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Diamond Turning of Soft Semiconductors to Obtain Nanometric Mirror Surfaces

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Diamond cutting is a viable alternative to grinding and polishing in the fabrication of high-quality soft semiconductors. Investigation of indentation provides useful information for understanding the practical diamond cutting process of brittle materials. Cutting forces and temperatures were analysed using a Kistler dynamometer and an infrared technique. A zero rake angle cutting tool was found to be most efficient, partly because the effective rake is really a strong negative rake brought about by the peculiar configuration of very low feeds and depths of cut. This is explained by means of the comparison of the force distribution between conventional turning and ultraprecision machining. Atomic force microscopy and scanning electron microscopy were used to study the surfaces. Zinc sulfide gave subnanometric surfaces (0.88 m) and zinc selenide gave Ra values of 2.91 nm.

Keywords: Diamond turning; Nanometric surfaces; Soft semi-conductors

1. Introduction

Earlier work has demonstrated the possibility of achieving a 1 nm finish on a hard semiconductor such as silicon by the turning process [1] and cutting conditions were determined using a taper scratch test which indicated conditions for the fracture mode and for ductile mode conditions. Obtaining a nanometric surface on soft semiconductors is even more difficult and this paper explains the strategy used, namely nano-indentation. The attempt to machine brittle materials such as zinc selenide and zinc sulfide in the ductile mode is a challenge because of their fragility. However, the observation of the morphology of the materials removed provides relevant information on the ductility extension and chip formation mechanism during machining. This can be used as a machinability parameter since fragile materials are very difficult to analyse when submitted to single-point diamond turning. The possibility of cutting these two typical materials in order to achieve an extremely good surface has motivated this study.

This study aims to analyse the ductile extension of these two brittle materials when single-point diamond turned. This paper also reports how mirror finishes with nanometric values and spherical/aspheric surfaces with a form accuracy of less than 0.3 μm can be produced on the brittle materials. Lucca et al. [2] studied the effect of depth of cut. Tamaniau and Dautzenberg [3] formulated an Eq. showing the relationship of the tool edge radius with the effective rake angle. Others [4–10] have contributed to many factors associated with ultraprecision machining. With that background, this work provides an understanding of the production of nanometric surfaces.

2. Experimental Approach

Nano-indentation can provide a correlation between the depth of indentation and the applied load, and the Nanotest (Fig. 1) [11] measures the movement of a stylus in contact with a

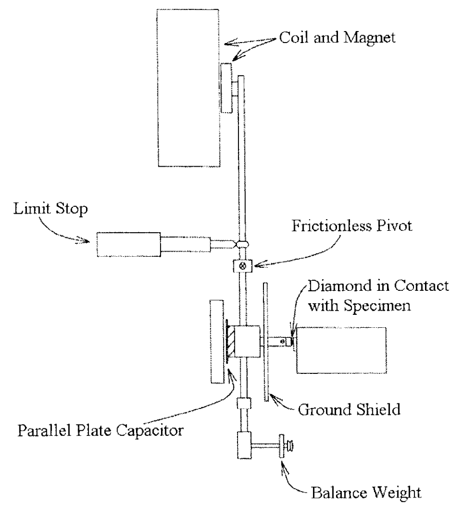

Fig. 1. Diagram of nano-indentation [11].

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surface. For some measurements, a varying load is applied and the stylus is impressed into the surface, whereas for others a load is applied, the substrate is moved, and variations in the topography or frictional force are indicated.

As shown in Fig. 1, the nano-indentation machine uses a pendulum pivoted on frictionless bearings. A coil is mounted at the top of the pendulum. With a coil current present, the coil is attracted towards a permanent magnet, producing motion of the diamond towards the specimen and into the specimen surface. The displacement of the diamond is measured by a parallel plate capacitor, one plate of which is attached to the diamond holder. When the diamond moves, the capacitance changes, and this change is measured by means of a capacitance bridge. The behaviour of materials was studied when indenters with different radius tips were impressed onto the surfaces. When a ductile material such as a metal is impressed with the indenter, plastic deformation is induced and cracks are not propagated, regardless of the size of the indenter.

