Size Effect on Fatigue Strength of Metallic Micro-materials

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ABSTRACT

Fatigue test systems with electrolic-polishing apparatus were developed to study the size effect on the fatigue strength of the micro-materials. This system has an electro-dynamic actuator to load small amplitude cyclic force. Fatigue tests were conducted after manufacturing small cross-sectional specimens by the electrolic-polishing apparatus without removing specimens from the system. Commercially pure aluminum and iron wires of 1.0 mm diameter were employed for the fatigue tests. The minimum diameter of each specimen was from 0.20 to 0.60 mm. To remove the effect of stress gradient, cyclic axial force was applied. The frequency of the cyclic force was 50 Hz with the stress ratio of 0.1. In pure aluminum, the fatigue strength was almost independent of the specimen diameter, and the variations in the fatigue life from specimen to specimen at the same stress amplitude were large. In pure iron, the variations were also large, but the fatigue strength tended to be shorter for smaller specimen diameter. In aluminum, three types of fracture morphologies were observed, and two types of them were observed in iron. In both materials, there was weak correlation between fracture morphologies and fatigue life

1. INTRODUCTION

It is believed that the materialization of micro-machines will bring us revolutionary new ways of inspections of structures and machine components, launching of space satellites, and medical care. Then, the manufacturing of the micro-machines has lately attracted considerable attention. The next stage of the study on the micro-machines is to ensure the integrity of them. The evaluation of the strength, especially the fatigue strength, is particularly important(1)-(3). The evaluation is also important for reliability assurance of large-scale integrated circuits in electronic packages.

The size effect on the fatigue strength in the metallic materials has been known for conventional macroscopic specimens, and it has been believed that the fatigue strength of large specimens is lower than that for small specimens(4)(5). Since the size effect is observed for bending type loading fatigue tests, and it seldom observed for axial-force fatigue tests, the stress gradient was considered to be responsible for the size effect. In the present study, the size effect on fatigue strength of micro-materials under the axial-force is examined, and microscopic observations of fracture mechanisms were conducting by using the scanning electron microscopy.

Silicon is believed to be a promising material for micro-machines because the system developed for manufacturing electronic devices can be applied for the material. This system is appropriate for the mass production of the same kind of components, but not for small production of components. Then, metallic materials that can be mechanically machined are also considered to be candidates of micro-machine material. Therefore, commercially pure iron and aluminum are employed for the fatigue tests in the present study.

2. EXPERIMENTAL PROCEDURE

In the present study, fatigue test systems with electrolic-polishing apparatus were developed. Electro-dynamic actuators were employed for loading. Two types of test systems were constructed. First system was consisted of electro-dynamic actuator that was originally designed for vibrator (shaker), and this system was controlled by a personal computer. The maximum loading capacity of this actuator was 50 N. Another type of test system was employed an audio speaker as an actuator, which was controlled by analog electronic circuits with negative feedback loop. The maximum loading capacity of this system was 10 N. In these test system, load controlled fatigue tests were conducted. Fatigue tests were conducted after manufacturing small cross-sectional specimens by the electrolic-polishing apparatus that was shown in Fig. 1. The counter electrode had a hole with 5 mm in diameter. Working electrode (specimen) was passing thorough the hole. Since the corrosion chamber was made of thin rubber sheet, the fatigue test can be conducted without removing it.

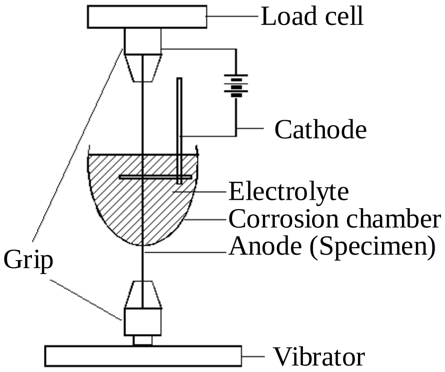


Fig. 1. Fatigue test system with electrolic polishing apparatus.

Commercially pure iron and aluminum wires of 1 mm diameter were employed for the fatigue tests. The grain size of iron was 35 μm, and it was 25 μm for aluminum. Dimensions and shape of the specimens are shown in Fig. 2. The minimum diameter, *d*, of each specimen was from 0.20 to 0.60 mm. To remove the effect of stress gradient on the fatigue strength, cyclic axial force was applied. The frequency of the cyclic force was 50 Hz with the stress ratio of 0.1.

