International Journal of Machine Tools & Manufacture 77 (2014) 1–15

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Experimental study of surface generation and force modeling in micro-grinding of single crystal silicon considering crystallographic effects

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ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
15 October 2013
Accepted 17 October 2013
Available online 30 October 2013

Keywords:
Micro-grinding
Undeformed chip thickness
Single crystal silicon
Crystallographic effects

ABSTRACT

In this study, surface formation mechanism in micro-grinding of single crystal silicon is investigated based on analysis of undeformed chip thickness h_m. A predicting model of grinding force considering crystallographic effects in micro-grinding of single crystal silicon is built. In this model, micro-grinding process of single crystal silicon is divided into two steps by one line on which h_m of single grit equals to lattice constant. Two micro-grinding experiments with different ranges of cutting depths and feed rates have been designed and conducted on single crystal silicon to verify the model this paper proposes. The relationship between micro-grinding parameters and crack length l_c is investigated and the empirical formula of l_c is derived based on analysis of experiment results. Ductile-regime transitions in micro-grinding process of single crystal silicon have been revealed, 20 nm and 100 nm are turned out to be two critical conditions based on analysis of experiment results. It is found that the grinding force has a sudden change when micro-grinding process comes within material's crystal boundary in experiment. The force predicting model this paper proposes has well explained this phenomenon in micro-grinding of single cyrstal silicon. When micro-grinding undeformed chip thickness h_m belows 0.5 nm, micro grinding force doesn't decrease with the decrease of cutting parameters but has a rising tendency, and these experimental measurements also provide a support to the result of model this paper proposes.

1. Introduction

Micro-grinding is one of primary current process methods of cutting hard brittle material in micro-scale with high precision, it has catch more and more research concern [1]. Tool diameter is usually less than 1 mm in micro-grinding, it also could solve problems which are caused in process of micro-milling such as burrs [2].

Researchers had got significant achievements in micro-grinding research field during last ten years. Morgan, C.J. et al. [3] verified that micro-grinding could improve surface quality of hard brittle and difficult to cut material, several micro-grinding experiments are carried out on glass, tungsten carbide. J.C. Aurich [4] achieved a 10 nm roughness surface by micro-grinding method. It is the most precise surface by micro-grinding in worldwide, he also fabricated a series of micro-grinding tools whose diameter between 13 μm and 100 μm. Cheng and Gong [5] built a model to decribe materials removal process in micro-grinding of soda-lime glass and verified it through experiment results. Cheng [6] proposed an analytical model to define ductile-regime transition in soda-lime micro-grinding process and finally gave two critical ductile conditions: 2 nm and 5 nm. Venkatachalam, Li and Liang [7] proved that undeformed chip thickness was an important value by annlysis of chip formation cutting force, surface texture in the process of defining cutting mode in micro-machining single crystal brittle silicon. Feng, Chen and Ni [8] built two surface generation models to decribe different material removal mechanisms and verified that by FEM method.

In silicon micro-grinding research field, Liang and Park [9] first proposed a model to analyse the relationship between cutting parameters and grinding force. This model was very significant to micro-grinding research of single crystal silicon, but didn't conclude different grinding parameters to a universal standard for theoretical analysis such as undeformed chip thickness. Tian and Zhou etc [10] gave the surface formation and texture elimination process of single crystal silicon in chemo-mechanical grinding. Liang [11] built a two-dimensional ultrasonic assisted grinding experiment on monocrystal silicon, it could have a grinding results raising such as material removal rate and surface quality comparing with traditional grinding method in different brittle material [12].

From researching summary of above, it is found that there isn't a systematically theory achievement for transferring and connecting single micro-grinding parameters to grinding results, especially to grinding force. Considering grain size of single crystal silicon could

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http://dx.doi.org/10.1016/j.ijmachtools.2013.10.003

influnce the grinding process, this relationship is supposed to integrate crystal effects.

In this study, undeformed chip thickness h_m is chosen to be the connection bridge between processing parameter and results in micro-grinding of single crystal silicon. When h_m of single grit equals or bellows to lattice constant of single crystal silicon, micro-grinding process of single crystal silicon would be within grains. There would be different grinding force phenomenons by deriving material's transgranular breakage calculation of single crystal silicon. Therefore, a model for predicting grinding force considering crystallographic effects in micro-grinding of single crystal silicon has been built in this paper. In this model, Surface formation mechanism and grinding force are divided to two steps by a line referring above. By conducting micro-grinding experiments on single crystal silicon, crack length l_c's empirical formula and ductile-regime transitions are derived, 20 nm and 100 nm h_m are turned out to be two critical conditions. 0.5 nm h_m which equals to lattice constant is a critical line, micro-grinding forces could have different performances in these two fields as the model predicting.

