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A method for orthogonal cutting experiments with diamond tools

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Abstract

This paper describes an experimental set-up to perform cutting tests on different materials using single-crystal diamond tools. The method uses a plunge cut into the edge of a rotating disk to approach two-dimensional or orthogonal cutting at realistic cutting speeds. Preliminary results of this method are reported.

Introduction

In supporting research projects at the Los Alamos National Laboratory, we are working on ultra-precision machining of various materials and shapes. The projects involve both optics and non-optical components, and some of this work has been reported at previous SPIE meetings.^{1,2} There is a need to expand our capabilities to materials other than those commonly diamond turned, and we would like to improve the surface finish if possible on optical components. Therefore, we have initiated a series of experiments to study cutting parameters using diamond tools. Our long-range goals are to better understand the cutting process and apply this knowledge to actual component fabrication.

The cutting tests are done by feeding at a constant rate into the edge of a rotating disk of material. An approximation of two-dimensional or orthogonal cutting is produced by making the disk thin compared to the radius of the diamond tool. The test set-up allows us to study the effects of many different parameters such as rake angle, lubricant, cutting speeds, as well as different materials. The surface finish in the direction of the cut can be easily determined by tracing circumferentially around the disk. Also, the cutting process can be observed using a microscope and video system viewing from the side. Current experiments have included cuts on copper and aluminum, with examinations of the chips which are collected during the tests.

This report describes the test set-up which we have started to use at Los Alamos; however, this set-up is only a small part of an overall program to study the mechanics of cutting with diamond tools. For meaningful experiments, the diamond tools have to be characterized as completely as possible. Some of the tool parameters such as diamond crystal orientation, rake surface smoothness, and freedom from edge chips have to be determined prior to experiments. The importance of crystal orientation is commonly known to be a very important parameter and has been described in some detail by Hurt³ and Hannah.⁴ Therefore, we will use the x-ray diffraction method to determine the orientation of the tools we use in the cutting experiments.

The actual edge sharpness is certainly very important also, but is difficult to quantify. Some experiments have started at the National Bureau of Standards (NBS) on methods of better diamond tool edge characterization.⁵ Our intent is to take advantage of methods for measuring edge sharpness as they become available and use the edge sharpness as a measure of tool wear relative to different cutting parameters and materials. As we continue to do experiments, we will attempt to determine, as best we can, all important parameters of the tool and material.

Orthogonal cutting

To aid in the understanding of the cutting mechanism, either with diamond tools or conventional tool materials, analytical modeling, such as the finite element work being done at the North Carolina State Precision Engineering Center,⁶ is that parameter studies can be carried out relatively easy. For example, the residual stress produced with different rake angles of the tool could be studied by running different cases of a finite element model more easily than doing experiments. However, the model has to be verified, at least for some variables in a few cases, by comparison to actual experiments. Therefore, in designing an experimental set-up, we decided to attempt two-dimensional, or orthogonal, cutting experiments. These experiments could more easily be compared to analysis because much of the finite

element work is done with two-dimensional geometry. Doing full three-dimensional finite element analysis is certainly possible, but it is far more time consuming and complicated. Also, it is best to make comparisons between analysis and experiments in the simplest cases possible. We have not progressed to the point where meaningful comparison can be made, but we have started our experiments with this intention.

E. M. Trent in Metal Cutting defines orthogonal cutting as, "the tool edge is straight, it is normal to the direction of cutting, and normal also to the feed direction. Strictly orthogonal cutting can be carried out on a planing or shaping machine, in which the work material is in the form of a plate, the edge of which is machined." ⁷ It is also pointed out that this method is limited in achieving some of the cutting speeds normal for lathe cutting, and, therefore, plunge cutting into the end of a thin-walled tube is suggested as a method of orthogonal cutting on a lathe. We chose a slightly different geometry of feeding the tool into the edge of a rotating disk. Our arrangement is shown in Figure 1.

Figure 1. Set-up for orthogonal cutting experiments

The configuration currently used is a 0.25 mm thick disk of about 50 mm diameter. Diamond tools of 3 mm (0.125 inch) radius with a one degree negative rake have been used. Cutting speeds of about 16 m/min. were used on the initial tests, but speeds up to about 300 m/min. can be obtained with this set-up. Disks of aluminum and copper have been used for the preliminary tests. The actual set-up is shown on our Pneumo MSG-325 lathe in the photographs, Figure 2 and Figure 3.

Figure 2. Photograph of set-up

Figure 3. Pneumo lathe and video system

Using a Bausch and Lomb "Microzoom" microscope and a video camera mounted to the lathe, we have observed and recorded some of the experiments. The video recorder and TV can be seen on top of the machine tool control in Figure 3. To get useful images for studying chip thickness or chip velocity, we do not currently have adequate lighting for the optical system. We are researching better lighting methods and hope to be able to observe the cutting process at 100X magnification with a high speed video system in the future. By using a high-speed video recording system, we will attempt to measure the chip velocity near the tip of the tool. By scribing fine lines on the face of the disk, we may be able to look at the deformation as well as measure velocity. The chip velocity is related to the chip compression factor.

Chip compression factor

Examining the chip compression factor in three-dimensional machining is very difficult, but is somewhat easier in the two-dimensional method used here. For the two-dimensional geometry, the chip compression factor, is the same as the chip thickness ratio, or $\lambda = T_1/T_2$, where T_2 is the chip thickness and T_1 is the depth of cut, as illustrated in Figure 4.