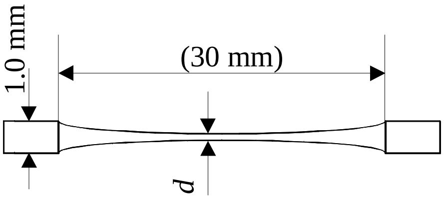


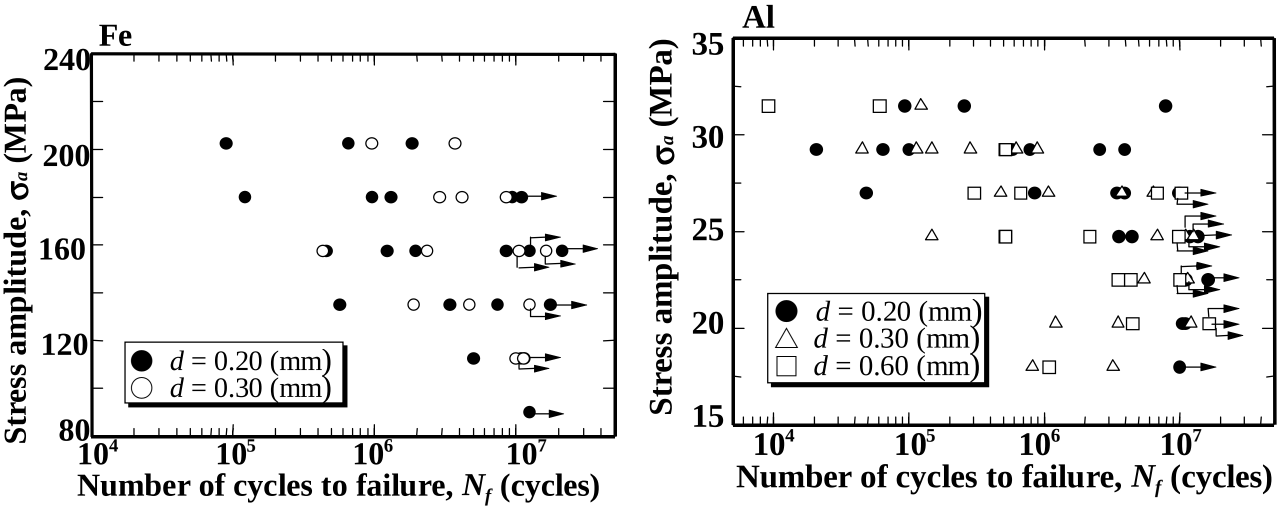
Fig. 2. Dimensions and shape of specimen.

3. EXPERIMENTAL RESULTS AND DIISCUSSION

3.1 Fatigue life

S-N curves obtained from the load controlled fatigue tests are shown in Fig. 3. Because of the loading capacity of the present system, the maximum diameter to be tested for iron was 0.30 mm.

As seen in the figures, scatters of fatigue life were very large compared with conventional size specimens. To examine the effect of specimen diameter on the fatigue strength, the fracture probability, *P* (%), for each stress amplitude versus number of cycles to failure, N_f, are shown in Fig. 4 for iron and in Fig. 5 for aluminum. For aluminum, the fatigue life was almost independent of specimen size. For iron, however, it was shorter for small cross-sectional specimens. This



(a) Iron (b) Aluminum

Fig. 3. Effect of specimen diameter on fatigue life.

