Column

Material failure at the MEMS scale

- Size effects on fracture behavior -

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Since beginning research several years ago regarding evaluation of mechanical properties of the micromaterials used in MEMS, I have begun to dip a toe into the world of MEMS. Whenever I make a presentation about evaluating the mechanical properties of micro scale materials, I am always asked, “What about the size effect?”. Size effect is generally used to mean the changes in material properties compared with bulk materials when the dimensions of a material are made smaller. But for those of us who have been involved mainly in mechanical characteristics, the question of how the mechanical characteristics change is what seems to interest us.

Generally it is said that brittle materials (such as glass and ceramic) increase in strength as their size gets smaller. This phenomenon is explained as being linked to the existing probability of defects being present in the material. In other words, as the dimensions of the material get smaller, so the number of defects included in the material becomes fewer, meaning that the starting points for failure are reduced, thereby raising the strength. However, with MEMS materials, the dimensions are in the order of microns, so that various other size effects come into play.

These size effects can be divided into intrinsic effects and extrinsic effects. Intrinsic effects are those where, as the dimensions become smaller, the deformation mechanisms of the materials change, with the result that the mechanical properties change. Extrinsic effects are those where the mechanical properties change due to exogenous elements such as the defects mentioned above. With MEMS materials especially, even nanosize defects may be located in stress concentration zones, causing the mechanical properties of the material to change significantly. With the materials used for MEMS, the changes in the mechanical properties caused in the manufacturing process can be said to be extrinsic size effects since the form of defects and their existing percentage depends on that process. However, because both types of effect are typically present together, size effects on mechanical properties are extremely complicated.

Incidentally, the dimension at which size effects begin to appear irrespective of mechanical characteristics is called the “characteristic length”. When electromagnetic properties or quantum effects are involved, characteristic lengths in the nanometer order are typical. However, among mechanical characteristics there are some with a characteristic length in the micron order which is the size of MEMS. For example, tension tests of ductile materials (materials that show significant plastic deformation until they break, like many metal materials) indicate that material strength largely does not depend on the dimensions of the material down to the micron size. However, if a stress gradient or strain gradient occurs such as with bending or twisting, a size effect becomes apparent in which the strength increases as the dimensions of the material decreases, as demonstrated experimentally and theoretically. There are differences between the types of material, particularly with metal materials. However when the characteristic length is in the micron order, in MEMS devices where metal is used for parts in which bending (as seen in cantilevers and hinges), and twisting stress is applied, this size effect becomes important.

Incidentally, for the design and development of MEMS devices with superior reliability and durability, it is very important to evaluate the rupture characteristics of microdimensional materials with high precision. Here I will present a relevant example of a size effect. When uniform force is applied to the material, stress is concentrated at the ends of any scratches or cracks. However, if the stress at the end of a crack exceeds the yield stress, plastic deformation will occur. If the size of the area where this plastic deformation occurs (in the case of failure, the parameter related to characteristic length) is very small compared to the ligament length (the length from the end of the crack to the free surface beyond it) brittle fracture will occur. However, if the size of the area is large, a size effect appears in which the fracture morphology of the material transitions from brittle fracture to ductile fracture. In ductile materials, the characteristic length in this case is in the order of millimeters or higher, so even if the size is reduced to micron order, the material still tends towards ductile fracture. However, in brittle materials, the fracture morphology may make a transition according to the size. In our group, we researched the fracture behavior from micro to macro sizes using single crystals of Fe-3%Si alloy (a material in which cleavage (brittle) fracture occurs at macro sizes, but with a characteristic length in the order of 10 μm or more). From our tests we discovered that although cleavage fracture occurs at the macro size, the behavior changes to ductile fracture at the micro size (**Fig. 1**).

In MEMS, in order to aim for higher performance it is considered necessary to use many materials such as metals, ceramics, polymers and so on, and as well as silicon materials. Furthermore, because there are many types of silicon and ceramic that undergo brittle fracture at macro sizes, I believe that our results showing the effects of dimension on fracture behavior will prove very important in designing MEMS devices that are reliable and durable.

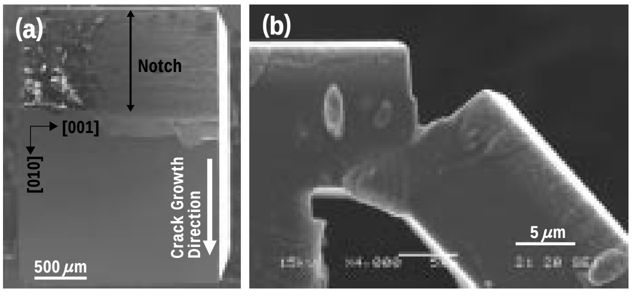

Fig.1 Changes in fracture behavior in (a) a macro size specimen, and (b) a micro size specimen of Fe-3%Si single crystal. At macro sizes, cleavage (brittle) fracture occurs, but at micro sizes, ductile fracture occurs. As this demonstrates, the fracture behavior and morphology of a single material differs when the dimensions of the material change to a micro order.