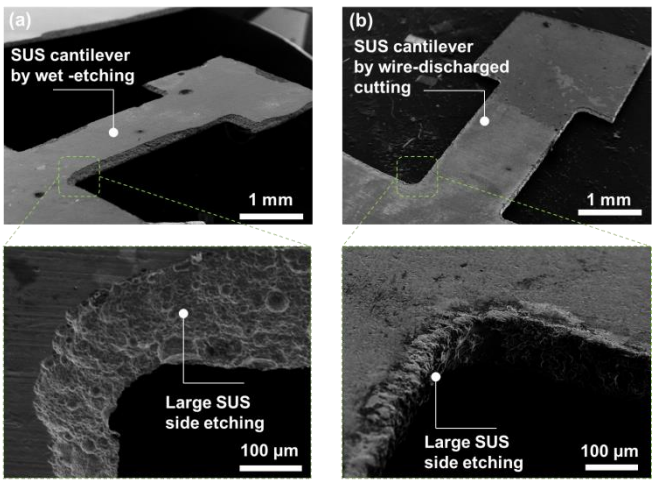


Figure 2. Scanning electron microscopic images (SEM) of micromachined SUS cantilevers: by $FeCl_3$ wet etching (a), by wire-discharged cutting (b).

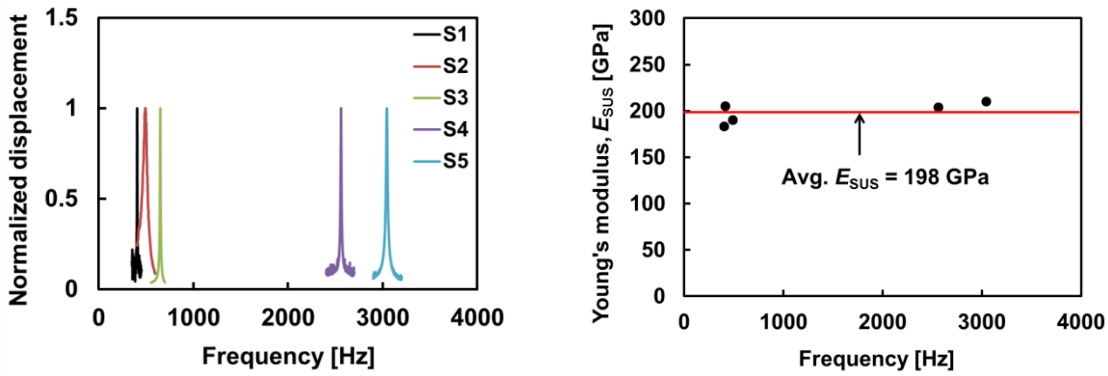
2.2. Fatigue specimens

We conducted fatigue test for three types of specimens including SUS304 large cantilevers and micro-cantilevers. The large specimens were fabricated by a dicer (DISCO DAD522). The micromachined specimens were fabricated by wet etching using $FeCl_3$ etchant at 40 ºC or by a wire discharge cutting (Sodick AQ360). Large cantilevers had beam geometric parameters including length of 1.9 mm, width of 9.4 mm, and thickness of 0.1 mm. The micromachined cantilevers had beam length of 3.0 mm, width of 1.6 mm, and thickness of 0.1 mm. A copper proof mass was attached at the tip of cantilever to turn the resonant frequency. Figure 2 show the scanning electron microscopic (SEM) images for both wet-etching and wire-discharge cutting SUS micro-cantilevers.

3. Results and Discussions

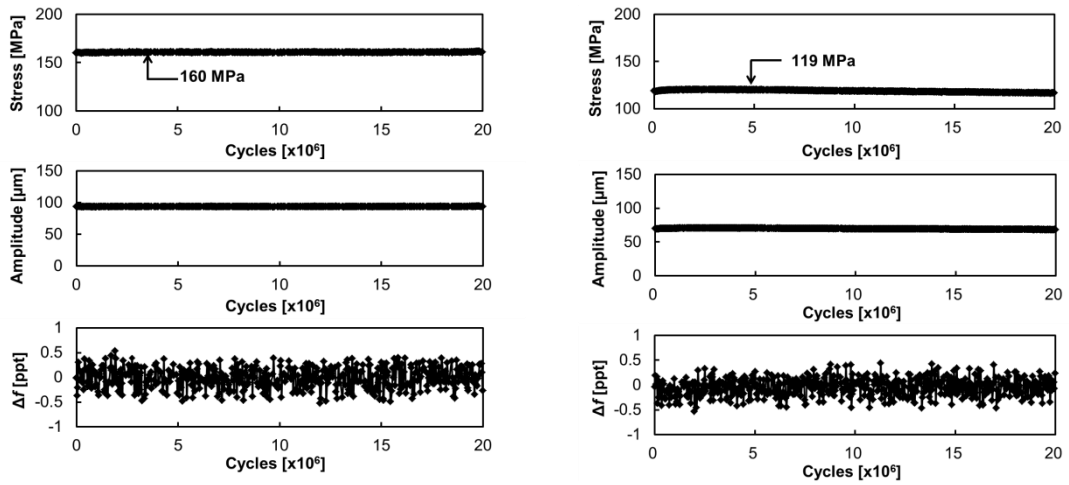
3.1. SUS304 Young's modulus

For determining the applied stress, at first, we determined the Young's modulus of the SUS304 materials. By using the micro-cantilevers, we measured the resonant spectra (Figure 3 (a)). The Young's modulus values were deduced from FEM simulation. The average Young's modulus of SUS304 was 198 GPa (Figure 3 (b)).



