Precision Engineering 34 (2010) 253–258

Contents lists available at ScienceDirect

Precision Engineering

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

Detection of orientation-dependent, single-crystal diamond tool edge wear using cutting force sensors, while spin-turning silicon

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ARTICLE INFO

Article history:
Received 26 February 2009
Received in revised form 21 May 2009
Accepted 15 June 2009
Available online 24 June 2009

Keywords:
Diamond turning
Spin-turning
Silicon

ABSTRACT

This paper shows results of an effort to turn brittle materials using a round insert that can be rotated to present a fresh edge to the cutting zone. The rotating cutting tool was originally proposed by Shaw to maintain edge sharpness during heavy lathe turning operations. His approach is applied here, with design enhancements, to precision diamond turning. This work seeks to experimentally determine the benefits of spin-turning infrared materials known to cause rapid wear of single-crystal, synthetic diamond cutting tools. The results explore the specific issues of maintaining satisfactory surface finish over anisotropic workpieces such as single-crystal silicon. This is demonstrated using a stiff and accurate spindle-based tool holder that is instrumented to provide feedback while cutting.

1. Introduction

Precision diamond turning of infrared crystals such as silicon can reliably achieve specular surface finish while maintaining minimal sub-surface damage when the proper equipment is used with effective diamond tooling. This is achieved by machining under conditions of small chip thickness dictated by the ductile regime machining model [1,2]. However, it may be possible to remove material faster and with improved surface finish if compression-strain heating and high pressure phase transformation phenomena are recognized and designed into the machining process [3–5].

Silicon's high pressure phase transformation under loading has been shown in a number of nanoindenting, scribing, and cutting experiments [6–10]. Raman spectroscopy has also been used to demonstrate the occurrence of a high pressure phase transformation in which silicon's atomic structure changes from diamond face centered cubic to other, metallic-like phases including β-tin [11]. Yan et al. have shown that upon release of the compressive stress of a cutting tool the silicon returns to an amorphous state with more favorable microplasticity [12].

When we seek to reconcile these laboratory experiments with the mass manufacture of infrared optics three significant obstacles remain. First, it is well known that single-point diamond-turned surfaces often show three- (1 1 1) or four-fold (1 0 0) regions (sectors) of distressed crystal. Furthermore, the surface finish often degrades towards the center of the optic, where the cutting velocity is lowest. Finally, silicon causes relatively fast deterioration of diamond cutting tools by both chemical wear and graphitization [13].

It would seem that the three- or four-fold sectors of distressed crystal are indicative of material removal by brittle-fracture interspersed with ductile machining on the octahedral (1 1 1) and cubic (1 0 0) crystal planes, respectively. Harder crystals and harder machining directions on those planes require more compression-strain-heating to complete phase transformation in those distressed crystal sectors [14].

We suggest that the phase transformation generated in a turning process is a function of the material removal rate (MRR), set by the turning parameters of cutting velocity, feed rate and depth of cut; tool rake angle; and the crystal's material properties. Higher MRR and negative rake angles generate more energy in the uncut chip region for phase transformation to occur. As the center of the optic is approached the MRR goes to zero, ductile machining tends to give way to brittle-fracture and surface finish degrades, leading to the familiar visible spoked patterns.

The challenge is that increased MRR and negative rakes, which enable the desirable phase transformation, also cause the tool edge to get hotter and therefore wear faster as a result of the fcc (diamond) carbon oxidizing and graphitizing. The rates of these chemical reactions rise exponentially with the temperature of uncut chip region and turning conditions. Flood cooling is recommended, and water, with ten times the heat carrying capacity, may be preferred over oil.

The rotating tool concept, first proposed by Shaw in 1952 and later taken up by several others, is revisited in this work to make use of the phase transformation in the uncut chip region while avoiding

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doi:10.1016/j.precisioneng.2009.06.004

the rapid degradation of the diamond tool by constantly providing a fresh cutting edge [15–17]. The demand for precision in infrared optics require that Shaw's original concept be enhanced with provisions for near perfect cutting tool roundness and centering on a stiff, accurate axis of rotation.

2. Spin turning with diamond cutting tools

Fig. 1 shows the hardware used in our testing of precision spin turning with diamond tools. The tilted-axis configuration works well to establish the negative tool rakes necessary for turning brittle materials. The silicon workpiece rotates within the usual range of cutting speeds, as dictated by size, material, and workpiece geometry. The circular cutting tool rotates at a much lower speed, or may even remain stationary with intermittent angular indices.

The workpiece form error is controlled by a number of error sources in diamond turning, including machine accuracy, spindle accuracy, and the tool-to-workpiece loop stiffness. For non-plano workpieces, the tool location and geometry are also important, even in conventional diamond turning. The spin-turning approach requires consideration of all these issues as well as the error motion and stiffness of the spin-turning spindle. These obstacles led to Ezugwu's comments summarizing the challenge of cutting with rotary tools [18]:

- likelihood of errors in profile
- likelihood of chatter due to large tool radius and compromised stiffness
- difficulty of producing small-radius features.