Figure 4. Orthogonal cutting, chip thickness

The chip compression factor is important in studying the cutting process. Following the approach described in Trent,⁷ if the chip compression factor is known, we can calculate the chip velocity, the shear plane angle, and the total plastic shear strain. Knowing the shear plane angle, and the yield shear strength of the material being cut, the cutting force can be calculated. From the total shear strain and assuming all the heat generated remains in the chip, the temperature rise of the chip can be calculated.

The most straight forward way to measure the chip compression factor or thickness ratio in our experiments is to examine the chips in a high power measuring microscope and measure the chip thickness, T_2 . The thickness, T_1 , is simply the depth of cut, or the feed rate divided by the rpm for our set-up. Then, $\lambda = T_2/T_1$ can be calculated. However, accurately measuring T_2 on photomicrograph is difficult with the size of chips we are interested in.

The chip compression factor can also be measured by examining the length of the chips, or $\lambda = L_1/L_2$. To make it easier to examine chip length, we have cut notches in the circumference of the disk for some tests. We are currently using disks with a 0.13 mm notch every 5° around the disk. Therefore, the undeformed length of the chip can be easily calculated. For the geometry, we are using the length of the undeformed chip is about 2 mm, and decreases a very slight amount as the chips are cut.

Preliminary results

Our first tests have been with copper and aluminum disks. An example of the chip produced in cutting copper is shown in Figure 5. This microscope photo at 180X magnification shows the edge of the chip.

Figure 5. Photo of chip, 180X magnification

Using a map distance measuring wheel, I estimated the chip length to be 0.83 mm by tracing along the edge of the chip in the photomicrograph. The undeformed length of the chip (the distance between notches on the disk) was 1.93 mm. Therefore, the chip compression factor for this test was $\lambda = 1.93/0.83 = 2.3$.

For comparison, Kronenberg⁸, gives a value of about 1.8 for when machining copper with a diamond tool. Kronenberg does not present a lot of information on the test which produced the results he quotes, so a direct comparison may not be meaningful; however, it indicates we are probably in a reasonable range with our preliminary data.

We are testing other methods of examining the chips and measuring the chip compression factor, such as casting the chips in plastic and polishing in the standard metallurgical methods. With this approach, we may be able to measure thickness, T_2 , and the length, L_2 , on the same chip comparison.

Another method of measuring chip compression factor suggested by Trent⁷ is to weigh the chip and measure its length. Then, the undeformed length would not have to be known, only the width. (In all of these methods, we assume the width to be constant and equal to the thickness of the disk being cut.) The method of weighing the chip may be more appropriate in conventional machining, but because of the very small chip sizes usually found in diamond turning, it might not be as useful. For example, the chip shown in Figure 5 was cut with a depth of cut of 1.25 micrometer from a disk 0.25 mm thick. Therefore, the mass of the chip would be only about 5 micrograms. The small mass is not impossible to measure, but may be very difficult to measure with the required precision. The method may be useful though in attempting to measure the chip compression factor in more brittle materials that do not produce a continuous chip. In these cases, a piece of a chip could be used if we could measure its length and mass.

Conclusions and future work

The preliminary tests with our orthogonal cutting set-up have demonstrated:

- a. The method is successful in producing uniform chips which are relatively easy to study,
- b. the test disk can be easily checked for surface finish in the direction-of-cut and normal to the direction-of-cut, and
- c. the cutting process can be observed with a microscope-video system.

We plan to improve the lighting system to allow high-speed video recording using a Spin-Physics system with up to 1,000 frames per second. This high-speed video will allow the chip formation to be observed in slow motion, which may add to the understanding of the process in some situations.

Future experiments being planned include:

1. Testing different tool geometries (rake angle, clearance angles, crystal orientation) with materials that diamond turn good, such as aluminum, copper, gold, and plastics.

2. Testing with materials, not normally diamond turned, such as beryllium to investigate wear and damage of the diamond tool, and compare parameters such as the chip compression factor.
3. Develop and test a cutting experiment that could be meaningfully compared to calculations. This would involve having a very well characterized material (with good dynamic stress-strain data, etc.), as well as a well characterized diamond tool.

The analytical work may be done at Los Alamos, or we may seek a joint project with a group outside the Laboratory to carry out an analytical study of some particular cases.

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References

1. Rhorer, R. L., A. L. Gauler, E. W. Colston, and J. R. Ruhe, "Ultraprecision Machining of Optics at Los Alamos," Proc. Soc. Photo-Optical Instrum. Eng., San Diego, California, August 25-26, 1981, Vol. 306, Pg. 122-129.
2. Rhorer, R. L., "Update on Precision Machining at Los Alamos," Proc. Soc. Photo-Optical Instrum. Eng., San Diego, California, August 24-26, 1983, Vol. 433, Pg. 107-111.
3. Hurt, H. H., "Tribological Consideration of the Diamond Single-Point Tool," Proc. Soc. Photo-Optical Instrum. Eng., San Diego, California, August, 1984, Vol. 508, Pg. 126-131.
4. Hannah, P., "The Physics of Diamond Tools," Proc. of the SPIE, this Vol., 1986.
5. Evans, C and Teague, C., personal communication with P. Hannah and R. Rhorer, May, 1986, at the Nat. Bureau of Standards.
6. Dow, Thomas A., (Editor) "Third Annual Report on Precision Engineering," North Carolina State University, Precision Engineering Laboratory, 1986.
7. Trent, E. M., Metal Cutting, Butterworth & Co., London, 1977.
8. Kronenberg, Machining Science and Application, Pergamon Press, Oxford, 1966, Pg. 6.