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Effect of cutting speed in single point diamond turning of (100)Ge

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Abstract

In this study the mechanical response of single crystal Ge machined over a range of cutting speeds of two orders of magnitude was investigated. Single crystal (100)Ge was machined by on-axis turning with a single crystal diamond tool. Surface topography was characterized by atomic force microscopy, and cutting and thrust forces were measured. It was found that increasing the cutting speed decreases the amount of brittle fracture left on the surface by the tool. It was also found that both the cutting and thrust forces decreased in magnitude as the cutting speed increased.

Keywords: Crystal structure, Deformation and fracture, Semiconductors, Surfaces

1. Introduction

The state of current understanding in the ultra-precision machining of brittle single crystal materials is that these materials can be successfully machined when using negative rake angle single crystal diamond tools at low depths of cut and low feedrates (i.e., low loads). It has been widely observed that in this regime, shear induced plasticity governs material removal as evidenced by the presence of remnant dislocations below the machined surface. This is the so-called “ductile regime” machining of brittle materials. As loads are increased the material removal process is seen to transition to a regime dominated by micro-fracture which produces a heavily pitted surface [1]. Our previous work on single crystal Ge [2] indicated that feedrate has a significant effect on the governing cutting mechanisms, similar to indentation depth in nanoindentation, and showed that for a given rake angle, damage increases with feedrate. Similar to increasing the material load due to increased feedrate, increasing cutting speed beyond the micro-fracture dominated regime has not been seen as a viable method to increasing productivity while maintaining a fracture free surface. However, to date, the effect of cutting speed on material behavior in single point diamond machining of brittle single crystal semiconductors such as Si or Ge has not been reported. In this study the effect of cutting speed over a range of two orders of magnitude in the single point diamond turning of (100)Ge was investigated in terms of the resulting surface topographies and cutting and thrust forces.

2. Materials and methods

A single crystal Ge specimen with a (100) surface orientation was machined using a Moore Nanotechnology 650FG-V2 in the configuration shown in Figs. 1a and 1b. A single crystal diamond tool with a 1 mm nose radius (R), a -25° rake angle (α) and a 10° clearance angle (γ), as shown in Figs. 1c and 1d, was used. A spray mist of mineral spirits and air was used for chip removal during cutting. Figure 1c. shows a top view of the cutting geometry. The cutting parameters were the axial depth of cut, a_p, the spindle speed, n, and the feed velocity, v_f. The key geometric parameters for the cutting operation were a_p and the feed per spindle revolution (feedrate), f_r. To guide the choice for depth of cut and feedrate to be used in the present study, results from our previous work [2] were employed. The study found that for given values of α and R, and a depth of cut in the range of 5-25 µm, a value of f_r = 0.3 µm/rev generated a surface with minimal surface or subsurface damage that was comparable to surfaces generated by chemomechanical polishing. When f_r was greater than 4 µm/rev extensive surface and subsurface damage was observed [2].

To examine the effect of v_c, the surface was first prepared by cutting successively with a_p = 5 µm and f_r = 0.3 µm/rev to remove any specimen tilt with respect to the spindle axis, and to minimize subsurface damage. For the cutting experiments, a_p and f_r were increased to 20 µm and 4 µm/rev respectively and held constant while four bands with a width of 5 mm were generated on the (100) surface of the specimen at an average cutting speed of 20 m/s, 10 m/s, 1.75 m/s, and 0.25 m/s. This was done by adjusting n in each band so that $v_c = rn$ was equal to the specified values in the center of each band. With a 50 mm diameter workpiece and 5 mm bands, the speed range in the outer band was 22.2 m/s to 17.8 m/s and in the inner band 0.33 m/s to 0.17 m/s so that the variation in speed in each band was small compared to the change in mean speed in the individual bands.

Force components F_c (cutting force), F_t (thrust force), and F_f (feed force) were measured with a three-component Kistler 9256C1 dynamometer with a loaded bandwidth of approximately 3 kHz. The data acquisition frequency was 10 kHz, more than three times the bandwidth, to avoid aliasing.

