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A Machining Parameter Study to Select Best Conditions for SPDT of Large Single-Crystal Silicon Optics

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Abstract

The interdependence of process parameters on diamond turning of single-crystal silicon is poorly understood. An experimental design technique based on methods of statistical analysis permits the determination of a specific parameter's influence and its co-dependence on other factors. This design technique enables the creation of an experimental matrix, considering all input parameters (surface velocity; feed rate; depth of cut; tool radius; tool rake/skew angle; cutting fluid), while substantially decreasing the overall number of experiments. After an initial survey the significant parameters for a subsequent response surface methodology (RSM) study can be selected. From measurements of tool wear, surface finish and sub-surface damage (SSD) the optimum parameter settings for the diamond turning process can then be determined.

Introduction

Contemporary high-power applications of infrared and x-ray and optics place high demands on any fabrication process. Silicon, a primary candidate for infrared optics is an anisotropic, brittle and hard-to-machine material. Diamond turning has the potential to generate products with precise forms; however, tool wear can be significant, especially for large parts. The result is profiling errors, poor surface finish and extensive SSD. These factors can be controlled to some degree by an appropriate choice of cutting fluid. Unfortunately, in a controlled environment, the selection of a fluid becomes difficult since aqueous and other liquids with high vapor pressure endanger thermal stability. An initial literature search on the single point diamond turning (SPDT) of silicon was undertaken to assess the influence of various machining parameters on the process and to choose initial starting conditions. A number of prior researchers have determined the effect of machining parameters on the ductile to brittle transition in silicon and the corresponding effect on surface finish and SSD. The majority of investigations have concentrated on the production of smooth surfaces with little thought to tool wear and related track length, SSD and the effect of coolants. In this work, we have attempted to determine the importance of process conditions on tool wear and the nature and extent of SSD for large SPDT silicon optics. Surface quality was determined from optical and atomic force microscope (AFM) images. Transmission electron microscopy (TEM) was used to assess SSD.

Experimental Procedure

Diamond machining was performed on the DTM II and Phoenix machines at Lawrence Livermore National Laboratory (LLNL). All silicon samples were taken from a single cylindrical boule with a diameter of 150mm and a nominal length of

300mm. (Supplied by TRW). Several 6.35mm thick wafers, perpendicular to the (100) orientation were taken from the boule. From these wafers, witness samples, 25.4 mm in diameter, were cut to have orientations perpendicular to [100] and [110] axis. All subsequent analysis was performed on these samples. Since the witness samples are limited in size, tool wear, representative of a long track length machining process, was generated using the remaining 250 mm section of the boule. Long track length preconditioning of the tool employed the same experimental parameters as the subsequent witness sample study. The boule and witness samples were prepared identically with a number of ductile regime semi-finish cuts creating a constant depth of SSD in preparation for each experiment. Single-crystal diamond tools used in the study were sharpened before each use. To measure tool wear, each nose radius was measured before and after the experiment. Acoustic emission (AE) was monitored in process and cutting forces were measured with a Kistler 3-component load cell. The temperature of the cutting fluid was controlled during all experiments (air: $20^0C \pm 0.5^0C$; cutting fluid: $20^0C \pm 0.1^0C$).

Analysis
Atomic force microscopy (AFM) and white light interferometry (WYKO) were used to determine surface quality. Sub-surface damage was assessed with transmission electron microscopy (TEM).

Experimental Design Technique
After the selection of seven process parameters, a methodology is used to select the experiments. A computer assisted experimental design is preferred to an in-process approach or to a full factorial design. The in-process changes one variable at a time, often missing the optimum setting. The full factorial design contains the complete matrix of every possible experiment and would result in an unreasonable number of tests. In general, experimental design is a systematic method of selecting experiments and analyzing results to determine optimal parameter settings from a limited set of experiments. In this manner, more information about the process can be extracted from fewer experiments. With appropriate experimental design the data can be analyzed using statistical tools; conversely, data from the in-process approach cannot be easily analyzed. An experimental technique known as D-optimal design was used to select the optimum set of experiments. This technique maximizes the determinant of the matrix that is inverted during the model fitting procedure, thus reducing the variance of the estimated model coefficients. D-optimal design requires the use of an a priori model. During the selection of the first set of experiments, we chose a simple linear model. However, once the data were analyzed, we were able to use a multiplicative model by raising each parameter to a power. This new model reflects previous work on conventional cutting.

