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DIAMOND-TURNING HP-21 BERYLLIUM TO ACHIEVE AN OPTICAL SURFACE

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September 25, 1975

MASTER

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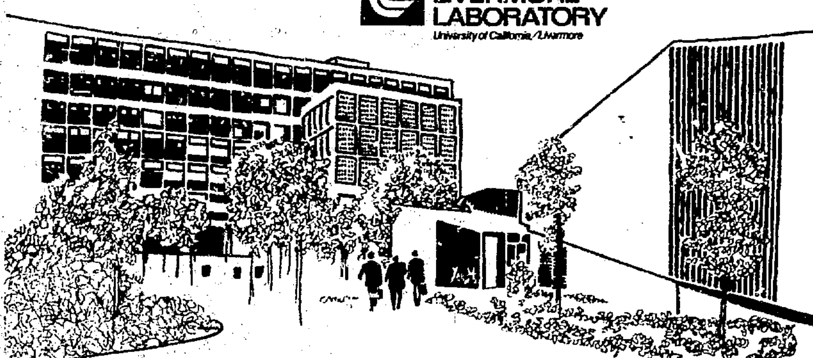

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DIAMOND-TURNING HP-21 BERYLLIUM TO ACHIEVE AN OPTICAL SURFACE

Abstract

The investigation of diamond turning on beryllium was made in anticipation of obtaining an optical finish. Although results of past experiences were poor, it was decided to continue diamond turning on beryllium beyond initial failures. By changing speed and using coolant, partial success was achieved. Tool wear was the major problem. Tests were made to establish and plot wear as a function of cutting speed and time. Slower speeds did cause lower wear rates, but at no time did wear reach an acceptable level.

The machine, tools, and procedure used were chosen based on the results of our preliminary attempts and on previous experience. It was unnecessary to use an air-bearing spindle because tool failure governed the best finish that could be expected. All tools of diamond composition, whether single cryatal or polycrystalline, wore at unacceptable rates. Based on present technology it must be concluded that beryllium cannot be feasibly diamond turned to achieve an optical finish.

Introduction

The United States Air Force, in conjunction with Honeywell, Inc., Radiation Center of Lexington, Massachusetts, is engaged in establishing new or improved fabrication and assembly techniques for avionics systems and subsystems. This study includes an investigation of diamond-turning techniques for achieving optical finishing of Kawecki HP-21 beryllium.*

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Because of extensive prior experience with diamond-turning techniques and the availability of specialized equipment, Lawrence Livermore Laboratory has been asked to undertake the machining investigation.

The objective of this investigation is to obtain an optical surface on an HP-21 beryllium test specimen, using diamond-turning techniques. In the event that an optical surface cannot be generated by this method, complete documentation will be furnished to the sponsor to aid in subsequent investigations.

Material

The test material used in this investigation is an HP-21 beryllium rod, 1.5 in. in diameter by 3 in. long, supplied by Honeywell. The mechanical properties of this material are:

a) Ultimate tensile strength = 45,000 psi

b) Yield strength = 35,000 psi

c) Elongation = 2% in 1 in.

d) Grain size is listed as not to exceed 25 μ

The chemical composition for HP-21 is given in Table 1.

Table 1. Chemical composition of HP-21 beryllium.

Beryllium assay	% minimum	98.0
Beryllium oxide	% maximum	2.0
Aluminum	% maximum	0.15
Carbon	% maximum	0.15
Iron	% maximum	0.18
Magnesium	% maximum	0.08
Silicon	% maximum	0.08
Other metallic impurities, each	% maximum	0.04

Note: The minimum bulk density is given at 1.84 g/cm^3. (Theoretical densit_ is 1.85 g/cm^3.)

As shown in Table 1 there is a considerable number of alloy elements and impurity metals in the HP-21 composition. Because of severe diamond wear problems the HP-21 beryllium was examined by a 14-kV x ray to determine the distribution and size of impurity elements as a possible explanation of the rapid diamond wear. Results of this examination are in Appendix B. It can be seen that a large number of impurity elements are distributed throughout the material. Although an investigation was not made to determine the actual form in which these elements were present, they are thought to be combined as beryllium carbide, $AlFeBe_4$, and $FeBe_{11}$.

