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A comparative study of conventional and high speed grinding characteristics of a thin film multilayer structure

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ABSTRACT

High speed and conventional speed grinding characteristics of a thin film multilayer solar panel were investigated. The grinding force and surface roughness were measured and the interface integrity of the ground workpieces was examined. The results indicated that when applying a high wheel speed of up to 120 m/s, the ground surfaces predominantly exhibited ductile flow and the interface integrity was significantly improved. The maximum undeformed chip thickness was found to be an important parameter to measure grinding performance and interfacial failure. Delamination was observed at interfaces when the maximum undeformed chip thickness exceeded a threshold value and the finite element method (FEM) analysis revealed that the interfacial failure was mainly induced by shear stress.

1. Introduction

Thin film multilayers are widely used in micro-electro-mechanical system (MEMS) devices [1,2], as well as in semiconductor and photovoltaic systems [3–5]. The application of thin film multilayer structures into device making usually requires machining of the multilayers. However, it is challenging to efficiently machine thin film multilayers without compromising their surface integrity, because the films are often not only extremely thin, but have dissimilar material properties [5,6]. Chipping and interfacial delamination could occur if machining conditions were not appropriately selected [7], which would lead to malfunction and hence affect device reliability. Therefore, it is of great significance to comprehensively understand the deformation and failure mechanisms of thin film multilayers involved in machining processes.

The previous studies [6–8] were largely concerned with structure failure and material removal mechanism of thin film multilayers involved in abrasive machining processes. For instance, Taro et al. carried out the studies on the grinding of thin film solar panels [6,7]. When a high material removal was employed, chipping occurred and thin film multilayers were damaged during grinding [7]. When significantly small depths of cut of several micrometres were used in their grinding process, surface integrity of the multilayers was considerably improved, similar to the quality produced by polishing [6]. The fundamental understanding of failure and removal mechanisms of solar panel multilayers was also carried out using nanoscratching [8,9], in combination of finite element modelling (FEM) [8]. It was revealed that delamination occurred at relative weak interfaces and plastic removal without fracture could occur in brittle thin film layers when a critical scratch depth was reached, which was also affected by tip geometry and material properties of thin film layers [9]. The FEM stress analysis [8] further revealed that the interfacial failure involved in an abrasive machining process was attributed to significantly high shear stress induced at the interface between two dissimilar materials. By controlling the grit depth of cut, or grit load, in a removal event, the thin film multilayer could be machined efficiently with good control of chipping and delamination, which enabled to achieve satisfactory surface quality [9].

High speed grinding has been long proven for its application in high efficiency machining of brittle materials [10,11]. In a high speed grinding process, an increased grinding speed can reduce the maximum grit depth of cut (or maximum undeformed chip thickness), and thus the grinding force [12–14]. The reduction in grinding force would help to improve the ground surface quality. For the machining of thin film multilayers, the reduction in normal force would be especially important for improving the machined surface integrity as it could lower the stress at thin film interfaces, and therefore decrease the possibility of occurrence for interfacial delamination [8]. Nevertheless, till now none has been reported

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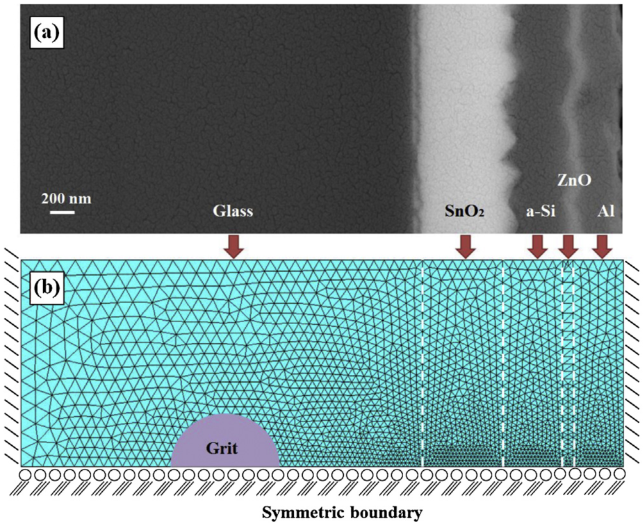

Fig. 1. (a) A SEM micrograph of the thin film multilayer. (b) Top view of the 3D FEM model with boundary conditions.

on the effect of high speed grinding conditions on the interfacial failure mechanisms.

This work studied the grinding characteristics and interfacial failure mechanisms of a thin film multilayer during conventional and high speed grinding processes. The effect of grinding conditions on the ground surface quality was systematically investigated. High grinding speed was performed in order to achieve smooth surfaces and intact thin film interfaces. The maximum undeformed chip thickness was used to interpret the transition between removal modes. The underlying mechanism of interfacial failure was also studied using FEM analysis. The critical stresses resulted from nano-scratching, lapping and grinding were compared.