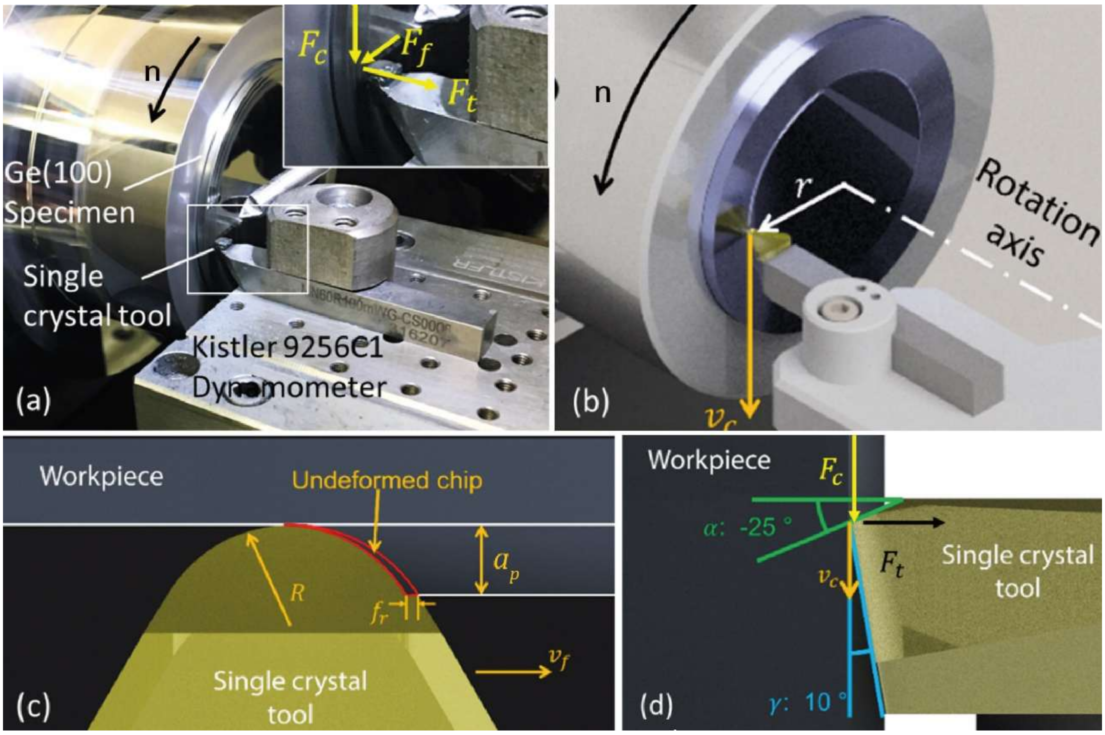

Figure 1: Single point diamond turning configuration indicating (a) the specimen, tool, dynamometer, and force components, (b) the relation between v_c, r and n, (c) the geometric cutting parameters, and (d) the rake angle, clearance angle, cutting speed v_c, cutting force F_c and thrust force F_t.

The surface topography of the bands was characterized by atomic force microscopy (AFM) using a commercial atomic force microscope in tapping-mode.

3. Results and discussion

On-axis single point diamond turning generated a surface that had different topographies depending on the relative cutting direction to the crystallographic orientation. This effect is well known for on-axis machining of single crystal materials and is consistent with the work of Nakasuji [3] and others. Figure 2a shows a photograph of the (100)Ge surface after on-axis diamond turning with the four cutting speeds that generated four bands. The variations in surface topography resulted in radial regions with similar topographies, referred to here as lobes. The schematic of Fig. 2b, shows how the lobes were radially distributed. Three distinct lobes were visible on the surface, referred to as the primary, secondary and tertiary lobe. The primary lobe (red) had a hazy appearance, the secondary lobe (yellow) had a hazy appearance for bands cut with speeds of 0.25 m/s and 1.75 m/s, and the tertiary lobe (green) had a specular appearance. The location of the lobes on the surface followed the four-fold symmetry of the diamond-cubic lattice on the (100) plane. The appearance of the lobes was affected by the cutting speed. As the speed increased, the secondary and tertiary lobes became indistinguishable. The primary lobe also became less apparent when the cutting speed was 20 m/s.