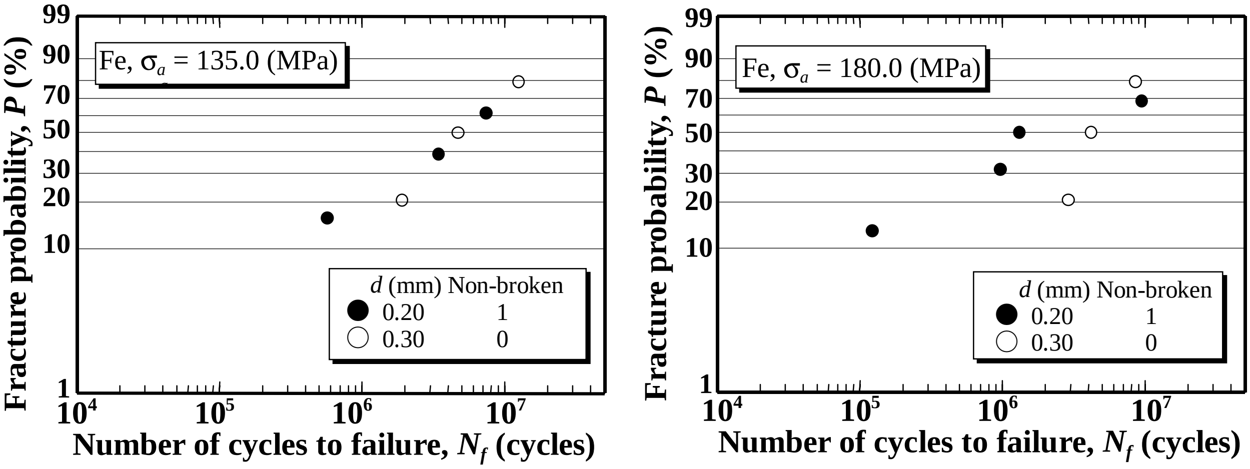
difference in size effect may come from the crack initiation mechanism. In steels, it is believed that the initiation size of the fatigue cracks is about grain size, while it is very small in aluminum(6).

The constraint for deformation from adjacent grains may one possible mechanism for the diminution of life with decreasing cross-sectional area. The slip motion is considered to be easier for small sized specimen where the constraint is small because of the number of adjacent grains are smaller for smaller specimens. Another possible mechanism for the size effect on the fatigue strength of the micro-materials is the crack propagation life. For macroscopic specimens, the fatigue crack propagation life, up to few mile meters in length, occupies the dominant fraction of the total fatigue life(7). For micro-materials, however, the crack propagation life depends on the cross-sectional area because the diameter of specimen is much less than 1 mm.

3.2 Fractography

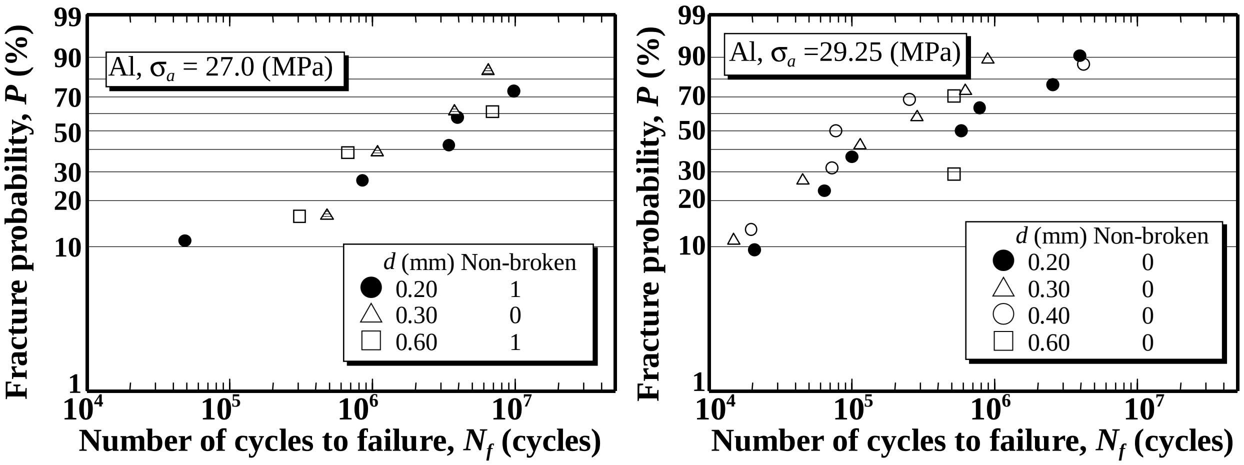
Fractographic observations were made to clarify the origin of the size effect. Figure 6 shows fracture morphology of aluminum. In Figure 6 (a), no fracture surface is observed. The specimen was separated by the plastic deformation, *i.e.*; the reduction in area of this case is 100%. In Figure 6 (b), the fatigue fracture surface is observed. Figures 6 (c) and (d) are fracture surfaces of the same specimen. They showed the cup and cone morphology, but essentially they are similar to Fig. 6 (a). The difference in the fracture morphology is considered to come from the difference in the orientation of slip plane in crystal grains at the minimum cross-section.