(a) (b)

Figure 3. The resonant spectra of SUS304 based cantilevers (a), SUS304 Young's modulus deduced from FEM model (b).



(a) (b)

Figure 4. Stress amplitude, tip deflection amplitude, and frequency shift, Δf (Δf *(ppt)* = $10^3\times(f-f_0)/f_0$) at applied acceleration of 24.5 m.s^{-2} over 20×10^6 cycles: wet-etching micro-cantilever (f_0 = 1140 Hz, Q-factor = 37) (a), wire-discharge cutting micro-cantilever (f_0 = 1160 Hz, Q-factor = 26) (b).

3.2. Fatigue measurement

Figure 4 (a) and (b) exhibit the data sets for the micromachined cantilevers by the wet etching and the wire-discharged cutting. The root-mean-square (rms) stress values were calculated from FEM and were 160 MPa and 119 MPa for the wet-etching and the wire-discharged cutting, respectively, at the acceleration of 24.5 m/s^2. The deviation of the stress values comes from the differences in the resonant frequency, f_0, and Q-factor. f_0 and Q were 1140 Hz and 37 for the wet-etching and 1160 Hz and 26 for

the wire-discharged cutting. The normalized frequency shift, Δf, defined as $ppt = 10^3 \times (f-f_0)/f_0$. Both of the micromachined cantilevers show small Δf of ±0.5 *ppt* over 20×10^6 cycles.

Figure 5 shows S-N diagram for the micromachined SUS and the large SUS cantilevers. By tuning the accelerations, various bending stress values were achieved for fatigue measurement. For the macro samples, at large stress levels, there was the instantaneous occurrence of fracture. The endurance limit approached 229 MPa after 10^7 cycles.

Further fatigue measurements were conducted on the micromachined SUS cantilevers. At the applied stress level of 311 MPa, the cantilever amplitude decreased after approximately 2×10^6 cycles The micromachined samples (enclosed by dot circle) had no fracture occurrence. Therefore, the endurance limit might be the average level of 213 MPa, being comparable with that of the large SUS specimen.

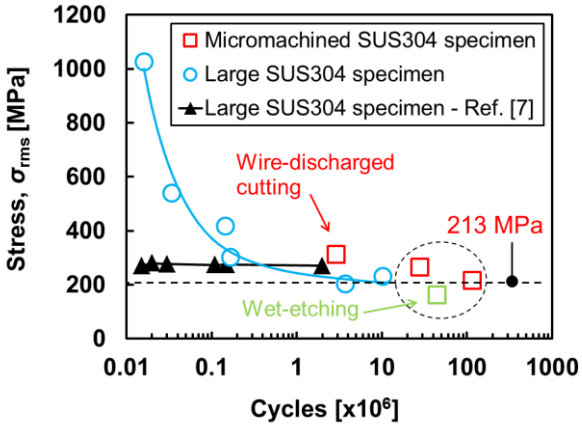


Figure 5. Stress-lifetime (S-N) for the SUS cantilevers including large cantilevers and micro-cantilevers fabricated by both wet-etching and wire-discharge cutting techniques.

4. Conclusions

Fatigue measurement for micro-machined stainless steel (SUS304) specimens was tested by using resonant bending mode. A cantilever structure with a proof mass was applied as fatigue specimen. They were micro-machined by $FeCl_3$ wet etching or wire-discharged cutting. SUS 304 had Young's modulus of 198 GPa. The endurance limit of micromachined samples was 213 MPa on average, being similar to those of the previous works on large SUS specimen.

References

[1] Van Minh L, Hara M, Horikiri F, Shibata K, Mishima T and Kuwano H 2013 *J. Micromech. Microeng.* **23** 035029
[2] Van Minh L, Hara M, Yokoyama T, Nishihara T, Ueda M and Kuwano H 2015 *IEEE Trans. Ultrason., Ferroelect., Freq. Control* **62** 11 2005-2008
[3] Cao Z, He J, Wang Q, Hara M, Oguchi H and Kuwano H 2013 *J. Phys.: Conf. Ser.* **476** 012034
[4] Cao Z, Zhang J and Kuwano H 2012 *Sensors and Actuators A* **179** 178-184
[5] Ando T, Shikida M and Kazuo S 2001 *Sens. Actuators A*, 93 1 70-75
[6] Kwak K, Otsu M and Takashima K 2010 *Sensors and Materials* **22** 1 51-59
[7] Hanby K R 1975 *Handbook on Materials for Superconducting Machinery* National Bureau of Standards p 579