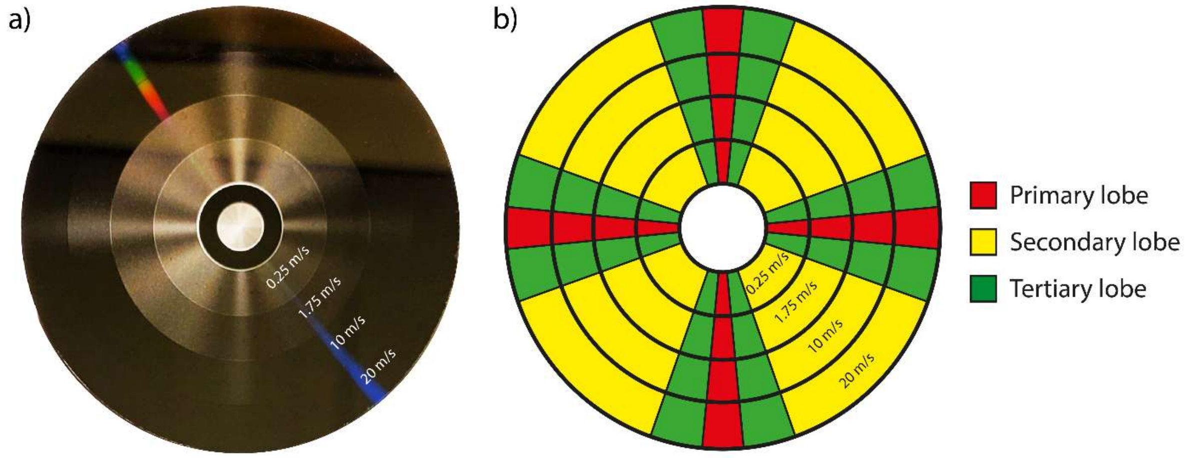

Figure 2: (a) Photograph of the (100)Ge specimen after on-axis diamond turning with different cutting speeds and (b) the schematic of the lobes with respect to the in-plane crystallographic orientations. Red, yellow and green indicate the primary, secondary and tertiary lobe respectively.

The topography was obtained over 40x40 μm^2 regions using AFM, as shown in Fig. 3. The measurements were performed at the center radius of each band and in the middle of the lobe. Tool marks can be seen on the surface, with a period of 4 μm and indicate the orientation of the areal scan relative to the cutting direction. The amount of brittle surface fracture varied between lobes and with cutting speed. The primary lobe exhibited the most brittle fracture that was seen to decrease with increase in cutting speed. The secondary lobe had less fracture on the surface when cut at 0.25 m/s when compared with the primary lobe. The amount of fracture diminished at 1.75 m/s and disappeared when the cutting speed was 10 m/s or higher. On the tertiary lobe, smaller amounts of fracture were present on the surface at the lowest speed, and similarly to the secondary lobe, fracture disappeared when the speed was equal to or greater than 10 m/s. Crystallographic features of the fractured regions were difficult to discern. The largest pits measured had a width of approximately 6 μm and a depth of approximately 0.5 μm. Most of the pits were smaller in size. The observation of the reduction or elimination of surface fracture with increased cutting speed was an unexpected result. A plausible explanation for this observation could be possible changes in the material response that could include an increased stress state due to inertia effects, material strain rate effects resulting in thermal softening or phase transformation. Ge is known to undergo a phase transformation from its diamond-cubic structure to a β-Sn structure at a hydrostatic stress of 10.5 GPa. When shear stresses are present the transformation pressure can be as low as 6.7 GPa [4]. Finite element modeling studies have predicted a region of phase transformation when single point diamond machining (111)Ge [5], although no direct experimental evidence that a phase transformation occurs in single point diamond machining of Ge has been reported.

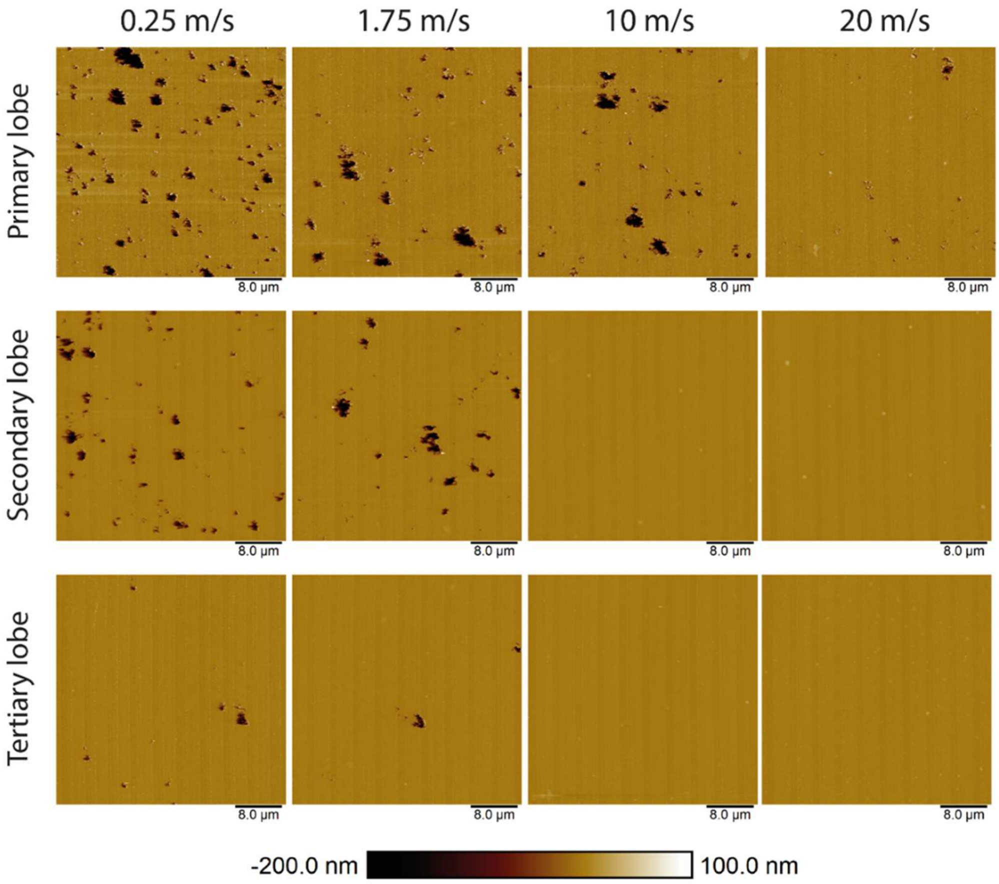

Figure 3: 40x40 µm^2 AFM measurements performed on the machined specimen. The cutting direction in each scan is vertical.