In contrast, in the case of indentation of a brittle material, initiation and propagation of lateral cracks are considered to contribute greatly to material removal in the diamond cutting process. A sequence of subsequent crack propagations in zinc sulfide is shown in Fig. 2. The sharp point of the indenter with an edge radius of about 1.2 μm produces a deformation zone. At some threshold, a deformation-induced flow suddenly develops into a small crack. Subsequently, an increase in the load causes a further steady growth of the cracks. During the experimental study, only lateral cracks have been found. This is confirmed by the smooth diagonal curve of indentation, as shown in Fig. 3.

A slight amount of elasticity is present but the bulk of the material has undergone plastic deformation (ductility). The results show that at a load of 125 mN, no cracks occurred, and hence this would be a region for ductile mode machining.

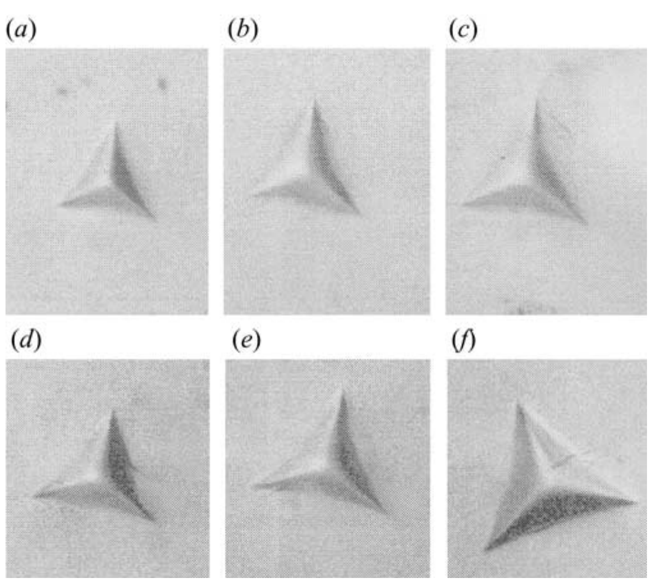

Fig. 2. Sequence of subsequent crack propagation in nano-indentation with an indenter of edge radius 1.2 μm. (*a*) 125 mN, no cracks. (*b*) 143 mN, cracks. (*c*) 161 mN, cracks. (*d*) 180 mN, cracks. (*e*) 220 mN, cracks. (*f*) 261 mN, cracks.

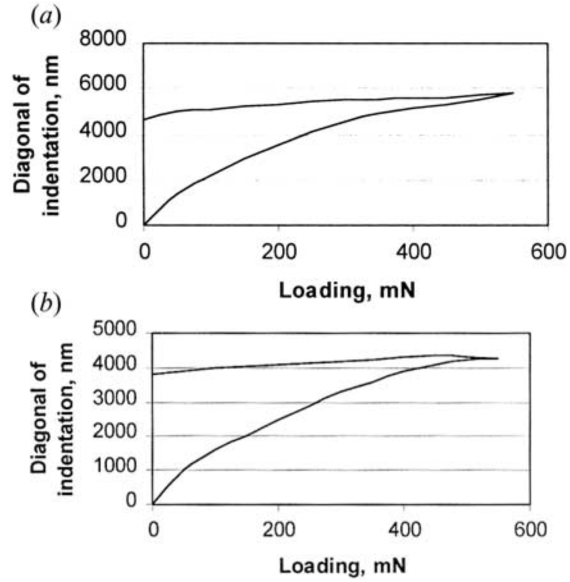

Fig. 3. Diagonal of indentation vs. loading for (*a*) zinc sulfide, and (*b*) zinc selenide.

Beyond 125 mN, partial ductile mode machining takes place. It can be seen that hysteresis occurs during the indentation process, as observed in Fig. 3.

3. Cutting Forces

In order to analyse the diamond cutting operation qualitatively, certain observations must be made before, during, and after machining. Although the number of observations that can be made during the cutting process is limited, one of the more important measurements is the determination of cutting force components. Changes in force can forecast the change in surface finish, owing to a shift in the minimum chip thickness as well as a change in figure accuracy, as the machine elastically deforms in response to increased tool forces. A Kistler turning dynamometer with a resolution of 0.01 N was used to measure the cutting forces.

Figure 4 shows that both the cutting force and the thrust force increase with an increase in the ratio of the mean undeformed chip thickness to the tool edge radius when the cutting speed is 175 m min^{-1}. The specific cutting force decreases dramatically with the increase of the ratio. The reasons for these force changes will be discussed in the next section.

