Advances in micro/nanomachining improve production of thin, brittle wafers

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By cutting brittle materials when they can bend as they break, monocrystalline silicon wafers can be produced more easily.

Many materials, including silicon wafers, are naturally brittle. Traditional machining of these materials produces a damaged layer that must be polished chemically. But micromachining of brittle materials is possible if one provides enough compressive stress to cause a ductile mode of fracture (where the material deforms) in which material is removed by plastic extrusion. Suppression of a brittle response when cutting on the nanometer scale helps avoid the generation of surface defects. The cutting process must be carefully studied to operate in the ductile regime, however. The cutting geometry and machining rates are the usual focus, but indentation is also used to study the brittle-to-ductile transition. This article discusses some recent achievements in the micro/nanomachining of brittle materials.

Increasing the rate of absorbed energy in nanoindentation

To achieve a nanometric surface, monocrystalline silicon must be cut below the threshold stress of dislocation. In nanoindentation, a small force is applied to a material and the depth of indentation is measured. This is an important technique for studying micro cracks in a brittle material. Load vs. depth curves of indentation (see Figure 1), however, do not provide direct information about surface cracks. We thus propose a new method that involves a new concept: the increasing rate of absorbed energy \( r_{n,n-1} \), defined as follows:

\[
 r_{n,n-1} = \frac{E_{a,n} - E_{a,n-1}}{F_{a,n} - F_{a,n-1}}
\]

where \( F_{a,n} \) and \( E_{a,n} \) are an applied load and the absorbed energy at this load; and \( F_{a,n-1} \) and \( E_{a,n-1} \) are the last applied load and the absorbed energy at the last load, respectively.

Figure 1. These load vs. depth curves are for nano indentation with a load of 110mN.

Figure 2. In this graph of increasing rate of absorbed energy vs. applied loads, the increasing rate of absorbed energy decreases when a crack forms.

Figure 2 shows that the increasing rate of absorbed energy drops when a new crack occurs. With this new concept, we can easily predict if a micro crack will appear.

Mechanism for nano-cutting silicon

Researchers have generally applied the shearing cutting model no matter how small the undeformed chip thickness is. There is insufficient evidence, however, to suggest that, in nanometric cutting, the work material is removed by shearing. In conven-
tional cutting, the depth of the cut is significantly larger than the radius of the cutting edge. But this edge effect cannot be neglected in nanometric cutting. Regardless of the nominal rake angle—either positive, negative, or 0°—the effective rake angle is always negative. This negative rake face produces the hydrostatic pressure that enables plastic deformation to occur in front of the cutting edge. As shown in Figure 3, a stagnation point $S$ (threshold) may exist in the ratio of the undeformed chip thickness, $a_c$, to the cutting edge radius, $r$. This ratio is associated with material properties, tool geometry and machining conditions. When the ratio decreases below the point $S$, chip formation does not occur, but elastic and plastic deformation do. After the work material has passed the lowest cutting edge point $L$, the elastic portion $D_e$ springs back. The plastic deformed portion $\Delta$ leads to a lasting deformation behind the point $P$: $\beta$ is the angle from the vertical direction to the resultant force direction.

If the ratio of the undeformed chip thickness to the cutting edge radius is above the stagnation point $S$, the material below the point $S$ undergoes an elastic and plastic deformation, as shown in Figure 3. After the work material has passed the lowest cutting edge point $L$, the elastic portion $D_e$ springs back. The plastic deformed portion $\Delta$ leads to a lasting deformation behind the point $P$. The material above the point $S$ is extruded to form chips.

Monocrystalline silicon is brittle at ambient temperature. Its amorphous modification, however, exhibits a plastic flow under low loads. As such, possible phase transformation events during machining are of great significance in the production of damage-free components.2–10

**Zero-rake-angle cutting of brittle materials**

In conventional machining, the cutting-edge radius of carbide tools can be considered sharp, as the radius is substantially smaller than the undeformed chip thickness. But in the ultra-precision machining of brittle materials, the cutting edge radius is larger than the undeformed chip thickness. Thus, even though the actual rake angle is 0°, the effective rake angle is a large negative value, as approximated with the following equation:

$$\gamma_e = \left\{ -\pi + \arccos\left(1 - \frac{a_c}{r}\right) \right\}/2$$

where $\gamma_e$ is the average effective rake angle and $r$ is the cutting edge radius. The effective rake angle varies with the tool edge radii and undeformed chip thickness when the nominal rake angle is 0°. Increasing the cutting edge radius and decreasing the undeformed chip thickness make the rake angle of the tool more negative. This large negative rake could produce the hydrostatic stress necessary for plastic deformation to occur in front of the cutting edge.6, 11, 12

**Generation of a 1nm silicon surface**

Figure 4 shows an example of monocrystalline silicon cut under the threshold stress of dislocation. The machining parameters of the depth of cut, feedrate, and cutting speed are 1µm, 400µm/min, and 90m/min, respectively. The single crystal diamond tool has a rake angle of 0° and a nose radius of 0.7mm (waviness controlled). Under the experimental conditions, nanometric surfaces were achieved by diamond cutting. Figure 4 shows a nanometric surface with a surface roughness of 1nm in $R_s$, where the analysis area is about $5 \times 5 \mu m$.11, 12

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References