M1-017 Determination of brittleness of brittle silicon in micro-end-milling process

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ABSTRACT

At room temperature, silicon is inherently brittle, i.e. no dislocation activity occurs at or near the crack tip. A number of technological barriers must be overcome if micro-end-milling is applied in cutting single-crystal silicon. Crack-free surfaces that are required in the optical and MEMS industries are achieved by ductile-regime machining. Micro-end-milling of silicon using diamond-coated tools is possible to use in order to achieve ductile cutting mode even though deformation mechanism of silicon is dominated by microfracture because of low fracture toughness. In this study, a simple brittleness values (B) in order to evaluate the performance of micro-end milling of silicon from cutting force data which enables the comparison of the machinabilities of silicon was introduced. The results confirm that good machinability of silicon in micro-end-milling process using diamond-coated tools was achieved when cutting performed at cutting conditions which have lower brittleness value.

***Keywords**: Micro-end-milling; ductile and brittle cutting mode; brittleness value*

1. Introduction

Single crystal silicon is known as a brittle material at temperature below 0.5 T_m (T_m is melting temperature) [1]. At room temperature, silicon is inherently brittle, i.e. no dislocation activity occurs at or near the crack tip. When silicon is deformed at room temperature in tension or bending, it fractures before any permanent measurable plastic deformation occurs because the dislocations are relatively immobile. As a brittle material, silicon is not amenable to conventional machining operation because of its low fracture toughness [2]. The fracture toughness of (111) silicon at room temperature was reported in the range of 0.81 – 1.03 MPa $m^{1/2}$ [3], therefore deformation mechanism of silicon is dominated by microfracture.

However, plastic deformation can be possible when the uncut chip thickness is small enough. When uncut chip thickness becomes small enough, the entire cutting region will be under the high-stress state. Many researchers proposed that high hydrostatic pressure produced during the machining process can play the important role in getting ductile cutting mode. Yoshino et al. have reported that hydrostatic pressure can minimize fracture and produce smooth surface [4]. Gogotsi et al. explained that the magnitude of the hydrostatic stress determines the extent of plastic deformation prior to fracture and this a high value of the hydrostatic pressure is a prerequisite for plastic flow of the ductile metallic phase silicon formed under pressure [5]. In their paper, Vodenitcharova and Zhang explained that the large plastic deformation in silicon single crystal is induced by amorphous phase transformation which is initiated in loading and further developed by the hydrostatic stress [6]. Yan et al investigated the role of hydrostatic pressure in the ductile machining of silicon experimentally [7]. They concluded that smooth surfaces and ductile machining of silicon can be accomplished under the conditions of high hydrostatic pressure.

Hard and brittle material such as silicon became desirable for advanced optics because of their ability to transmit light over a variety of wavelengths [8]. As important substrate material in MEMS and infra red optical application, silicon must satisfy stringent requirements for flatness, higher quality surface and contamination control. These applications require a crack-free surface which is achieved when silicon is cut in ductile cutting mode.

Some researchers have reported that they were success in getting ductile cutting mode when machine silicon single crystal [2,4,7-11]. But none of them could explain quantitatively machinability of brittle silicon. Brittleness is one of the important mechanical properties of brittle materials. The definition of brittleness as a mechanical property varies from author to author [12]. This is because of brittleness of materials depends on the material properties and the loading conditions. Lawn and Marshall gave a definition of brittleness as a measure of the relative susceptibility of a material to deformation and fracture [13]. The ratio of hardness to toughness was proposed as a simple index of brittleness for an indentation mechanical analysis.

$$B = \frac{H}{K_C} \qquad (1)$$

where H is hardness (resistance to deformation) and K_c is toughness (resistance to fracture). Toughness is also defined as the amount of energy that a material can adsorb before rupturing [14]. The effects of cutting conditions were missing in Eq. 1 because hardness and fracture toughness values were calculated from static conditions test with given load. For dynamic conditions, scratch hardness tests can represent a better simulation of material behavior in machining process. Li et al. studied the scratch test on the soda-lime glass [15]. They found that the crack density (fraction of scratch covered by cracks) decreases with increasing scratching speed. This result indicates that in high speed grinding, cracking may not be as frequent as in low speed grinding.

Scratching of material is greatly influenced by the modes of material's deformation namely ductile and brittle. There is a drastic change in the material response when there is a change in the material behavior from brittle to ductile and vice versa. This mode of deformation depends on parameters such as the attack angle, normal load, scratching speed, temperature and so on [16].

Scratch hardness, H_s, is defined as the normal force, F_N, per unit normal projection of load bearing area, A_{LB}.

$$H_s = \frac{F_N}{A_{LB}} \qquad (2)$$

When carrying out a scratch hardness test the tangential force F_T is often also monitored. Axen et al. performed scratch hardness tests on polished surfaces of ceramic materials. They investigated the material's response by measuring the fluctuations in the tangential force during scratching. They found that measurement of the tangential force during scratch testing can be used to detect changes in the damage mechanism [17].

