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Sapphire as a single-crystal cutting tool for mac hining ferrous-based optics

Amit Dodmani[1], Sathyan Subbaih[1] and A. Senthil Kumar[2#]

1 Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
2 Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, 117575, Singapore
Corresponding Author / Email: mpeask@nus.edu.sg, TEL: +65 6516 6800

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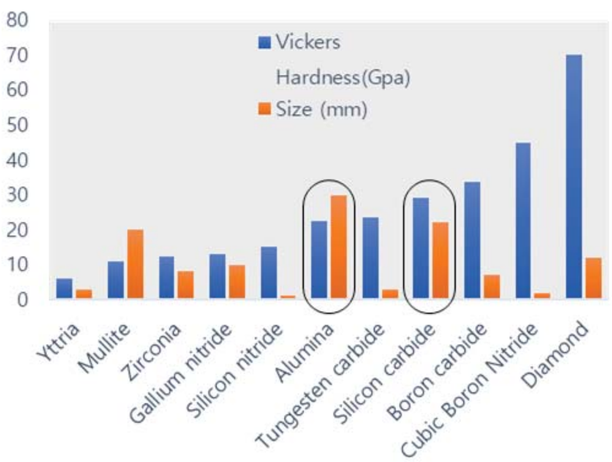
Ultra-precision machining produces smooth optical surfaces with nanometric surface finish using a single crystal diamond (SCD) tool. SCD tool can maintain very sharp and uniform cutting due to its high hardness and is used to machine nonferrous alloys, plastics, and polymers. However, excessive tool wear occurs when a SCD tool is used for cutting ferrous alloys because of carbon's chemical affinity towards iron. Many techniques like cryogenic turning, ultrasonic vibration cutting, and ion implantation techniques are used to suppress the SCD tool wear. But, in this study we use an alternate single crystal tool to machine the ferrous optics. Single crystal alumina (Sapphire) is selected as a cutting tool material because of its hardness and availability in bulk size. A lapping setup is developed to fabricate a sharp cutting-edge sapphire tool with zero rake and 7° clearance angle. The cutting-edge radius on sapphire tool obtained is comparable to the SCD tool edge radius. Orthogonal cutting of steel is performed in an ultra-precision machining facility using these sapphire tools and SCD tool. The surface finish on the workpiece, and cutting forces are studied for different depths of cut and cutting speeds. Comparison of sapphire and diamond tool performance during orthogonal cutting of steel in terms of surface roughness and cutting forces is studied.

1. Introduction

Optical components with nanometric surface roughness find applications in space technologies, defense, camera lenses, and medical implants. The ultra-precision machining produces such smooth surfaces using a single crystal diamond (SCD) tool, which can maintain a very sharp and uniform edge with a radius of a few tens of nanometers because of its high hardness [1]. The polycrystalline cutting tools like CBN (Cubic Boron Nitride) and PCD (Polycrystalline Diamond) cannot have the cutting-edge radius in nanometers because of the grain size being in micrometers. With single crystal material, sharp cutting tool can be generated with edge radius in nanometers.

Using a sharp-edged SCD tool, nanometric surface roughness can be achieved when cutting nonferrous alloys, plastics, and polymers. However, excessive tool wear (chemical wear) occurs when a SCD tool is used for cutting ferrous alloys because the carbon in the diamond structure has an affinity towards the iron and diffuses into the workpiece. This changes the diamond cubic structure to hexagonal graphite at the cutting edge. Graphite structure being weak at shear causes continuous tool wear. Even though popularly used in common engineering applications, ferrous-based optical components are seldom used despite their advantages. Many techniques have been reported on diamond tool wear reduction such as cryogenic turning [2], ion implantation [3] and ultrasonic vibration cutting [4].

In this study, we look for an alternate single crystal tool to machine ferrous-based optics. Fig. 1 compares ceramic single crystals in their increasing order of hardness (GPa) and corresponding bulk single crystal size (mm) in which they are commonly available. An alternative to diamond, which has high hardness and large enough single crystal, needs to be fabricated the with sharp cutting edge. The graph shows two choices: alumina (sapphire) and silicon carbide; they are available as a large enough single crystal, and their hardness



is more than ten times that of steel. We investigate single crystal alumina (sapphire) as the choice of tool material for machining ferrous alloys.