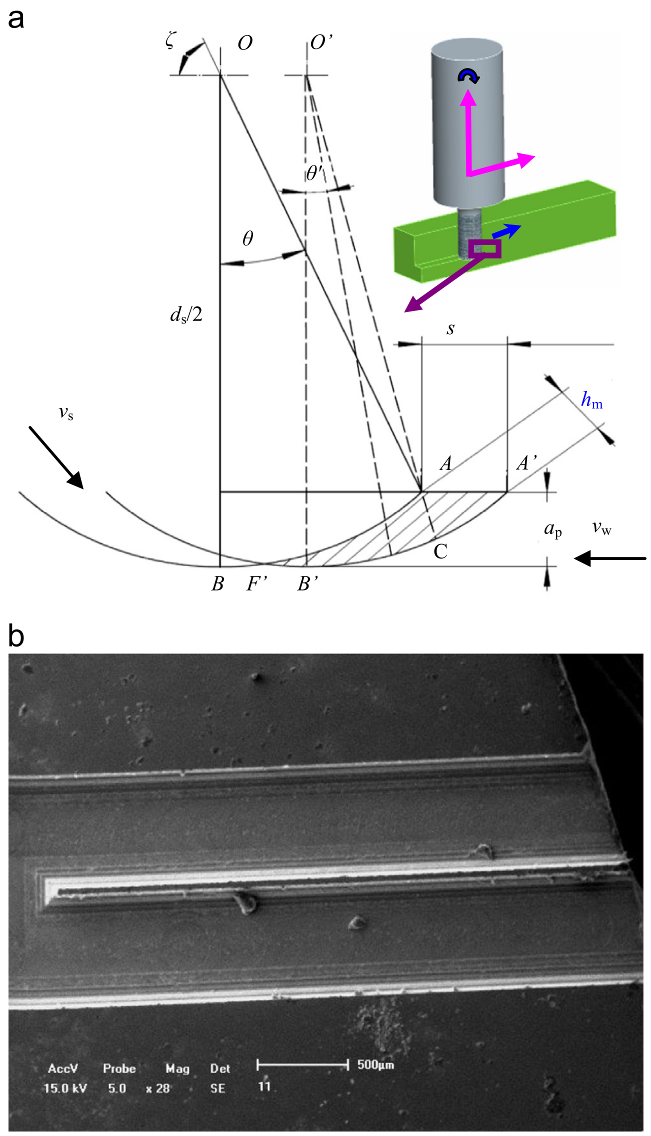

Fig. 1. Micro-surface grinding process. (a) Micro-surface grinding geometry model [5], (b) Micro thin-wall obtained by micro-surface grinding.

2. Micro-grinding process modeling

2.1. Undeformed chip thickness in micro-grinding

Fig. 1(a) shows the micro-surface grinding path of single grit and its geometry model. The work piece's movement "s" during time of two adjacent grits cutting could be expressed by work piece's feed rate speed (v_w) multiplys time as Eq. (1).

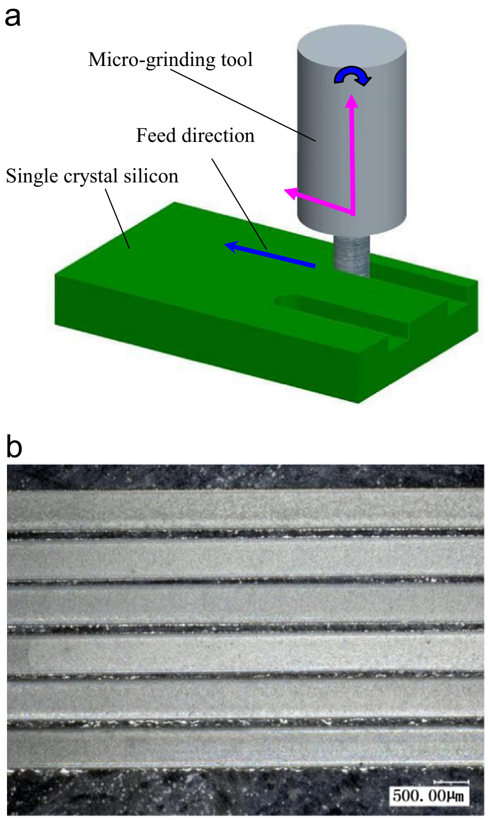

Fig. 2. Micro-slot grinding geometry model, (a) micro-slot grinding geometrical process, (b) micro slot-array obtained by micro-slot grinding.

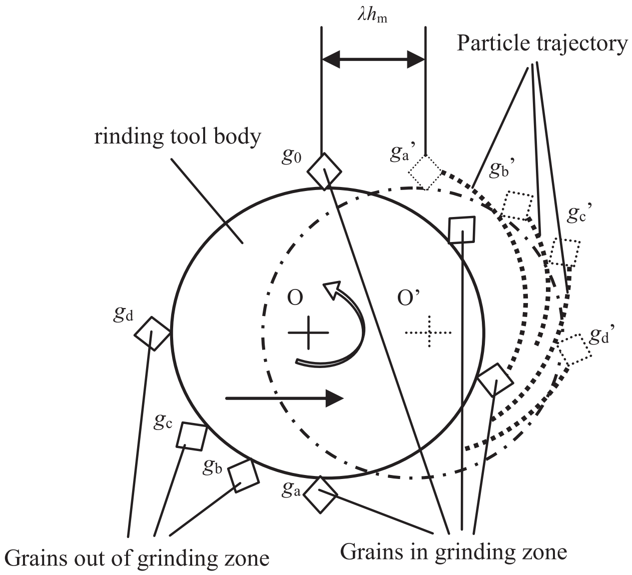

Fig. 3. Undeformed chip thickness h_m in micro- slot grinding.