2. Material and methods

2.1. Specimens

Thin film multilayer specimens being investigated in this study were taken from a Si thin film solar panel. The multilayer consists of a glass substrate, a front transparent conductive oxide layer of SnO_2, a photovoltaic layer of a-Si, a transparent conductive oxide layer of ZnO and an Al metal contact layer, with layer thickness of approximately 4 mm, 800 nm, 600 nm, 80 nm and 550 nm, respectively, as shown in Fig. 1(a). The mechanical properties of the thin film material were studied previously and are shown in Table 1. The specimens for grinding had a rectangular shape of 15 mm × 10 mm, which were wire-cut from the solar panels. For grinding experiments, two pieces of such specimens were glued face to face (thin film side) using epoxy resin, so both grinding directions could be examined under the same condition. The surfaces to be ground were well polished to make sure that the defects from sample preparation would be fully removed.

2.2. Grinding procedure

Grinding experiments were performed on a precision grinding machine (Okamoto UPZ315Li, Japan). The machine spindle is capable of running up to 20,000 rpm for a wheel diameter of 180 mm. The power of the spindle drive motor is 2.2 kW. The infeed resolution is 0.1 µm. Diamond wheels (A.L.M.T. Co., Japan and Asahi Diamond, Japan) with different grit sizes and bonds were used. Two resin bond wheels used had average grit sizes of 17 µm (SD800) and 7 µm (SD2000) and a vitrified wheel (SD6000) had an average grit size of 2 µm. Vitrified bond was used because resin bond is unable to hold very fine diamond abrasives. The error of wheel deformation caused by the use of different bond materials was assumed to be insignificant as the three wheels had similar hardness values and the same geometries (which are consisted of an abrasive layer of 2 mm thick and an aluminium core of 176 mm in diameter) [15]. A conventional wheel speed of 40 m/s and two high-speeds of 80 m/s and 120 m/s were used to examine the effect of wheel speed. Table speed was varied from 250 mm/min to 4000 mm/min and the grinding depth of cut (DOC) was changed from 1 µm to 20 µm. All the grinding experiments were conducted on the cross-sectional surface via down grinding and table feeding direction was kept perpendicular to thin film layers. Prior to each grinding test, the grinding wheel was trued by a silicon carbide truing wheel of 800 in mesh size using the same conditions as those in the grinding process. Dressing was followed by using an alumina stick of 800 in mesh size to gently contact the rotating wheel for approximately 20 s. The truing process had the same conditions as those used in the grinding experiment. The wheel was balanced at the grinding speed being used during each test to attenuate vibration and improve grinding performance [16,17], using a dynamic balancing instrument (Sigma Electronics SB-8002, USA). Five preliminary grinding passes were carried out using a depth of cut of 5 µm prior to each grinding test to make sure all the samples had the same surface status. Water miscible coolant (Kyodo Noritake COOLN-50TC, Japan) was applied to the grinding zone with a coolant/water ratio of 3%.

2.3. Characterization methods

The normal and tangential grinding forces were directly measured by use of a piezoelectric dynamometer (Kistler 9257B, Switzerland) and the data was recorded into a personal computer for further analysis. The forces measured during a grinding test were in fact the sum of the "real" grinding force and the force induced by coolant. It is well documented that the coolant induced forces in high speed grinding could be significant [14]. Therefore, in this study the grinding force was first measured by conducting a grinding pass without infeed, which gave the coolant induced force. The "real" grinding force was then calculated by subtracting the coolant induced force from the force measured in the actual grinding test. An atomic force microscope (AFM, Ambios Tech., USA) was used to measure surface roughness of the ground thin film layers. For each test, grinding was repeated for three times and roughness of the ground surface was measured at three different locations on each sample. The ground surface was cleaned in an ultrasonic bath for 10 min prior to surface examination using a scanning electron microscope (SEM, JEOL JSM-7001F, Japan).

2.4. Maximum undeformed chip thickness (h_m)

The maximum undeformed chip thickness, h_m, was used to measure the effect of grinding conditions on grinding performance [18–20]. The h_m value was calculated as [21]:

$$h_m = (3/C\tan\theta)^{1/2}(v_w/v_s)^{1/2}(a_e/d_s)^{1/4} \qquad (1)$$

where θ the semi-included angle of the active grain point, v_w the workpiece velocity, v_s the peripheral wheel speed, a_e the depth of cut, d_s the wheel diameter. For the wheels used in this study, $\theta = 60°$. C represents the active grain density and it can be calculated using a geometric relationship derived by Xu et al. [22] as follows:

$$C = 4f/{d_g}^2(4\pi/3v)^{2/3} \qquad (2)$$

where f is the fraction of diamond particles that were active in grinding, d_g is the equivalent spherical diameter of diamond particle, and v is the volume fraction of diamond abrasives in the

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