Tangential force in milling of silicon using diamond-coated end mills is a function of force due to cutting action, force due to tool penetration and plowing force. When cutting action plays a dominant role, plastic deformation due to material flow will be occurred. Meanwhile, the amount of energy that a workpiece can adsorb before rupturing during milling process can be expressed by total specific cutting energy (u). This total specific cutting energy, u, varies according to the spindle speed, the feed rate, and the axial depth of the cut. The high value of total specific cutting energy can also be attributed to the higher energy needed for plastic deformation during the cutting process. The total specific cutting energy, u, is:

$$u = \frac{Fv}{fd_a w} \qquad (3)$$

where F is the total force, v is the cutting speed, f is the feed rate, d_a is the axial depth of the cut, and w is the width of the cut.

On the other hand, because of higher cutting speed, friction between a tool and a workpiece is a crucial factor in determining the main machining output. Since friction plays a dominant role in the cutting action, and affects the machined surface and forces, one should consider this friction in determining brittleness of silicon.

Since brittleness is closed related to the machinability of material, now we can modify Eq. 1 in order to define the brittleness of silicon because of effect of cutting parameters. Brittleness values of silicon in micro-end-milling process can be defined quantitatively as:

$$B = \frac{\mu}{u}\frac{F_T}{A} x100 \qquad (4)$$

A smaller value of B infers a better machinability of silicon in micro-end-milling process using diamond-coated tools.

The machinability of silicon can vary according to the cutting conditions. The purpose of this study is to introduce a simple brittleness values in order to evaluate the performance of micro-end milling of silicon from cutting force data which enables the comparison of the machinabilities of silicon.

2. Experiment

The silicon cutting experiments were conducted on the micro-end-milling machine. The machine was set on the pneumatic bench to isolate the external vibrations. A digital tachometer was used to measure the spindle rotational speed. Cutting force measurements were carried out using a Kistler 9256C1 triaxial load cell which was mounted on the actuator stage. The dynamometer measures the cutting force in three mutually perpendicular directions notationally the x-, y- and z-axis.

Commercial two flute carbide diamond-coated end mill tools were used in the experiments. The tool tips were 0.178 *mm* in diameter, the edge radius was approximately 9 µ*m* and its helix angle and rake angle were 30^o and 4^o respectively. Single crystal silicon wafers with (111) orientation were machined along the feed direction of $[1\bar{1}0]$. The performance of milling silicon was investigated by varying axial depth of cut from 0.3 to 0.7 µ*m*, feed rate from 2 to 12 µ*m/s* and spindle speed from 50,000 – 100,000 *rpm*.

3. Results & Discussion

The brittleness values vs. feed per tooth are plotted and it is seen that there is no specific correlation between feed per tooth and brittleness values (Fig.1). High values of brittleness were found at very small feed per tooth. Feed per tooth are obtained from combination between feed rate and spindle speed. Each two cutting conditions contribute to the brittleness of workpiece material. Small value of feed per tooth is obtained by decreasing feed rate and increasing spindle speed. A reduction of the feed rate led to an improvement of the surface finish and increasing spindle speed will naturally be accompanied by an increase in surface temperature due to frictional heating. When cutting at very small feed per tooth, the negative rake angle could be much higher. At this condition chips may not be formed from cutting action, therefore chip removal was occurred by crushing and fragmentation mechanism due to the tool penetration.

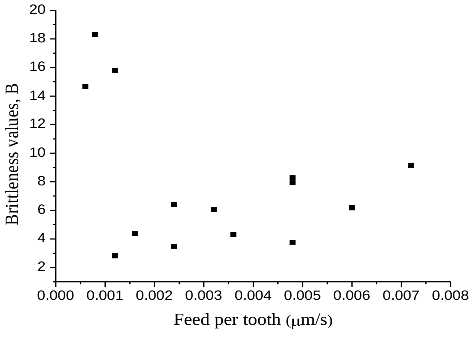

Fig. 1: Feed per tooth vs. brittleness values

The frictions between tool and the workpiece surface were checked with respect to the feed per tooth (Fig. 2). The results show that cutting at very low feed rate has higher friction between tool and workpiece. This high friction can generate damage on the machined surface.