Fig. 1 Size and hardness of ceramic single crystals. Only alumina and silicon carbide are available as bulk size crystals.

2. Experiment setup and Methodology

2.1 Sapphire lapping and polishing

Cylindrical sapphire crystal with dimensions 12 mm diameter and height 6 mm is taken having top surface polished with surface roughness less than 5A°. The polished face is chosen as rake face and the side face is chosen as flank face. Sapphire tool with zero rake angle and 7° clearance is used. The side face of the crystal is lapped to make sharp cutting edge. The sharp cutting edge is developed by lapping and polishing. The sapphire lapping setup is developed in Bruker tribo-lab CMP. Fig. 2 shows the sapphire lapping setup, #400 Boron carbide slurry on the cast iron lap is used and the lapping load is 12N [5]. After lapping, sapphire is polished to improve surface finish on flank face and obtained sharper cutting edge. Fig. 3 shows the polishing 6 µm diamond slurry is used on the Kemet copper lap with lapping load of 10N [6].

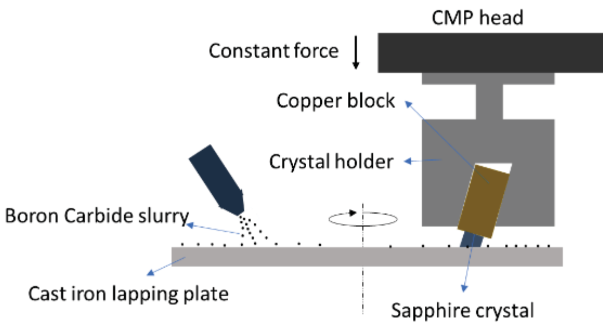


Fig. 2 Schematic of sapphire lapping setup. Lapping of flank face is performed using #400 Boron carbide slurry on cast iron lap with constant load of 12N.

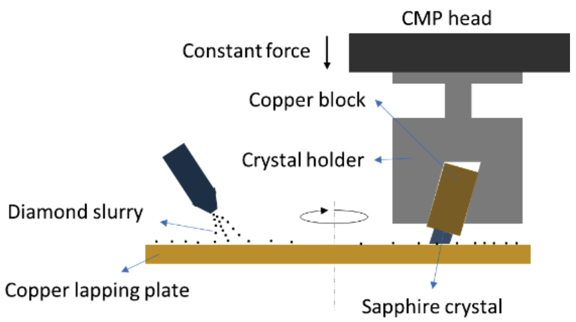
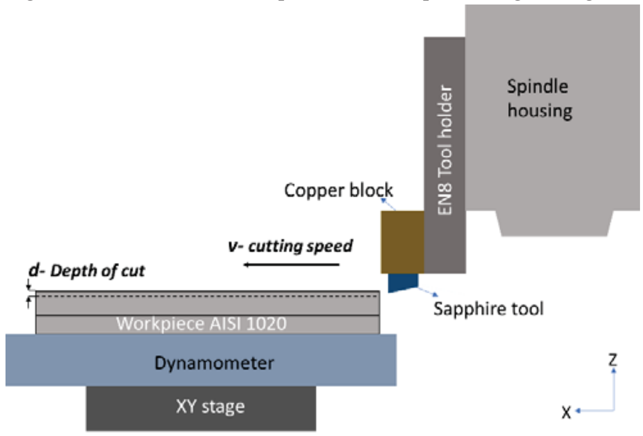


Fig. 3 Schematic of sapphire polishing setup. Polishing of flank face after lapping is performed using 6µm diamond slurry on copper lap with constant load of 10N.