4. Theoretical Approach

The mechanics of diamond cutting have long remained unclear owing to the experimental difficulties involved in making precise physical measurements on such a small scale. The complexity of the action of a rounded edge has been noted by Lucca et al. [2] and Tamaniau and Dautzenberg [3] who used Abdelmoneim and Scrutton's model [4]. Materials which form

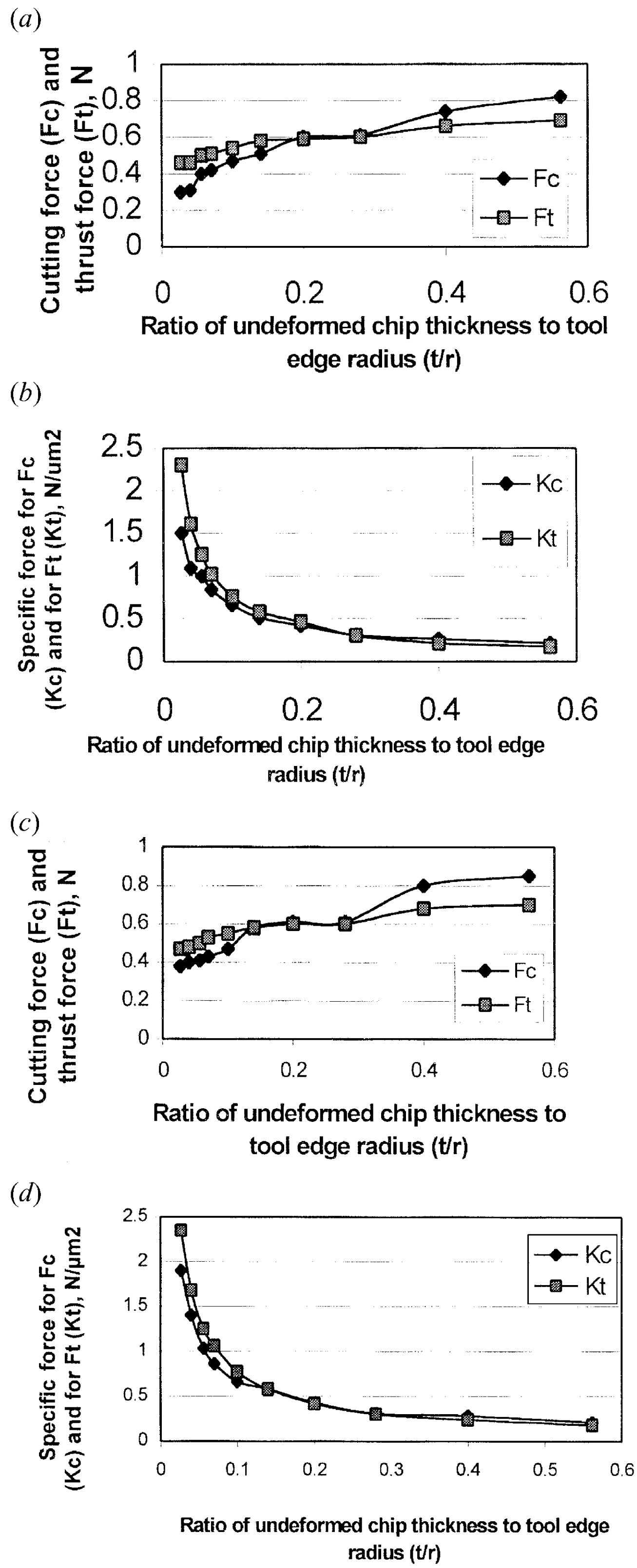

Fig. 4. Cutting and thrust forces of (*a*, *b*) zinc sulfide, and (*c*, *d*) zinc selenide. Cutting velocity, $V_c = 175$ m min^{-1}; feedrate, $f = 1.0$ mm min^{-1}.

stagnant zones when being machined are frequently characterised by a large strain-hardening coefficient for the commonly observed decrease in zone size at higher cutting speeds. Therefore, in the absence of a large stagnant zone, it would seem reasonable to assume the existence of a small strain-hardening coefficient for the workpiece material. It is known that the size of the stagnant zone also depends on the cutting speed and the rake angle of the tool. However, the variation in the stagnant size when cutting at a small depth of cut does not seem to have been investigated.

