Fluent simulation and experimental analysis of polishing edge abrasion of single crystal germanium

Zhiyi Leng1,*, xiaojing Yang2

1Department of Engineering and Technology, Dalian Maple Leaf College of Technology, Dalian, Liaoning, 116036, China
2Faculty of Mechanical and Electrical Engineering, Kunming University of Science and Technology, Kunming, Yunnan, 650500, China
*Corresponding author’s e-mail: zyleng1992@163.com

Abstract. Single crystal germanium has good physical property and is widely used, but it is hard to process the surface of single crystal germanium by traditional processing technology. Although using two-phrase flow polishing technology can make effective processing on the surface of single crystal germanium, but it could also cause edge abrasion as well. The paper was based on two-phrase flow polishing theory, which built a flow-path simulation model based on the location relationship of each part of polishing machine, used Fluent to simulate the polishing process and designed experiment to analyse the polishing process. By simulation and experimental analysis we can find that, during the polishing process, the liquid-solid two-phrase flow would cause edge abrasion of test-piece, but the abrasion degree on each side of the test-piece is different. The difference of pressure which caused by liquid flow and the change of flow-path size are the main reasons of edge abrasion. Under existing processing conditions, using diamond abrasive could get higher surface accuracy, but the edge abrasion of the specimen is obvious. To reduce the edge abrasion, larger size of abrasive should be used.

1. Introduction
Single germanium has good physical property and it is widely used in infrared optics, aerospace and other fields. Meanwhile, due to the brittleness of single crystal germanium, it is difficult to process the surface effectively by traditional technology. Nowadays the two-phrase flow polishing technology has been developed. Using two-phase flow polishing technology can make the surface of brittle and hard materials smoother. However, the surface edge abrasion appeared after the surfaces of test-piece was polished. The researchers thought the edge abrasion caused by uneven pressure distribution has nothing to do with two-phrase flow impaction [1-4], meanwhile, many researchers thought during the process of polishing, the flow of mixture would have effect on the surface of test-piece [5-13]. There is little research on the two-phrase flow polishing abrasion which on the edge of test-piece, therefore, the paper was based on two-phrase flow polishing theory, established a flow-path model based on the relative location of machine parts and motion relationship, used Fluent finite element software to simulate the polishing process and designed experiments to verify the correctness of simulation. The paper provides a new researching idea on single crystal germanium two-phrase flow polishing.
2. Two-phrase flow polishing theory

2.1. Impact theory of abrasive
The motion of abrasive causes the removal of material on the surface of the single crystal germanium during the polishing process. At present, the main idea of describing this process is the theory of abrasive insertion cutting proposed by Hrosovsky. During the polishing process, the abrasive is thought to be inserted into the surface of material, ploughed and cut materials during the process. The irregular shape abrasive is simplified as a cone, the shadow part is the material removal part. The cutting effect is shown as figure 1.

![Figure 1. Schematic diagram of the cutting effect of abrasive on the material](image)

With the effect of hard contact, the cone is pressed into the material, based on definition of hardness $\sigma_0$, the equation is:

$$\Delta F_N = \sigma_0 \pi r^2$$

The projection area of the cone on the test-piece surface is $rh$, when relative displacement is $dx$, the removal volume of material $dV$ is:

$$dV = rhdx = r^2 \tan \theta dx = \Delta F_N \tan \theta dx / \pi \sigma_0$$

Combining removal volume with material abrasion volume, and getting derivative of displacement on both sides of formula, the removal rate of material in unit displacement is:

$$dV / dx = \Delta F_N \tan \theta / \pi \sigma_0$$

By integrating $x$ on both sides, the volume of the removed fragment is equalled to:

$$V = (F_N \tan \theta / \pi \sigma_0)x$$

$\tan \theta$ is the weighted average of all abrasives and micro-contact on test-piece surface $\tan \theta$ which is:

$$V = (k_{abr} F_N / \sigma_0)x$$

The removal material volume is proportional to positive pressure and displacement, inversely proportional to material property. The $k_{abr}$ represents the geometrical shape of the abrasive surface.

2.2. Particle dynamics theory in solid-liquid two-phase flow
The interaction between abrasives is affected by fluid and fluid motion, if the influence of abrasives on abrasive flow was neglected, the research on solid-liquid flow motion is changed into the research on abrasive dynamic. According to the Newton's Second Law, the simplified single abrasive motion equation is:

$$m(dv / dt) = \sum F$$

Where the $m$ is abrasive quality, $m(dv / dt)$ is abrasive inertia force, $\sum F$ is resultant forces on abrasives, the resultant efforts are as follows:

$$\sum F = F_d + F_g + F_a + F_m + F_B + F_P + F_M + F_S + ...$$
3. Simulation and analysis of impact effect of abrasive flow

3.1. Establishment of simulation model and simulate

Rotary polishing machine is widely used in the polishing process. This kind of polishing machine consists of polishing disk, carrier disk, polishing pad and polishing liquid delivery system, the polishing process is shown as figure 2(a). In this paper, the impact abrasion effect of polishing liquid on material edge in polishing process is studied. Therefore, assuming that carrier disk and polishing disk are relatively stationary, only polishing liquid flows in a single direction. Eventually, the abstract model is shown as figure 2(b). To simplify the abstract model, the surfaces of single crystal germanium, carrier disk and polishing disk are taken as the boundary of the flow-path, the flow-path model is shown as figure 2(c). During the simulation process, the boundary of flow-path is thought to be static, only polishing liquid flows in the flow-path, so the constraint condition of each edge of flow-path is shown as figure 2(d).