2.2 Orthogonal cutting of AISI 1020 using Sapphire tool

Orthogonal cutting of AISI 1020 channels is performed using sapphire tool in Ultra-precision machining center (KERN Evo). The experimental setup as shown in the Fig. 4. The thickness of steel channel is 0.5 mm and length 80 mm. The top surface of channels is machined with micro end milling cutter to make surface flat. The sapphire crystal is mounted in the copper block for soft contact and avoid brittle failure of sapphire. The copper block is then fixed on to the EN 8 tool holder which is clamped to the spindle housing. The fly cutting diamond tool shank is also mounted on the EN8 tool holder. Three cutting speeds 5 m/min, 7.5 m/min and 10 m/min are used and three depth of cuts 0.5 µm, 1 µm and 2µm are used. The orthogonal cutting conditions are shown in the Table 1. Workpiece is mounted on the dynamometer to collect the cutting and thrust force data.

Fig. 4 Schematic of the experimental setup showing orthogonal



cutting of AISI 1020 channels using sapphire tool in Ultra-precision machining center (KERN Evo).

Table 1 Orthogonal cutting conditions

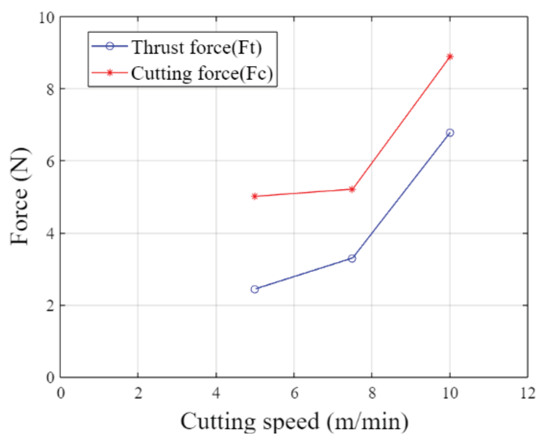
Cutting tools	Sapphire and Diamond
Workpiece material	AISI 1020
Workpiece dimension	0.5 mm x 80 mm
Cutting speed (m/min)	5, 7.5, 10
Depth of cut (µm)	0.5, 1, 2
Cutting length	0.4 m

3. Results and Discussions

3.1 Effect of cutting speed

The depth of cut is kept constant and the effect of cutting speed is studied on cutting forces and surface finish. During the orthogonal cutting the cutting forces (Fc) and the thrust forces (Ft) are measured from the dynamometer (Kistler Type 9256C). The Fig. 5 shows the plot of cutting force(N) and thrust force(N) obtained for three different cutting speeds 5, 7.5 and 10 m/min for constant depth of cut of 1 µm.

Fig. 5 Cutting force(N) and thrust force(N) obtained for three different



cutting speeds i.e., 5, 7.5 and 10 m/min for constant depth of cut of 1 µm.

It is evident from the Fig. 5 that cutting force is greater than the thrust force which indicates ductile mode of machining, which indicates the edge radius of the sapphire tool is less than the uncut chip thickness. Cutting and thrust forces increases with increase in the cutting speed due to high material removal rate.

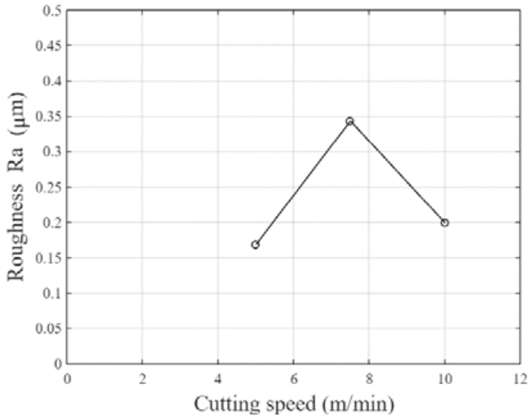


Fig. 6 Surface roughness plot obtained for three different cutting speeds 5, 7.5 and 10 m/min at constant depth of cut of 1 µm.

After orthogonal cutting of AISI 1020 with sapphire and diamond tool, the surface roughness of the machined channel is measured in contact profilometer (Talysurf-120). The sampling length is 10 mm, and the cut-off length is 0.8mm. Fig. 6 shows the plot of Arithmetical mean surface roughness (Ra) with three different cutting speeds 5, 7.5 and 10 m/min for constant depth of cut of 1 µm. The plot indicates roughness (Ra) value increases with increase in the cutting speed. This phenomenon is due to increase in the cutting forces with cutting speeds can cause more tool wear which leads to poor surface finish.