Although there is an active and small stagnant zone, it has occasionally been thought of as existing under certain circumstances when machining materials which do not exhibit large active stagnant formations. According to the above nanoindentation results, a plastic region exists beneath the lower curved surface of a round edge when cutting, in the absence of an active stagnant zone formation. The workpiece material which passes beneath the tool is, therefore, assumed to slide past a small, incipient stagnant zone and then to traverse a plastic region, termed the rubbing region as shown in Fig. 5. The analysis here is checked by comparing the results with the cutting and thrust forces.

A situation ($t \leq r(1 + \sin\gamma_e)$) is often met in ultraprecision machining of brittle materials (Fig. 5), therefore, the analysis provides a convenient starting point for an adequate treatment of a complex phenomenon. It is assumed that the edge is subject to two independent but simultaneous actions:

1. A rubbing action at and beneath a portion of the curved tool base.
2. A cutting action above the rubbing region [4].

Sticking friction conditions will be assumed to prevail for depths of cut $t < r(1 + \sin\gamma_e)$, since, in this region, pressures may be assumed to be sufficiently high [4]. The rubbing action may play a major part when the depth of cut is small, which can be demonstrated by the chip temperature measured at a depth-of-cut of 1 μm.

An infrared imaging system was used to detect the temperature. The temperature range was selected and the level and span of the image was adjusted to produce a recognisable image. The infrared camera was filled with liquid nitrogen, positioned at a safe distance from the workpiece in order to avoid any possibility of damage by the swarf, and was connec-

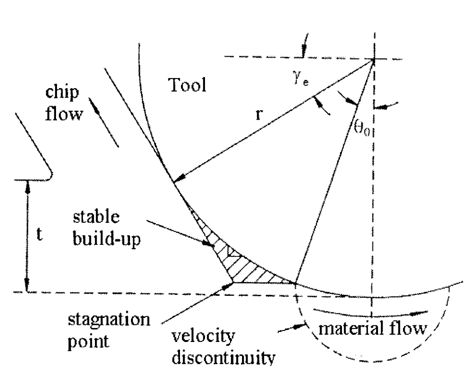

Fig. 5. The Abdelmoniem and Scrutton's model [4]. *t*, undeformed chip thickness (μm); *r*, tool edge radius (μm); γ_e, effective rake angle; θ_0, maximum rubbing action angle.

ted to the system controller. The automatic image storing sequence was initiated. After the sequence was recorded, the images were recalled and analysed using the imaging analysis software. When placed over the image, these gave the temperature at a particular point. The chip temperature was therefore recorded for each test. Figure 6 shows that the chip temperature is about 60°C, which is obviously lower than the chip temperature of 110°C obtained when machining aluminum under identical conditions.

When machining zinc selenide and zinc sulfide, the major tool wear mode was found to be flank wear, as shown in Figs 7(*a*) and 7(*b*), which is different from cutting aluminium where the wear of the edge radius was predominant (Fig. 7(*c*)). This is because the depth of cut for aluminium cutting is generally much larger than the tool edge radius, but the depth of cut for zinc selenide and zinc sulfide is of the same order as the edge radius. Because of the size effect, the rubbing action at and beneath a portion of the curved tool base becomes serious. Analysis shows that in addition to the low cutting temperature in the above analysis, zinc selenide and zinc sulfide have complete electron shells with no unpaired electrons. Thus, there is low chemical wear and diffusive wear during diamond cutting. Abrasive wear also seems low compared to that for other hard brittle materials, e.g. silicon, because both zinc selenide (Knoop hardness of 105–120 kg mm^{-2}) and zinc sulfide (Knoop hardness of 150–156 kg mm^{-2}) are soft brittle materials. Further investigation is in progress for confirming the above conjecture.

The best surface finish can be achieved on zinc sulfide and zinc selenide with a zero rake tool as shown in Fig. 8, but considerable fracture occurs when using a large negative rake tool. Figure 9 shows a spherical zinc selenide lens of radius 120 mm which was machined using a zero rake tool. There is a tool offset at the beginning, as shown in Fig. 9(*a*), whose value of 8.93 μm was detected by a laser interferometer. Figure 9(*b*) shows the final profile of the lens once the tool offset is eliminated.