Cutting and thrust forces were measured during machining. Figure 4 shows the data corresponding to a single revolution of the specimen with colors shown for each lobe based on the size of the sectors shown in Fig. 2b. The minimum force region was assigned to the primary lobe since our previous work indicated that the forces decrease at the onset of fracture [1]. The four-fold symmetry of (100)Ge can be seen with four peaks and four valleys for each revolution. The measured forces varied in magnitude in each band. The forces were calculated using the maximum of each oscillation for 30 revolutions. The maximum force decreased monotonically with the increase in cutting speed. Using the measured data, the resultant force acting at the tool-workpiece interface, viz. $\sqrt{F_C^2 + F_T^2}$ for the lowest cutting speed was found to be 0.54 N. Estimates of the stresses acting at the tool-workpiece interface based on this resultant force and an estimate of the tool-workpiece contact area are consistent with those under which a phase transformation in Ge could occur.

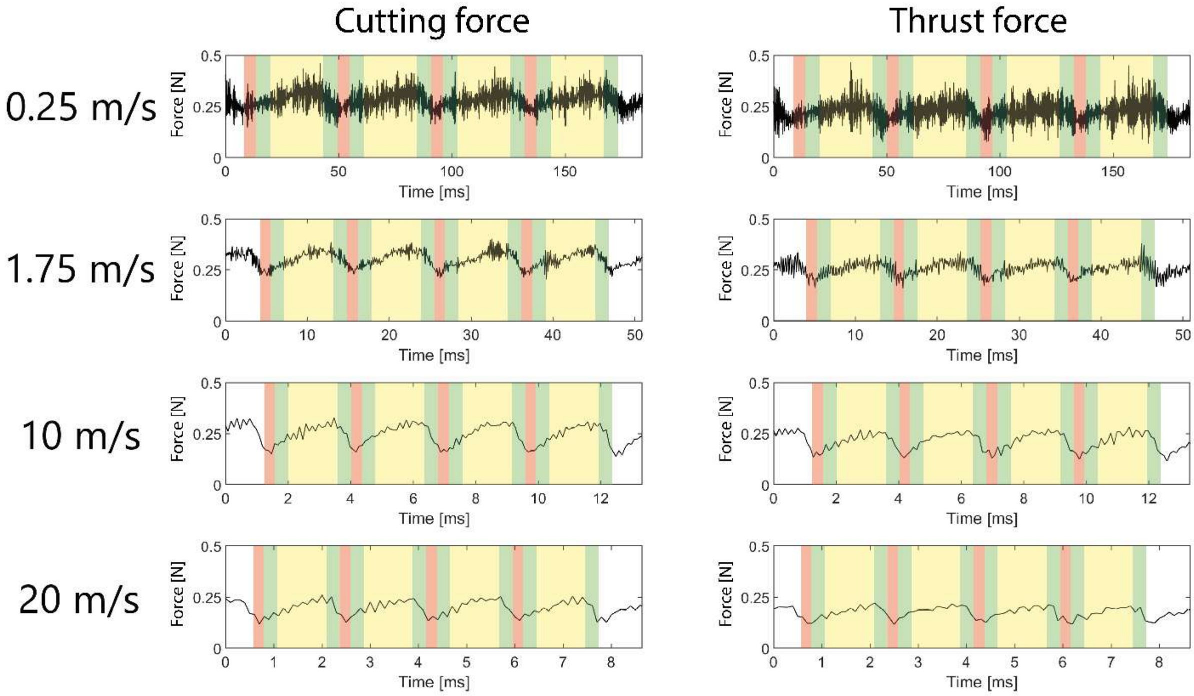

Figure 4: Cutting and thrust forces measured during machining. The plots represent a single complete revolution of the (100)Ge specimen exhibiting four-fold symmetry.

4. Conclusions

On-axis single point diamond turning of (100)Ge resulted in three distinct radial regions with similar surface topographies or lobes. The topography of these regions was seen to change with an increase in cutting speed. The unexpected result that an increase in cutting speed led to a reduction or elimination of surface fracture was observed. Both the cutting and thrust forces were also seen to decrease with increase in cutting speed. Both the reduction or elimination of fracture and the decrease in cutting and thrust forces point to a possible shift in material response as cutting speed is increased.

Acknowledgments

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