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A numerical investigation on the effect of tool geometry in single point diamond turning of silicon

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Abstract

A simulation study using mesh-free Lagrangian Smooth Particle Hydrodynamics (SPH) formulation in conjunction with machining experiments was carried out to study the effect of different rake angles of diamond tool on the machining mechanism of silicon. A 3D SPH model is developed to estimate the cutting forces and stresses for different tool geometry. An experimental study is performed to study the effect of different rake angles on chip formation mechanism. The simulation and experimental results show that tool geometry significantly influence machining quality and transition into different machining modes. The study also reveals that SPH is a valuable and easily implemented approach in studying brittle machining and its results are adequately in good agreement with experimental results.

Keywords: FEM, cutting, diamond turning, SPH

1. Introduction

Silicon has been widely used in semiconductor and opto-electronics industries and its applications extend to aerospace and astronomy fields. Due to its high mechanical, tribological and chemical properties, it is non-trivial to understand cutting mechanism of silicon to obtain nano-metric surface finish and reduced tool wear which are the prerequisites of concerned industries. When machining silicon, the brittle fracture occurs which deteriorate the surface quality of silicon. Also because of high hardness of silicon, diamond tool undergo severe wear. Brittle fracture of silicon and rapid diamond tool wear are the two major challenges in ultra-precision turning of silicon. Literature study reveals that it is possible to machine silicon in ductile mode [1]. High-pressure phase transformation (HPPT) is found to be the prime mechanism responsible for the brittle-ductile transition of brittle materials. Negative rake angle tools are found to acquire required hydrostatic stress for the ductile machining of silicon. Finite element analysis of metal cutting using Lagrangian and Eulerian approach has been extensively exploited. However, machining of hard materials using positive and negative rake angle tools is still a challenge due to mesh distortion. Lagrangian method evolved to mesh-less smooth particle hydrodynamics method providing a solution to large mesh distortion. Unlike mesh-based approach, SPH offers connectivity-free nodes that eliminate the problem of mesh distortion during large deformation. In this paper a 3D SPH model was developed to investigate the machining mechanism of silicon.

2. SPH Simulation Model

Fig. 1 illustrates the work-piece boundary conditions and tool motion and schematically represents the orthogonal 3D SPH cutting simulation of SPDT process.

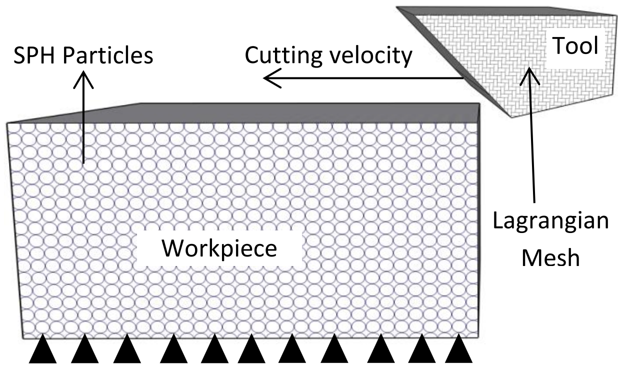

Figure 1. Schematic of SPH model of orthogonal cutting simulation

The tool was kept rigid and modelled using Lagrangian mesh formulation. The work-piece was modelled using SPH particles. The work-piece bottom was entirely fixed with encastre condition. Johnson's cook (JC) constitutive model was used to characterize the ductile mode machining of silicon. Since no experimentally acquired JC parameters are available for silicon, an optimization technique (Nelder-mead) is employed to obtain the JC parameters of silicon. The detailed procedure of the optimization technique is discussed in [2]. No friction parameters were used as SPH employ internal friction between the particles instead of using theoretical friction parameters.

Table 1 JC parameters of silicon obtained from Nelder-mead technique

JC parameters	A	B	C	n	m
Silicon	960	620	0.41	0.34	1

In the 3D SPH model, the work-piece dimensions were kept 250µm x 200µm x 50µm and machined using tools with rake angles of -40°, -25° and 15°. The rake 15° is not suitable for machining silicon and it is only used in simulation for comparison. The same experimental depth of cut of 10 µm and cutting speed of 6m/sec was used in the simulation in order to obtain comparative results. All cutting parameters including depth of cut, cutting velocity, particle density, and work-piece geometry are kept same in all three simulations.

3. Experimental work

Silicon wafers with crystal orientation (111) were machined with -25° and -40° rake angle tools. Machining for both the tools was carried out with cutting speed of 380m/min, feed of 1µm/rev and 10µm depth of cut. Cutting forces developed during machining were monitored and recorded using three-component Kistler dynamometer 9250B.

