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3D characterisation of tool wear whilst diamond turning silicon

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Abstract

Nanometrically smooth infrared silicon optics can be manufactured by the diamond turning process. Due to its relatively low density, silicon is an ideal optical material for weight sensitive infrared (IR) applications. However, rapid diamond tool edge degradation and the effect on the achieved surface have prevented significant exploitation. With the aim of developing a process model to optimise the diamond turning of silicon optics, a series of experimental trials were devised using two ultra-precision diamond turning machines. Single crystal silicon specimens (1 1 1) were repeatedly machined using diamond tools of the same specification until the onset of surface brittle fracture. Two cutting fluids were tested. The cutting forces were monitored and the wear morphology of the tool edge was studied by scanning electron microscopy (SEM).

The most significant result showed the performance of one particular tool was consistently superior when compared with other diamond tools of the same specification. This remarkable tool performance resulted in doubling the cutting distance exhibited by the other diamond tools. Another significant result was associated with coolant type. In all cases, tool life was prolonged by as much as 300% by using a specific fluid type.

Further testing led to the development of a novel method for assessing the progression of diamond tool wear. In this technique, the diamond tools gradual recession profile is measured by performing a series of plunging cuts. Tool shape changes used in conjunction with flank wear SEM measurements enable the calculation of the volumetric tool wear rate.

Keywords: IR optics; Diamond turning; Diamond tool wear; Tool life; Silicon optics

1. Introduction

Nanometrically smooth infrared silicon optics can be manufactured by the diamond turning process [1,2]. Due to its relatively low mass density, single crystal silicon is an ideal optical material for weight sensitive infrared (IR) applications. An additional benefit of silicon is its low cost when compared to other IR optic materials. Other optical applications in which diamond-turned ultra-smooth silicon surfaces exhibit great potential are X-ray optics, X-ray interferometers and MEMS components [3,4].

During manufacture, material removal at the new surface ideally occurs in the ductile regime [5]. For the silicon substrate to be plastically deformed at the cutting plane, the use of an extremely stiff and smooth ultra-precision machine is required. This demand is needed in order to ensure the small scale of deformation required for plasticity is maintained during machining.

In practice, diamond tools degrade whilst machining silicon resulting in a rapid transition from the ductile to the brittle fracture cutting regime. This degradation causes poor quality surfaces and often extensive subsurface damage. As a consequence, IR silicon optics technologies have not been fully exploited to date.

Despite recent contributions [6,7], understanding of the mechanisms causing tool edge degradation is still poorly understood and cannot be accurately predicted. Therefore, adequate characterisation of tool-wear behaviour, and the identification of the significant factors, is crucial to retard tool wear and consequently prolong the useful life of the tool.

Currently, diamond tool wear is typically characterized by measuring the tool's flank wear land (VB) and/or the tool-tip profile recession using direct and indirect measuring methods. Direct methods consist of measuring the diamond tool flank wear

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Table 1
Typical physical properties of fluids ‘A’ and ‘B’

Physical property	Fluid type A	Fluid type B
Specific heat at 20 °C (kJ/kg K)	4.18	1.86
Density at 20 °C (g/cm^3)	0.998	0.803
Kinematic viscosity at 40 °C (mm^2/s)	0.658	1.49

after cutting for predetermined lengths. This assessment is performed using microscopy techniques such as scanning electron microscopy [8,9]. Indirect methods often consist of imprinting the tool profile onto a ‘softer’ more malleable material by a plunge cut or an indentation. Subsequently these are measured using microscopy techniques or profilometry [10,11]. A more robust and practical characterisation method would be an advantage to aid tool wear progression understanding.

This paper presents the results of a series of meticulously designed and performed diamond turning experiments. The influence of the type of cutting fluid and the tools top rake angle on tool life has been investigated. This work has also developed a new technique to characterise diamond tool wear whilst single point diamond turning.

2. Experimental

2.1. Experimental procedures

Two experiments were devised with the aim of developing a process model to optimise the diamond turning of silicon optics.

Experiment 1 was designed to investigate the effect of coolant type on the diamond tool life. The application of coolant has been shown to have a significant effect on the life of diamond tools compared with dry cutting, yielding longer cutting distances [6]. Two different coolants were tested, fluids ‘A’ and ‘B’. Fluid ‘A’ is a water-based machining coolant, whereas fluid ‘B’ is an oil-based coolant commonly used in diamond turning. Some important physical properties of fluids A and B are shown in Table 1. Both coolants were applied using an evaporative spray mist system. The test specimens were single crystal silicon with a crystal orientation (1 1 1), a diameter of 50 mm and a thickness of 5 mm. Four *Contour Fine Tooling* diamond tools of identical specification, 0.5 mm tool nose radius, −25° top rake angle and 10° clearance were used for all the machining trials in Experiment 1.

The machining parameters employed are shown in Table 2. These parameters were established in previous experimentation [12], and ensure adequate conditions for the machining of optical-quality silicon surfaces.

Table 2
Machining parameters used

Machining parameters	
Cutting speed (rpm)	600
Depth of cut (μm)	10
Feed rate (μm/rev)	1

Table 3
Diamond tool-coolant type arrangement for Experiment 1

Tool #	Coolant type
1	B
2	B
3	A
4	A

The cutting operations in Experiment 1 consisted of performing repetitive 10 μm deep facing cuts using one of the two coolant types until brittle fracture was observed on the surface of the specimen. A duplicate specimen was machined to establish the experiment’s repeatability. The diamond tool-coolant type arrangement used in Experiment 1 is shown in Table 3.

The experimental response was measured in terms of cutting distance (km) before the onset of brittle fracture. Cutting forces were monitored for each of the cutting iterations. SEM was used to study the morphology of tool edge wear at the end of each test. Prior to machining, a 1 mm diameter recess was removed from the centre of all specimens to avoid machining where the cutting speed approached zero. With the conditions described in Table 2, the cutting distance reached at the end of each cut was approximately 1.81 km.

Experiment 2 was designed to study progressive tool wear, as well as investigating the effect of the tool top rake angle on the life of the diamond tool. The specimens were single crystal silicon specimens with crystal orientation (1 1 1) of 100 mm diameter and 5 mm thickness. Three *Contour Fine Tooling* diamond tools having top rake angles of −15, −25 and −45° with a 0.5 mm tool nose radius and 10° clearance were used. The results observed in Experiment 1 were incorporated into Experiment 2 by using the coolant type that yielded the longer cutting distance.

In Experiment 2, the cutting operations consisted of performing a series of plunge and facing cuts, until the onset of brittle fracture. Tool plunges were carefully performed to a depth of 20 μm at a 0.2 μm/rev in-feed rate, in a central ‘reserved’ area of the specimens. An initial plunge produced an imprint of the ‘fresh’ diamond tool edge prior to cutting. Subsequent tool plunges were performed after each facing operation. Facing operations were performed using the cutting parameters described in Table 2. After the initial facing operation, the traverse distance was reduced by 1 mm, proportionally reducing the cutting distance. This series of tool plunges and facing cuts resulted in a concentric tool imprint pattern, as well as a ‘stepped’ profile from the facing operations, see Fig. 1. The sequence of plunge-traverse cutting continued until the brittle fracture was visually observed on the face machined surface of the specimen.

The experimental response was measured in terms of cutting distance (km). Cutting forces were also monitored. Surface finish assessment was performed on the cut surface using a Wyko-Topo 3D phase shift interferometer.

Tool wear was examined directly on the diamond tools using a FEI XL30 environmental scanning electron microscope (ESEM) by measuring the tool flank wear land (VB) after each plunge cut.