Empirical Survey Study
In order to choose the final parameter set, an initial survey study was undertaken. Using D-optimal design and the a priori model, the optimum 14 experiments for the initial survey study were selected. Where possible, these experiments were conducted in a random order minimizing dependent effects on the primary factors (Table 1).

Symbol	Parameter	Range of Values
V	surface velocity [m/s]	0.51; 3.81
FR	feed rate [μm/rev]	1.27; 3.05
DOC	depth of cut [μm]	1.27; 5.08
RAD	tool nose radius [mm]	0.76; 1.52
RAKE	negative rake angle [deg]	0; 40
SKEW	tool skew angle [deg]	0; 40
F	cutting fluid	1; 2; 3

Table 1: survey study - parameter

The cutting fluid numbers correspond to pure polyalkalene glycol (PAG), (1), a solution of PAG and water (2), and a solution of PAG, water and tri-potassium phosphate (3). A tool analysis after each experiment shows that tool wear is uniform with no detectable cracking. The analysis of initial data will be discussed in the final paper.

Statistical Analysis

To determine significance of each parameter, statistics such as the Mallow's Cp-statistic and the adjusted R^2 statistic are used. The influence of each parameter on tool wear, surface finish and sub-surface damage is determined. The purpose of the model is to determine the influence of the parameters rather than to predict the outcome at specific parameter settings; therefore, the model cannot be used to either interpolate between or extrapolate outside of the parameter ranges tested. Since each parameter only had two settings, it is not possible to predict the outcome between the extremes or outside of the extremes.

Supplemental Experimentation

After a complete analysis of the experiment data, a supplemental set of experiments was designed with help of the same statistical tools used in defining the survey study matrix. However, we used the multiplicative model rather than the original linear model to select the optimum experiments; permitting the study of higher order effects. The range of parameter values used in this set is either extended above previous maximum values (RAD; RAKE) or is placed in between the old range (V) (Table 2). This second set of experiments consists of 6 new parameter combinations and two previous experiments from the first set. The repeat experiments are used to demonstrate consistency between the original and the supplemental experiments.

Symbol	Parameter	Range of Values
V	surface velocity [m/s]	0.51; 3.05
FR	feed rate [μm/rev]	1.27; 6.35
DOC	depth of cut [μm]	1.02; 5.08
RAD	tool nose radius [mm]	1.52; 5.08
RAKE	negative rake angle [deg]	0; 60
F	cutting fluid	PAG

Table 2: RSM study - parameter

Supplemental Statistical Analysis

Statistical tools and engineering judgement are used again to find the influence of each parameter. Results for tool wear, sub-surface damage ([100] and [110] orientation) and surface finish ([110] orientation) fit the predicted models. Strong pitting in [100] direction caused difficulty in interpreting surface roughness data. The pitting is likely a result of a different material removal mechanism occurring under those particular machining conditions. Unfortunately, this prevents the use a simple model and complicated data analysis. Nevertheless, we can determine the influence of the machining parameters on [110] silicon with present surface finish data. The effect on tool wear can be summarized as follows: To keep tool wear to a minimum, maximize velocity and feed rate while minimizing depth of cut with a -30^{o} tool rake. For best surface finish (minimum roughness), maximize velocity and depth of cut while increasing tool rake to -60^{o}. It is important to remember that these conclusions are only valid with in the experimental space defined by the survey experiments.

Conclusions

The experimental design technique is a useful method to show how machining parameters influence the SPDT process of silicon within a well-defined range. The optimum settings for the seven parameters can be determined after 20 experiments. A discussion of the errors in the technique will be presented in the data.

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