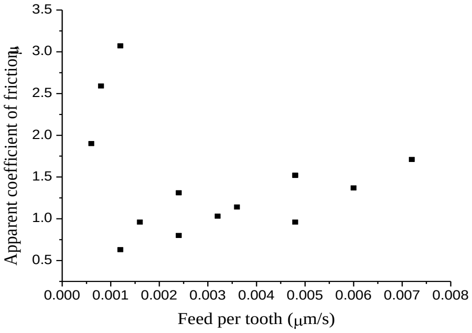

Fig. 2: Feed per tooth vs. apparent coefficient of friction

The effect of the variations of feed rate on the brittleness values were studied using various spindle speed and axial depth of cut of 0.3 □ *m*. The variations of brittleness values with the variation in feed rate and spindle speed are shown in Fig. 3. It is seen that the brittleness values for all various spindle speeds decreases with increasing feed rates below a feed rate of 4 □ *m/s*, and then increases slightly with increasing feed rates. In this study, the ductile cutting mode was achieved when milling silicon using a spindle speed of 100,000 *rpm*, a feed rate of 4 □ *m/s* and an axial depth of cut of 0.3 □ *m*. Therefore, it was concluded that a feed rate of 4 □ *m/s* was the critical feed rate in this study.

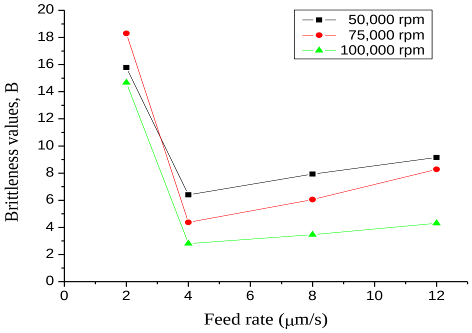

Fig. 3: Variation in the brittleness values with feed rate for various spindle speeds.

The brittleness values due to the variation in axial depth of cut were shown in Fig. 4. The brittleness values were studied at various feed rates and a spindle speed of 100,000 *rpm*. The brittleness values are seen to increase with axial depth of cut. The increase in brittleness values with increasing axial depth of cut can be attributed to the large tool penetration and uncut chip thickness. As the uncut chip thickness increases from small to large, the compressive stress in the cutting zone decreases, giving way to crack propagation in the chip formation zone [18].

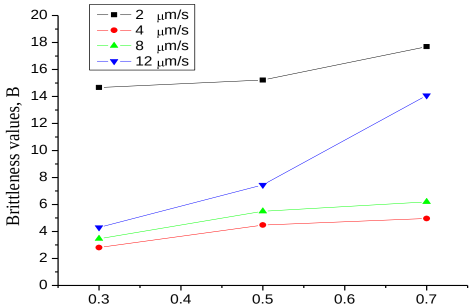

Fig. 4: Variation in the brittleness values with axial depth of cut for various feed rates.

As mentioned above, the ductile cutting mode was achieved when milling silicon using a spindle speed of 100,000 *rpm*, a feed rate of 4 μ*m/s* and an axial depth of cut of 0.3 μ*m*. This cutting condition has a brittleness value of 2.81. To investigate how the tool-workpiece interaction effect the brittleness value of silicon during milling process, additional experiments were carried out at higher axial depth of cut (0.5 μ*m*) using oil and deionized water as coolants. As expected, using oil as coolant decreases the brittleness values from 4.48 (dry) to 2.84, giving ductile cutting mode for this cutting condition because the value of apparent friction coefficient also decreases from 0.79 to 0.59. On the other hand, small decreases of brittleness values and apparent friction coefficient (from 0.79 to 0.74) were found when using water as coolant. Surface damages still found on the machined surface at this environment condition. Zhang and Zarudi explained that chemical reaction during machining plays an important role in the nano-wear deformation of mono-crystalline silicon [22]. To understand more detail the environmental conditions effect on cutting mode of silicon during milling process, further investigation must be carried out.

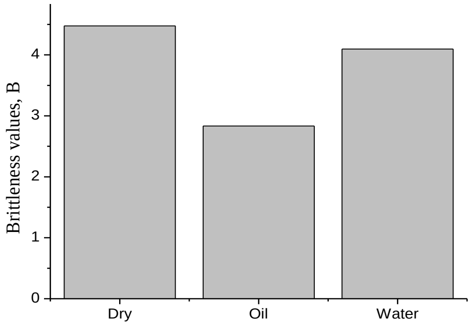

Fig. 5: Effect of using coolant on brittleness values

4. Conclusions

A simple brittleness value in order to evaluate the performance of micro-end milling of silicon from cutting force data which enables the comparison of the machinabilities of silicon was introduced. Knowing the brittleness values of silicon during milling process with various cutting conditions would lead to an improved milling performance. The brittleness value is affected by the plastic deformation represented by cutting force per unit area; the amount of energy that a material can adsorb before rupturing represented by total specific cutting energy; and friction condition between tool and workpiece. Experimental results showed that as the spindle speed increases, the brittleness value decreases. There is a critical value of the feed rate for brittleness value. The cutting mode changes from ductile to brittle. The brittleness value is seen to increase with axial depth of cut. It is also found that the brittleness value decreases with decreasing cutting friction. As brittleness value decreases, machinability of silicon in micro-end-milling process increases. Ductile cutting mode occurs when the brittleness value of silicon is lower than 3.45.

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