4. Results and Discussion

4.1. Chip formation and stresses

Fig. 2 shows the chip formation at steady-state condition for different rake angle tools. Negative rake angle tools (Fig. 2b and 2c) first pushed the material downward causing high pressure resulting in continuous chip. The chip length was found to decrease and thickness increased with increasing negative rake angle. Continuous chip was observed for the negative rake angle tools for which the value of von-mises stresses in the cutting zone reached 11GPa and 14 GPa for -25° and -40° rake angle tools respectively. The stress values exceed the theoretical yield strength of the silicon representing chip formation through plastic deformation. Broken chip was observed for the 15° rake angle tool (Fig. 2a) and relatively low stresses of 3GPa (less than the yield strength of silicon) was obtained representing deformation of material through fracture. In fig.2, it can also be observed that decreasing the rake angle resulted in increasing compressive stresses facilitating ductile machining.

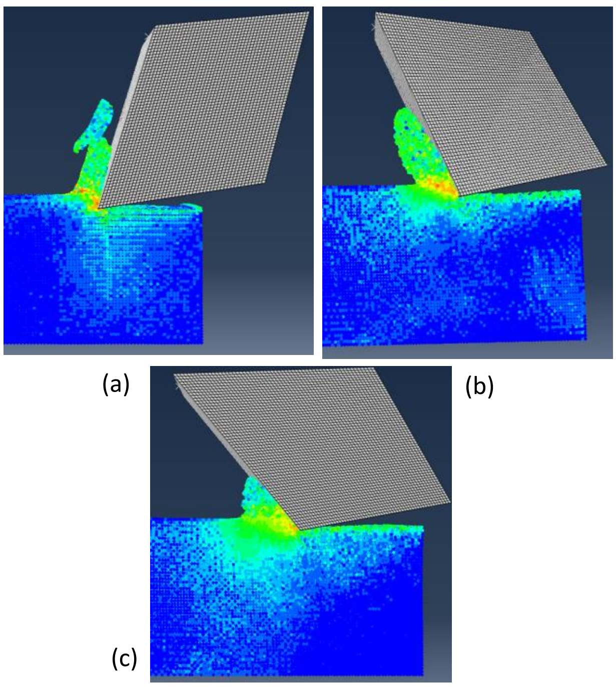

Figure 2. Chip formation for different rake angles at steady-state condition (a): Rake (15), (b): Rake (-25), (c): Rake (-40)

4.2. Cutting forces

Fig. 3 shows the normal cutting forces in the simulation process for different rake angle tools. In the cutting simulations, cutting forces are found to increase sharply on tool-workpiece contact and then stabilize with minor variations throughout the cutting process representing steady cutting. Decreasing the rake angle results in increase of cutting forces. Silicon offers higher resistance to plastic deformation than brittle fracture and therefore requires higher energy which results in higher cutting forces. This forces trend can be observed from changing positive to negative rake angle.

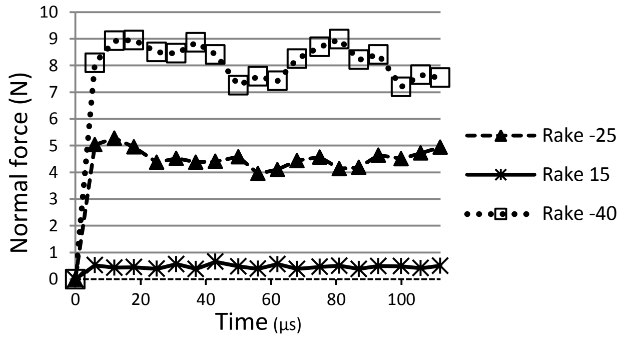

Figure 3. Cutting force trend during cutting simulation

Fig 4. Illustrates the force comparison of experimental and simulation results for the different rake angles. Cutting forces during simulation are slightly higher than the experimentally obtained values, however, cutting forces trend obtained in the simulation study are found consistent with the experimental values. Further experimental tests with different silicon wafers will clarify the difference in the cutting forces. Also Split Hopkinson tests will be conducted to obtain the real parameters of JC model. Such tests are planned and will be reported in future articles.

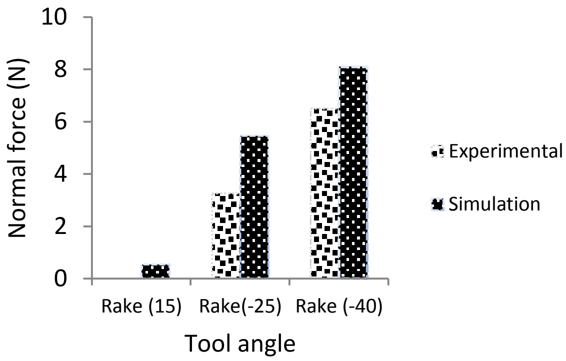

Figure 4. Force comparison of experimental and simulation with different rake angles

5. Conclusion

Experimental and simulation results suggest that cutting forces, stresses and chip formation are significantly influenced by the tool geometry. The difference in the cutting forces predicted by SPH model and experimentally obtained values could possibly be due to optimised parameters and wafer quality.

References

Examples:

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