There was no correlation between the fracture morphologies and the specimen diameter and



(a) σ_a = 135.0 MPa (b) σ_a = 180.0 MPa

Fig. 4. Fracture probability of iron in fatigue.



(a) σ_a = 27.0 MPa (b) σ_a = 29.25 MPa

Fig. 5. Fracture probability of aluminum in fatigue.

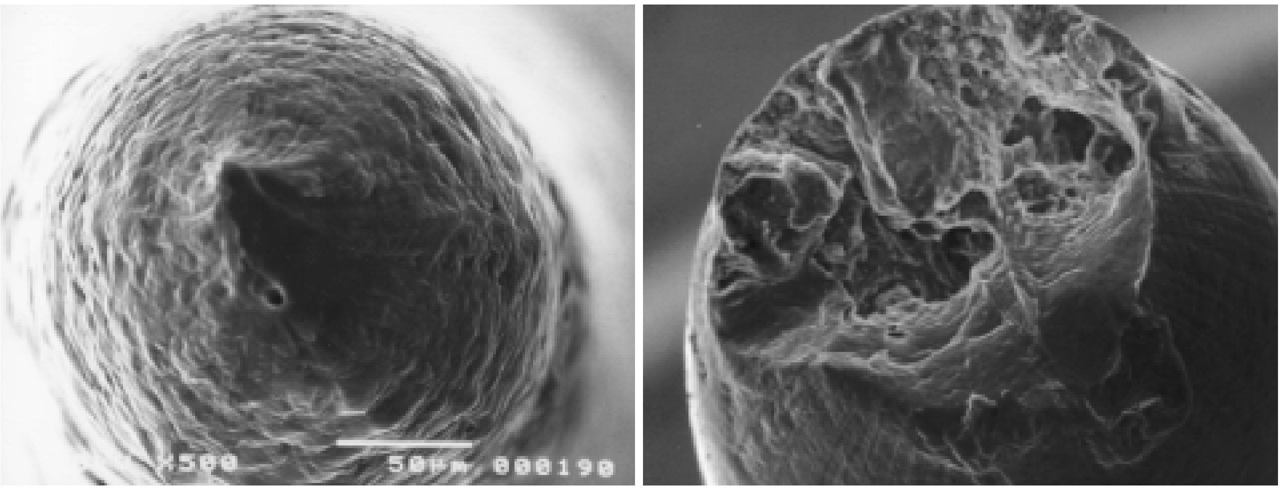
the stress amplitude. The fatigue life, however, could be correlated to the fracture morphologies. The morphologies like Fig. 6 (a), (c), and (d) tended to give shorter fatigue life, while that like Fig. 6 (b) which had the fatigue fracture surface brought longer fatigue life.

As shown in Fig. 7, all iron specimens had the fatigue fracture surface. In Figures 7 (a) and (c), the final unstable fractures occurred eccentrically. It means that single fatigue crack propagated until the final unstable fracture. In Figures 7 (b) and (d), it is considered that the crack initiated at multiple sites and they propagated to the center of specimen almost at the same rate because the final unstable fracture took place at the center of the specimens. The latter case tended to give longer fatigue life than the former case. The size effect on fatigue life may come from the difference of the propagation life of fatigue cracks.