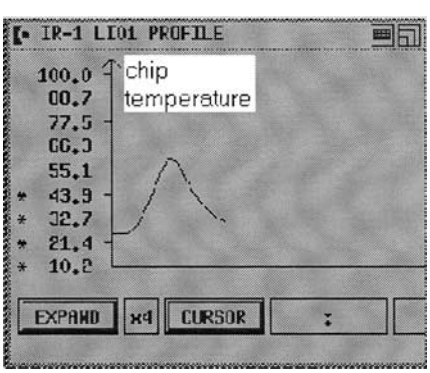

Fig. 6. Chip temperature of zinc sulfide. Cutting velocity, $V_c = 80$ m min^{-1}; feedrate, $f = 1.0$ mm min^{-1}; depth of cut, $a_p = 1.0$ μm.

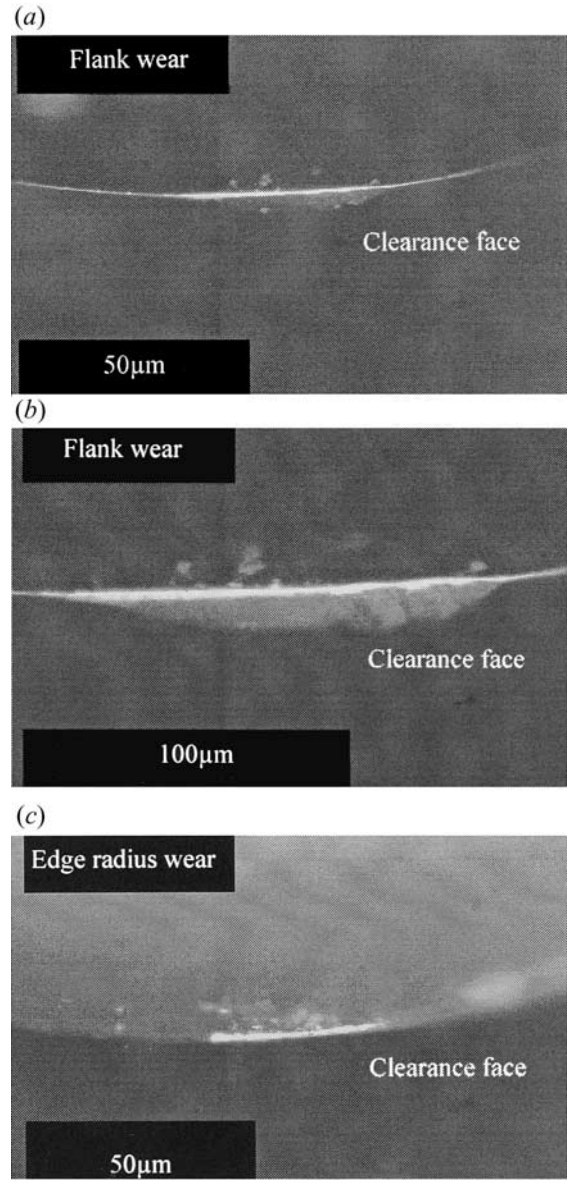

Fig. 7. Tool wear at the cutting distance of 200 km. (*a*) Zinc selenide. (*b*) Zinc sulfide. (*c*) Aluminium.

5. Conclusions

An experimental study has been carried out on machining soft semiconductors such as zinc selenide and zinc sulfide. The results have been good. Investigation of the indentation and specific cutting forces provides useful information for understanding the practical diamond cutting process of brittle materials.

1. This work confirms that during finish machining at small depths of cut, the role of the rounded edge is important.
2. The crack propagation in zinc sulfide/selenide was analysed by nano-indentation. The indentation is an indication of the applicability of ductile mode cutting of brittle materials.

