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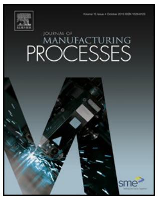

Technical Paper

Experimental work on micro laser-assisted diamond turning of silicon (111)

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ABSTRACT

Single point diamond turning (SPDT) is coupled with the micro-laser assisted machining (μ-LAM) technique to machine silicon (111). The μ-LAM system is used to preferentially heat and thermally soften the work piece material in contact with a diamond cutting tool. Cutting fluid, odorless mineral spirits (OMS), is used to decrease tool wear and improve the surface quality. An IR continuous wave (CW) fiber laser, wavelength of 1070 nm and max power of 100 W with a minimum beam diameter of 10 μm, is used in this investigation. Various machining parameters such as laser power, cross feed rate and tool rake angle were experimented and the resultant surface finish was analyzed. Results show that an optical quality surface finish can be obtained using the μ-LAM technique.

1. Introduction

Single crystal silicon is a very important material with many applications in MEMS, electronics and optoelectronics. It is hard, strong, and light weight, and can easily be used in microfabrication. When attempting to machine ceramics and semiconductors, such as silicon especially to improve the surface finish, it is important to carry out a "damage free" machining operation. Often, severe fracture can result during the machining process due to the material's low fracture toughness (0.83–0.95 $\text{MPa.m}^{0.5}$ for silicon based on direction). Brittle fracture occurrence during process results in poor surfaces and causes detrimental subsurface damage, which then has to be removed in subsequent processing steps such as polishing or lapping [1,2].

Machining mirror-like surface finishes contribute significantly to the total cost of a part. The cost is mainly due to many parameters such as expensive tools that wear out rapidly, long machining time, low production rate to get acceptable surface roughness. In some cases, polishing alone can account for 60–90% of the final product cost [3]. The low production rate is primarily due to the occurrence of surface/subsurface damages, i.e., cracks and brittle fracture. In order to develop a suitable process, ductile regime machining, considered to be one of the acceptable precision machining techniques, has been continuously studied over the last two decades [4–12]. In these researches, it has been demonstrated that ductile regime machining of semiconductor and ceramic materials is possible due to the high-pressure phase transformation (HPPT) occurring in the material caused by the high compressive and shear stresses induced by the single point diamond tool tip [13–19]. To further augment the ductile response of these materials, traditional SPDT is coupled with the micro laser assisted machining (μ-LAM) technique [1,2,20–22]. Previous feasibility tests have successfully demonstrated the use of IR fiber laser and green laser [22] to preferentially heat and soften the high pressure metallic phase of silicon during scratching, which is the essence of the μ-LAM system. A schematic of the working process is shown in Fig. 1. As seen in Fig. 1, a laser beam is transmitted through an optically transparent diamond (cutting tool) and focused precisely at the tool-workpiece interface, where the material is under high pressures induced by the diamond tool. Under high compressive stresses, a HPPT occurs. The HPPT zone then absorbs the laser radiation to soften the material which leads to lower cutting forces.

In the present research, the effect of μ-LAM on the surface roughness and material removal rate of single crystal silicon has been studied. Previous studies of this group were on semiconduc-

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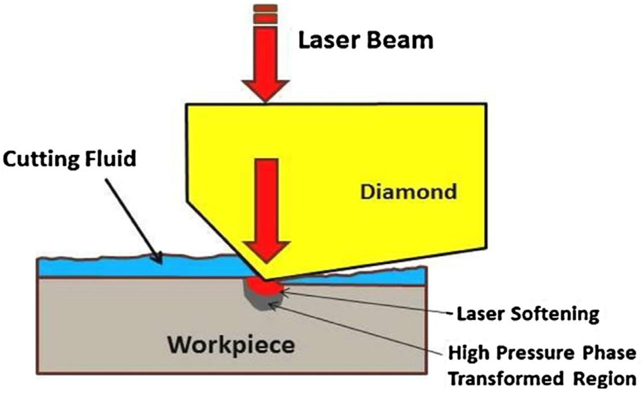

Fig. 1. Schematic of the μ-LAM process with cutting fluid.

tor grade silicon (100) wafers [21–24], while in the current work optical grade silicon (111) is under focus.

2. Experimental

Single crystal optical grade silicon (111) with a diameter of 28.1 mm was selected to be machined in this experimental study. A 1 mm nose radius single crystal diamond cutting tool was used for this set of experiments. An IR CW diode laser ($\lambda = 1070$ nm and $P_{\max} = 100$ W) with a Gaussian beam profile and minimum diameter of approximately 10 μm is used. The laser beam is guided through a single mode fiber optic cable to a collimator, which is attached to a Beam Delivery Optics (BDO) unit. The BDO then converges the beam and delivers it through the diamond cutting tool as Fig. 2. Other function of the BDO is aligning the beam by moving the tool in a plane perpendicular to the beam axis.