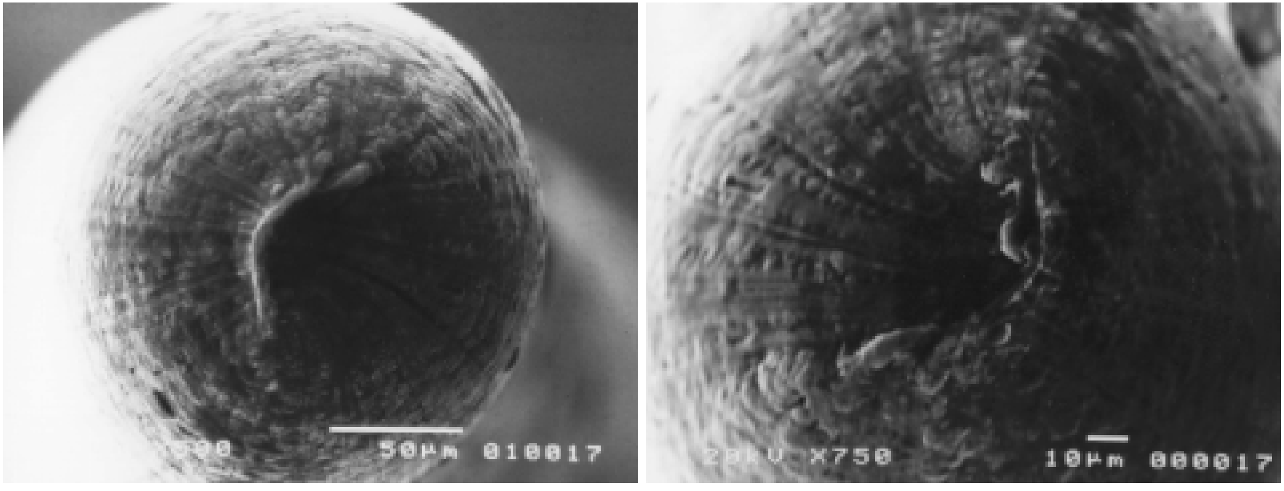
4. CONCLUSIONS

In the present study, fatigue test systems with electro-dynamic vibrators and electrolic-polishing apparatus were developed to study the fatigue strength of micro-materials. Commercially pure aluminum and iron were employed for the fatigue tests. In the range of specimen diameter from 0.2 to 0.6 mm, the following results were obtained

(1) In pure aluminum, the fatigue strength was almost independent of the specimen diameter, and variations of the fatigue life from specimen to specimen at the same stress amplitude were large.
(2) In pure iron, the variations of the fatigue life from specimen to specimen at the same stress amplitude were also large, but the fatigue strength tended to be shorter for smaller specimen diameter.
(3) In aluminum, three types of fracture morphologies were observed, and two types of them were observed in iron. In both materials, there was weak correlation between the fracture morphologies and the fatigue life.

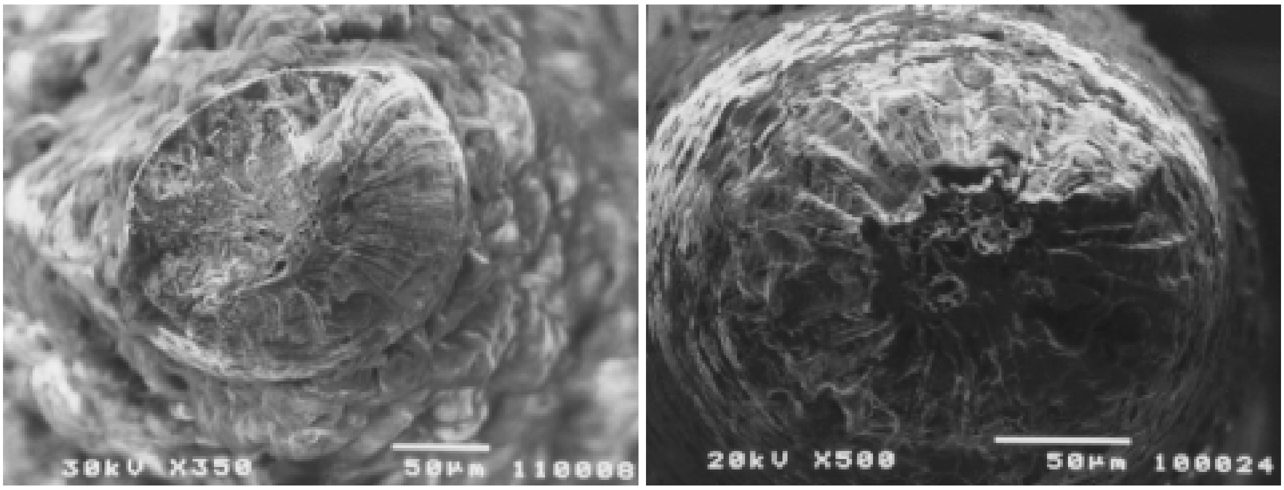


(a) d = 0.20 mm, σ_a = 29.25 MPa, $N_f = 5.8\text{x}10^5$ (b) d = 0.60mm, σ_a = 27 MPa, $N_f = 6.9\text{x}10^6$