3.2 Effect of depth of cut

The cutting speed is kept constant and the effect of depth of cut is studied on cutting forces and surface finish The Fig. 7 shows the plot of cutting force and thrust force obtained three different depth of cuts 0.5, 1 and 2 µm for constant cutting speed of 5 m/min. Fig. 7 indicates increase in cutting and thrust forces with increase in the depth of cut. At constant speed material removal rate is higher in the case of 2µm depth of cut than 0.5µm and 1µm. Therefore, we see a raise in cutting and thrust forces.

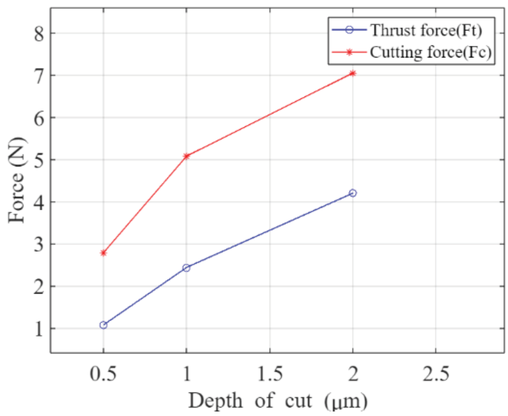


Fig. 7 Cutting force(N) and thrust force(N) obtained for three different depths of cuts 0.5µm, 1µm and 2µm for constant cutting speed of 5m/min.

Fig. 8 shows the surface roughness (Ra) obtained three different depth of cuts 0.5, 1 and 2 µm for constant cutting speed of 5 m/min. We see the roughness (Ra) value increases with increase in the depth of cut. The increase in cutting forces due to higher depth of cuts cause more tool wear resulting in the poor surface finish.

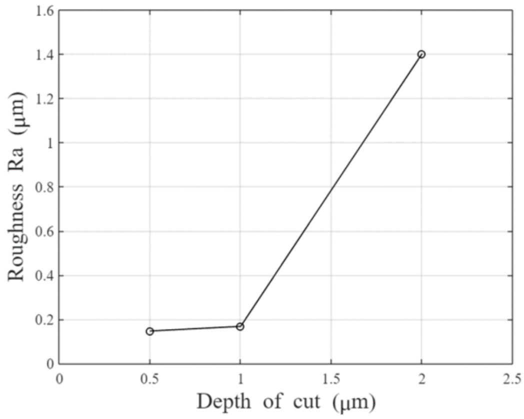


Fig. 8 Surface roughness (Ra) obtained for three different depths of cuts 0.5µm, 1µm and 2µm for constant cutting speed of 5m/min.

3.3 Comparison of sapphire and diamond tool performance.

We compared the performance of sapphire tool and diamond tool in orthogonal cutting of AISI 1020 steel in terms of cutting forces and the surface finish. Fig. 9 shows the plot of cutting and thrust forces versus cutting distance obtained from orthogonal cutting of steel using sapphire and diamond tool. Orthogonal cutting using both the tools is performed under similar conditions of depth of cut 1µm, cutting speed 10 m/min and cutting distance of 400mm. As observed from plot that cutting forces are higher than the thrust forces which indicates ductile mode of machining. The cutting force is increasing w.r.t to cutting distance due to the tool wear. The maximum thrust force is 11.72N in case of diamond tool whereas in sapphire tool it is 9.03N. From the plot the average thrust force for diamond tool is 8.032N and for the sapphire tool the thrust force is 7.09N. The thrust force in diamond tool is greater than sapphire tool which suggests that the tool wear in diamond tool is slightly higher compared to sapphire tool.