Although spin turning is not likely to match the accuracy of turning with stationary tools, the mitigation of accelerated wear in workpiece materials such as silicon may justify its use in some applications. Furthermore, the impact of several error sources is reduced by process design built around the principles of precision engineering. We have found that the cutting tool radius, which affects workpiece form error in both spin-turning and stationary-tool turning, may be controlled to 100 nm. Furthermore, the tool radius may be reduced to a size within the customary range of conventional diamond tooling by tilting the spin-turning spindle with respect to the workpiece (which has the side benefit of achieving the significant negative rake angles used in brittle materials).

Tool centration on the axis rotation is of considerable importance to obtain satisfactory results in spin-turning. The eccentricity of a round tool with respect to its axis of rotation could be corrected by CNC compensation given adequate inspection hardware. In our proposed approach, we instead use a system of interchangeable carbide pilots during both the manufacture of the tools and their installation on our diamond turning machine. The pilots are made of lapped carbide spheres and enable the tool maker and end user to exchange worn diamond tools as easily as a standard cutting insert. Piloted carbide tooling ensures that the spin-turning tool remains on axis within 200 nm.

The anisotropy of diamond can lead to profile error in the cutting edge of the tool that will affect the workpiece accuracy. This is an issue whenever non-plano shapes are turned and originates from the manufacture of the cutting tools themselves. Before the tools can be used to turn silicon, they must first be ground and polished to the desired shape. Unfortunately, diamond shows the same direction-dependent behavior as the silicon we seek to machine. This anisotropy can lead to out-of-roundness during the generation of the cutting edge at the 100 nm level. In the work shown here, the cutting tool edges are finished with a chemo-mechanical process that nearly eliminates this effect. We have made no attempt to compensate for any residual tool profile error because of the difficulty of adequately characterizing the error, although this has been successfully demonstrated by Thompson [19].

Finally, the error motion and compliance of the spin-turning spindle presents a challenge to maintaining workpiece form accuracy. This work shows results from cutting tests run with two different spin turning spindles. The first is an air bearing spindle (Professional Instruments 3R) with error motion of less than 25 nm in the sensitive direction. The error motion of this spindle is negligible compared to other workpiece error sources. In a second round of testing, a tapered roller bearing spindle (Professional Instruments 4RT) was used to achieve higher stiffness and load capacity, but with 330 nm of error motion in the sensitive direction, as shown in Fig. 2. If necessary, the tapered roller bearing spindle's error, which is repeatable and mappable provided that the spindle's angular position is known, may be removed by compensation.

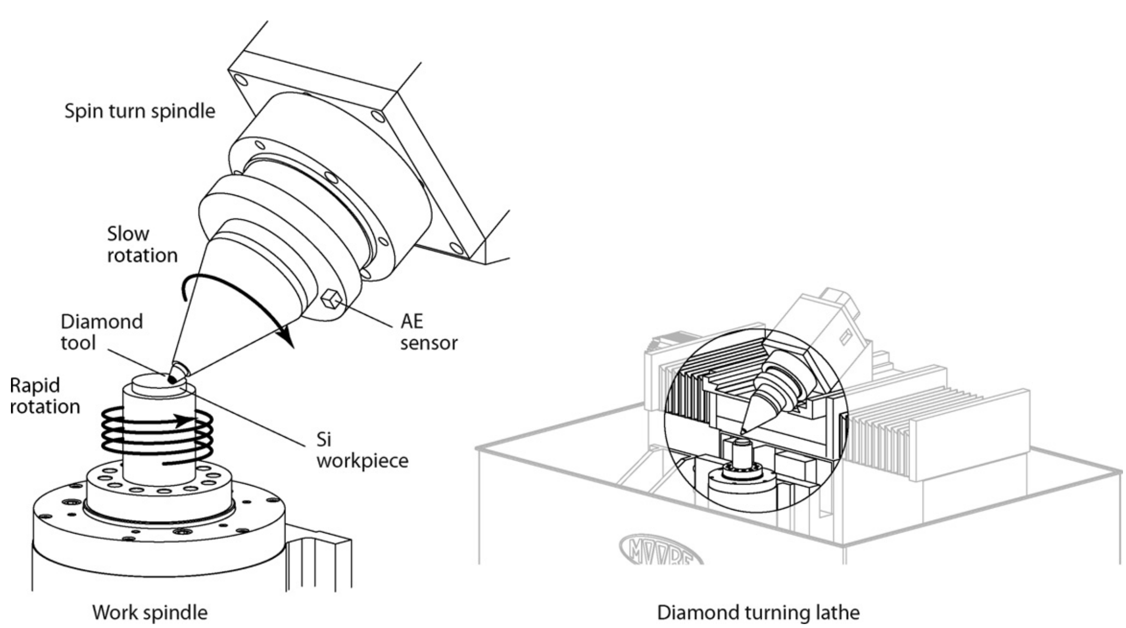

Fig. 1. Machine configuration for spin-turning silicon optics. The tool spindle is tilted with respect to the work spindle for an effective rake angle of -45°.