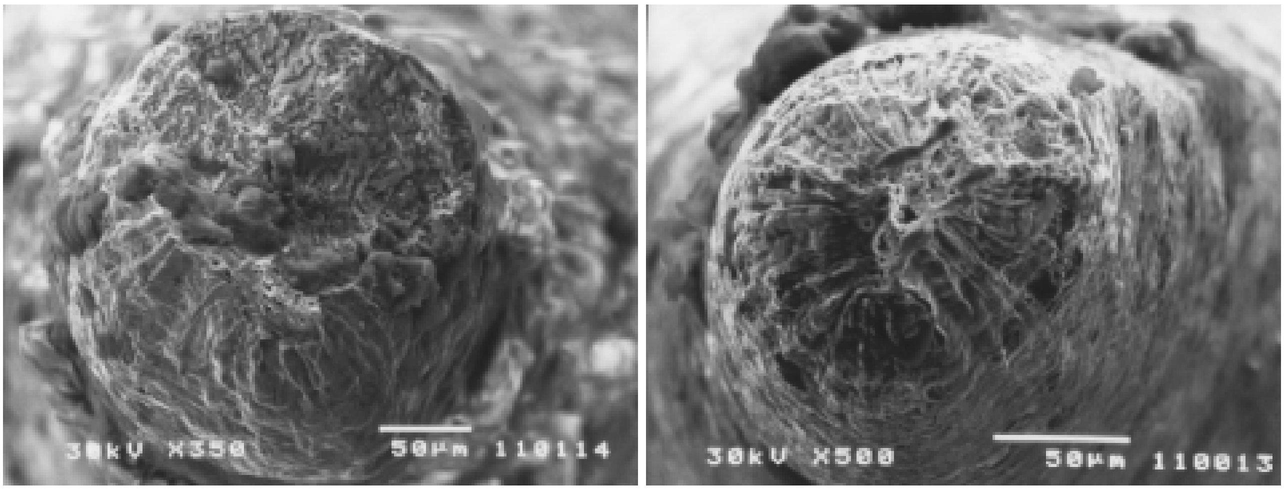


(c) d = 0.20 mm, σ_a = 29.25 MPa, $N_f = 1.0\text{x}10^5$ (d) d = 0.20 mm, σ_a = 29.25 MPa, $N_f = 1.0\text{x}10^5$

Fig. 6. Fracture surface of commercially pure aluminum.



(a) d = 0.20 mm, σ_a = 112.5 MPa, N_f = 5.0x10^6 (b) d = 0.20 mm, σ_a = 180 MPa, N_f = 9.5x10^6



(c) d = 0.30 mm, σ_a = 157.5 MPa, N_f = 2.4x10^6 (d) d = 0.30 mm, σ_a = 135 MPa, N_f = 1.3x10^7

Fig. 7. Fracture surface of commercially pure iron.

ACKNOWLEDGMENT

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5. REFERENCES

(1) T. Torii, A. Ibata, and K. Honda, J. Soc. Mat. Sci., Vol. 44, No. 500, pp.637-642 (1995).
(2) K. Komai, K. Monoshima, H. Tawara, S. Inoue, and K. Sunako, Trans. JSME, Vol. 60, No. 569, pp.52-58 (1994).
(3) K. Komai, K. Monoshima, S. Inoue, and H. Hujii, Trans. JSME, Vol. 62, No. 596, pp.978-984 (1996).
(4) N. E. Frost, K. J. Marsh, and L. P. Pook, “Metal Fatigue”, pp.54-65, Oxford University Press, London (1974).
(5) M. Klesnil and P. Lukáš, “Fatigue of Metallic Materials”, pp.164-167, Elsevier Scientific Pub. Co., Amsterdam (1980).
(6) K. Takao and H. Nisitani, Trans. JSME, Vol. 46, No. 402, pp.123-130 (1980).
(7) K. Tanaka, M. Hojo, and Y. Nakai, ASTM STP 811, pp.207-232 (1983).