A Moore Nanotech 350FG diamond turning machine was used for the experiments. A tool post compatible with the BDO was attached to the diamond turning machine to perform the laser assisted machining experiments. Even though the resulting tool wear with the laser (μ-LAM technique) is significantly lower than with no laser, odorless mineral spirit (OMS) as cutting fluid is added to further minimize the tool wear and to assist with flushing the machined chips away. The experimental setup used for machining silicon sample is shown in Fig. 2. The μ-LAM process does not have limitations that other processes and techniques utilizing thermally soften by preheating the material or shining the laser in front of the tool have. For those processes, use of cutting fluid interrupts the laser beam path and cools down the workpiece, however in μ-LAM, the laser is shining through the diamond tool and only softens a region of the material in contact with the tool. A combination of mechanical machining and laser softening and at same time using the cutting fluid is one of the unique advantages of this process. There are many parameters to evaluate including machining parameters (speed, feed, depth, cutting fluid), optical parameters (laser power, wavelength, and beam size), cutting tool type (single crystal, polycrystals, nanocrystalline amorphous) and etc. However machining parameters used in this test are summarized in Table 1.

Table 1
Machining parameters.

Machining parameters	Values
Spindle rotational speed	2000 RPM
Laser power[a]	0, 20 W, 30 W
Roughing feed rate	4 μm/rev
Roughing depth of cut	10 μm
Finishing feed rate	1 μm/rev
Finishing depth of cut	5 μm

[a] Actual output at the tool tip is about 40% due to scattering, reflection and etc.

3. Results and experimental data

Ductile mode μ-LAM (coupled with SPDT) was carried out on unpolished side of the single crystal silicon (111) with a starting surface roughness of ~770 nm (Ra). The surface roughness of each region was measured after machining using a white light interferometric profilometer. The machined surfaces are also observed by an optical microscope to find any signs of brittle mode or imperfection. Achieving a high quality surface finish is very challenging and therefore machining parameters should be selected carefully. Adding the laser as a new parameter increases the level of complexity in the optimization process.

A roughing pass is done to flatten the sample, primarily to avoid an interrupted cut for the finishing pass. The roughing pass was carried out with and without the laser to study the effects on improving surface roughness. The cuts were programmed at a 10 μm depth of cut, along with a 4 μm/rev cross feed. The roughing pass without the laser had a surface roughness of 80 nm Ra compared to a 16 nm Ra with optimal laser power (see Fig. 3). At the 4 μm/rev feed rate, there is a possibility for 'pull outs' in the sample, but due to the laser heating effect, pull outs have been significantly reduced resulting in a better surface quality. In fact laser heating decreases the brittleness of the material and avoids brittle fracture of material in the machining region. An optical microscopic image of the unmachined silicon surface at 400× is shown in Fig. 4a. Fig. 4b also shows the sur-

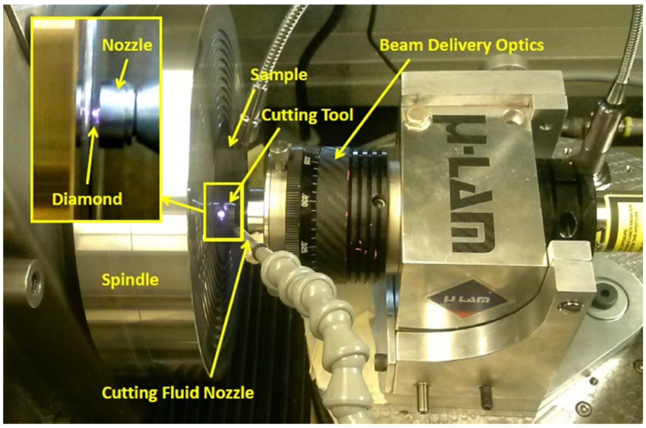

Fig. 2. μ-LAM setup mounted on a diamond turning machine.

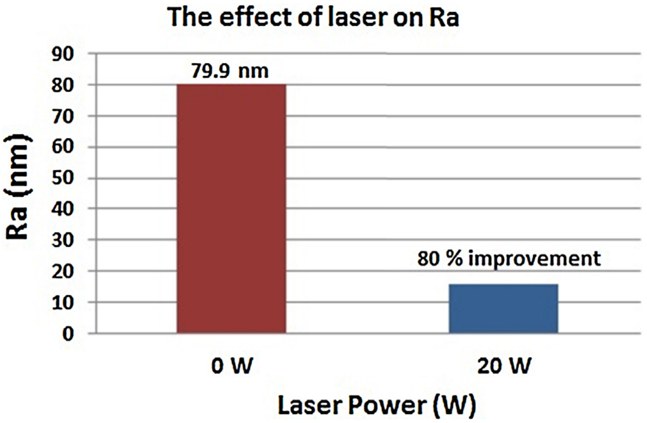

Fig. 3. Effect of laser power on surface finish for the roughing pass.