Eventually, used ANSYS Workbench to grid the model and simulate. The initial velocity was set in 90m/s, the size of abrasive was 0.5μm, the material of abrasive was diamond. The first simulation result and vector graph of abrasive are shown as figure 3.

It can be seen from figure 3(a) during the polishing process, the pressure decreases sharply at the abrupt change of flow-path shape. It can be seen from figure 3(b), that the pressure difference drives abrasives in polishing fluid to move along the direction of pressure change, at this moment, the speed vector significantly changes, which causes the edge abrasion on the inlet and outlet side of the flow-path. Meanwhile, because of the negative pressure area at the outlet side is large, the increase of the disorder of abrasives moving direction, makes the edge abrasion on the outlet side is more serious than inlet side. From simulation result we can conclude that the pressure change caused by shape change of flow-path is the main reason of edge abrasion.
3.2. Simulation analysis of abrasive impact of different materials

During the polishing process, the material of abrasive would have effect on the surface quality of test-piece. According to this conclusion, the paper selected silicon dioxide, diamond, alumina and cerium dioxide four common abrasives to simulate, the size of abrasive was set in 0.5μm, the speed of polishing liquid flow was 90m/s. The simulation results are shown as figure 4.

From the results of first simulation we know that, the pressure change caused by shape change of flow-path have effect on the direction of abrasive motion. From figure 4(b) and figure 4(c) we can see that by using diamond and cerium dioxide abrasive, the negative pressure area near the outlet is relatively large, it can be inferred that, using those two abrasives could cause relatively obvious edge abrasion. The pressure difference caused by using diamond abrasive is larger than that caused by using cerium dioxide, the simulation result shows that, the negative pressure area caused by those two abrasives are extended to narrower flow-path area. By analysing the simulation results we could make following assumptions: 1) After processing, the degree of abrasion on both sides of the material will be different, 2) Using diamond abrasive would cause the most serious surface edge abrasion.
4. Experimental design and results analysis

4.1. The design of experiment
In order to verify the effectiveness of simulation, the polishing experiments were carried out with polishing machine. The size and material of abrasives used in experiment were: 0.1μm diamond 0.1μm silicon, 0.5μm alumina and 0.5μm cerium dioxide. After processed the test-pieces were cleaned and tested.

4.2. Analysis of the experimental results
The experimental results are shown as figure 5. By analysing the surface topography we can see, after processed, the edge abrasion of four test-pieces are in different degree. By using diamond abrasive the edge of test-piece has most obvious abrasion. By using silica and cerium dioxide abrasives, the edge abrasion of test-piece is relatively light, but on one side of the test-piece is badly worn. Using diamond and alumina abrasive would make abrasion to extend along the horizontal direction, using diamond and cerium dioxide would make abrasion to extend along the vertical direction. From the simulation results we can see that, the negative pressure area caused by using diamond and cerium dioxide abrasive extend to the narrow place of flow-path, which causes strong impact on the edge of test-piece and edge abrasion. The size of abrasive has effect on edge abrasion. By analysing the polishing effect of diamond and alumina abrasive, which have similar density, we can find that using smaller diamond abrasives would cause more obvious edge abrasion. By comparing the results of experiment and simulation, we can know...
that the experimental results are consistent with the simulation conclusions and assumptions mentioned above. It could prove that using Fluent software can analyse the edge abrasion of test-piece by comparing the pressure difference. Meanwhile, it could also prove polishing liquid which has an effect on the polishing results in the process of polishing.

(a) 0.1μm diamond abrasive  
(b) 0.5μm alumina abrasive

(c) 0.5μm cerium dioxide abrasive  
(d) 0.1μm silica abrasive

Figure 5. The experimental results

5. Conclusion
1) A flow-path simulation has been built based on correlation theory and relative position of each element during the polishing process. By analysing the results of simulation and experiment, we can conclude that, during the process the liquid effect could cause edge abrasion of test-piece, but the degree of abrasion on the edges of both sides are different.
2) The pressure difference caused by liquid flow and the change of flow-path size was the reason of edge abrasion of the test-piece.
3) The effect of abrasive size on edge abrasion decreases premier and then increases with the increase of abrasive size.
4) Processing with existing conditions and polishing liquid, using 0.1μm diamond abrasive could get higher surface accuracy, but the edge abrasion of the specimen is obvious. Using larger abrasives can reduce edge abrasion.

Acknowledgment
Thanks for the support of the National Natural Science Foundation of China (foundation item number: 51765027). And thanks to the support and help of my teacher Professor Yang.
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