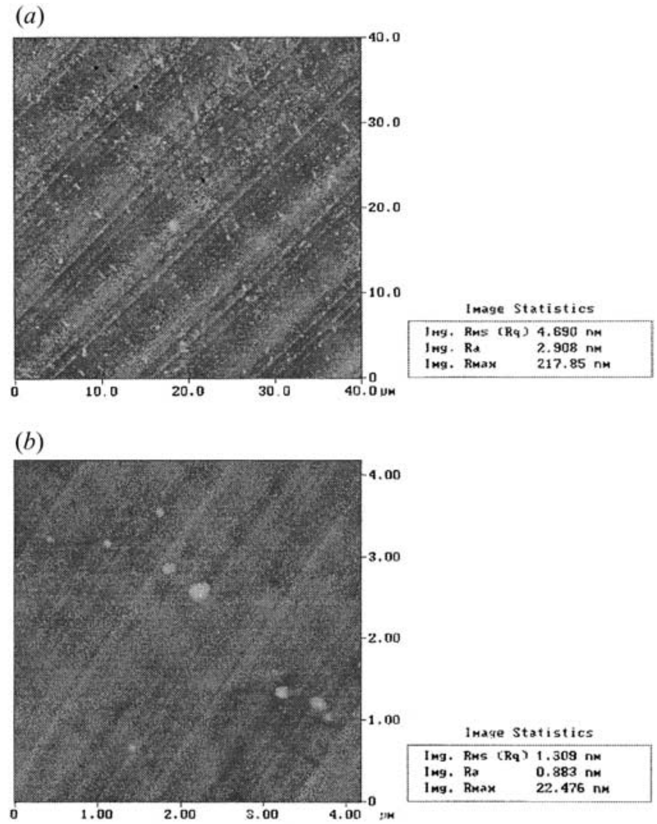

Fig. 8. Surface finish analysis by AFM. (*a*) Zinc selenide. (*b*) Zinc sulfide. Cutting velocity, $V_c = 80$ m min^{-1}; feedrate, $f = 1.0$ mm min^{-1}; depth of cut, $a_p = 1.0$ µm; coolant, light oil mist.

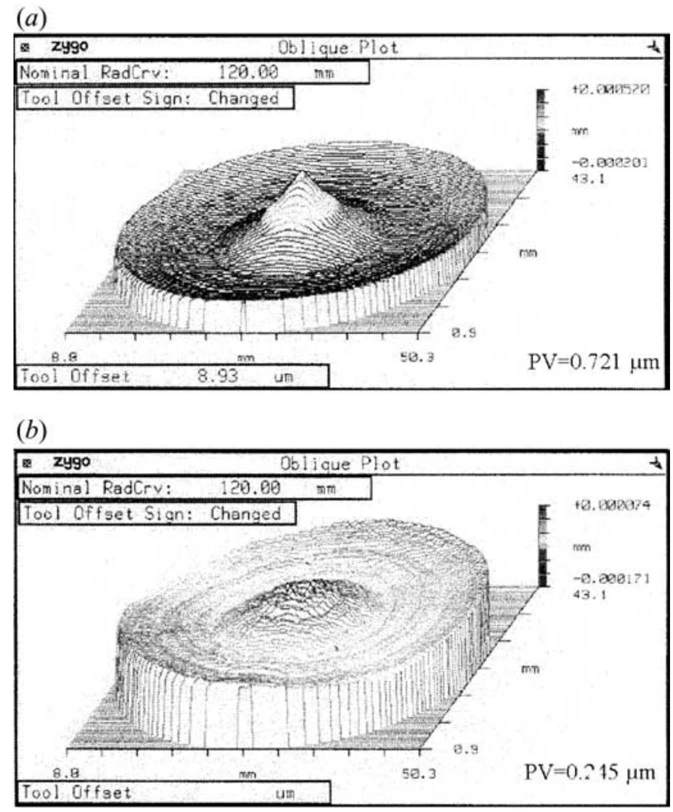

Fig. 9. Form accuracy analysis by Zygo interferometer. (*a*) Form error from tool offset. (*b*) Spherical form after eliminating tool offset. Cutting velocity, $V_c = 80$ m min^{-1}; feedrate, $f = 1.0$ mm min^{-1}; depth of cut, $a_p = 1.0$ µm; coolant, light oil mist.

3. The effective tool rake angle when machining in the range $t \le r(1 + \sin\gamma_e)$ is determined by the value of undeformed chip thickness t as observed by others.
4. Cutting forces and cutting temperature were measured in this study. The cutting force plays an important part in ultra-precision machining. The ratio of the thrust force to cutting force increases exponentially, whereas temperature was constant in this regime.
5. Nanometrric surface finishes have been achieved in ductile mode cutting, where surface roughness value is $Ra = 0.88$ nm on zinc sulfide and $Ra = 2.91$ nm on zinc selenide.
6. A spherical profile on zinc selenide was successfully obtained with an excellent form accuracy of 0.245 µm.
7. The experimental results show that the tool wear mode in the diamond cutting of zinc selenide and zinc sulfide is different from the tool wear mode in the aluminium cutting, and flank wear is predominant.

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