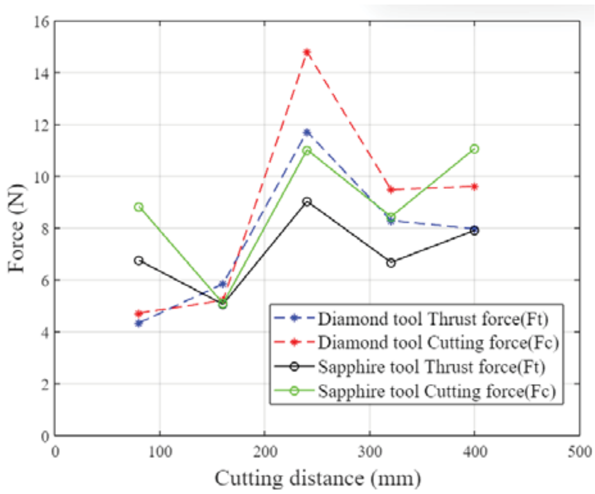


Fig. 9 Cutting force(N) and thrust force(N) obtained for three different

depths of cuts 0.5µm, 1µm and 2µm for constant cutting speed of 5m/min.

Table 2 Roughness (Ra) of the surface machined using sapphire tool and diamond tool.

Cutting tool	Sapphire	Diamond
Surface roughness (Ra)	0.199 µm	1.479 µm

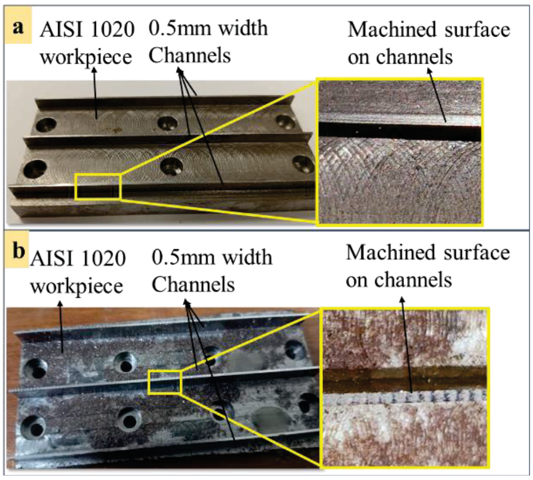


Fig. 10 Machine surface AISI 1020 channels a) machine using a sapphire tool b) machined using a diamond tool

Table 2 shows the roughness (Ra) of the surface machined using sapphire tool and diamond tool. The roughness of surface machined using diamond tool is 1.479 µm whereas when sapphire tool is used its 0.199µm. Only abrasive wear takes place when sapphire tool is machining the steel but incase case of diamond tool along abrasive wear the chemical wear happens and is significant. Therefore, in case of diamond tool wear is more compared to sapphire tool. This affects the cutting performance increases the thrust forces and leads to poor surface finish. Fig. 10a and Fig. 10b shows the AISI 1020 steel channels machined using sapphire tool and diamond tool respectively. It is evident that quality of the machined surface is better in case of sapphire tool compared to diamond tool. Chatter marks were observed on machined surface using diamond tool, which led to increase in it the roughness (Ra).

4. Conclusion

Use of alternate single crystal tool to machine ferrous-based optics is proposed in this paper. Identified single crystal alumina (sapphire) as tool material based on hardness, bulk size, chemical inertness towards iron and availability. Sapphire lapping and polishing set up is developed to make sharp sapphire cutting tool. Orthogonal cutting of AISI 1020 steel is performed using sapphire tool for different cutting speeds and depth of cuts. During machining cutting forces were higher than thrust forces which indicated ductile mode of machining.

In both the cases constant cutting speed and depth of cut. Observed cutting, thrust forces and roughness increase with increase in the cutting speed due to high material removal rate and tool wear. Under similar orthogonal cutting conditions of 10 m/min cutting speed, 1µm depth of cut and 400mm cutting distance, both sapphire and diamond tool is tested. The maximum and average thrust force for diamond tool is higher compared to sapphire tool. The roughness (Ra) on machined surface in case of sapphire tool is 0.199µm which is better than 1.479µm roughness (Ra) obtained using diamond tool.

We demonstrated that sapphire can be used as cutting tool for machining ferrous based optics. Roughness (Ra) obtained on surface machined using a sapphire tool is better compared to using a diamond tool. In this study comparison of diamond tool and sapphire tool is only done in terms of surface roughness and cutting forces. In future studies quantitative comparison of sapphire and diamond tool will be performed w.r.t tool wear and edge radius. Also perform modelling and analysis of tool wear.s

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