To give some idea of the abrasiveness of these hard intermetallic compounds, the following figures are cited: diamond registers 10 on Mohs' scale, beryllium oxide 7.8, aluminum oxide 9+, and beryllium carbide 9+. All these particles are very abrasive, and some are used as lapping compounds.

Investigation of single beryllium crystals reveal the extreme anisotropy present. For example, preliminary compression tests by London *et al.*[1] and McLean[2] indicate that plastic flow and/or fracture occur at stresses on the order of 300,000 psi at room temperature along the c axis. However, shear stresses required to initiate fracture along the basal plane are only about one-thousandth of that necessary for c-axis fracture. The above figures are for single crystals, but it could be expected that when machining polycrystalline beryllium, a wide variation of mechanical shear stresses would be encountered due to differences in grain orientation.

Equipment and Tooling

HARDINGE PRECISION LATHE

We used a Hardinge model HLVD-11, 1.5-hp precision lathe. This lathe was chosen because of its excellent spindle bearings and its ability to achieve optical finishes. It is equipped with an infinitely variable spindle speed and carriage feed drive ideally suited for machining studies. The minimum speed is 30 rpm, and the minimum crossfeed rate is 0.130 in./min.

The lathe was enclosed in a protective hood produced by Allied Engineering and Production Corporation to contain any beryllium chips produced during the test. A high-velocity air system pulled all beryllium particles into a special filtering system. The lathe and hood setup are shown in Fig. 1.

Pending the successful outcome of initial test cuts, the Moore diamond-turning machine, using an air-bearing spindle, was to be used to achieve the ultimate in precision turning. However, because of problems that will be discussed later, this machine was not required to carry out the test.

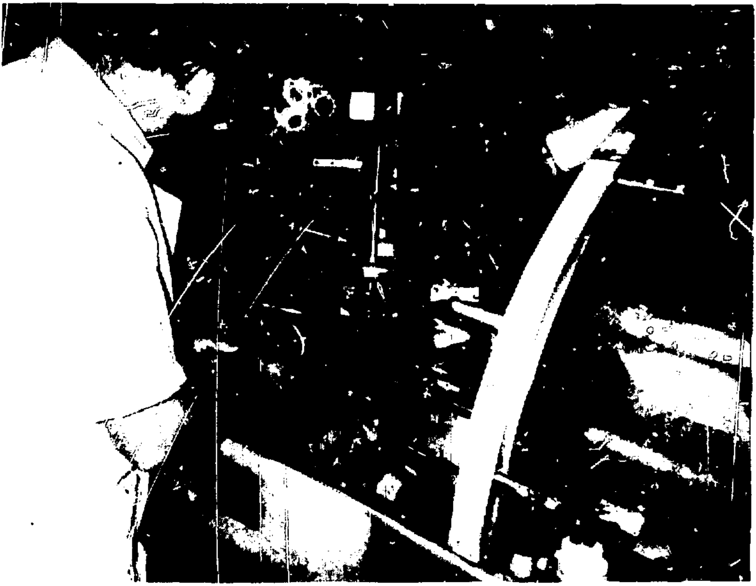


Fig. 1. Harding Lathe and enclosure.

CUTTING TOOLS

Although this study primarily investigated diamond turning on beryllium, other turning tools were also tried because of the rapid wear on diamond. The various tool materials used are shown in Table 2. They include single-crystal diamond, polycrystalline diamond, carbide, and ceramic tools.

CUTTING FLUIDS

Several cutting fluids were also used to ascertain their effect in reducing tool wear. These fluids included liquid Freon TF (trichlorotrifluoroethane), Freon spray (dichlorodifluoromethane), and perchloroethylene. The fluids were intended to reduce both the temperature at the tool chip interface and friction, and a steady flow of fluid was maintained on the tool by a special dispenser (Figs. 1 and 2).

Table 2. Tool materials used in beryllium machining study.

Tool types	Nose radius, in.	Clearance angle
Moore single-crystal diamond	0.030	4° 40' to 9° 38'
Megadiamond, polycrystalline diamond	0.015	4° 20'
907 carbide	0.030	7° 40'
Co-6 ceramic	0.030	4° 40'
Citco single-crystal diamond	0.030	5°

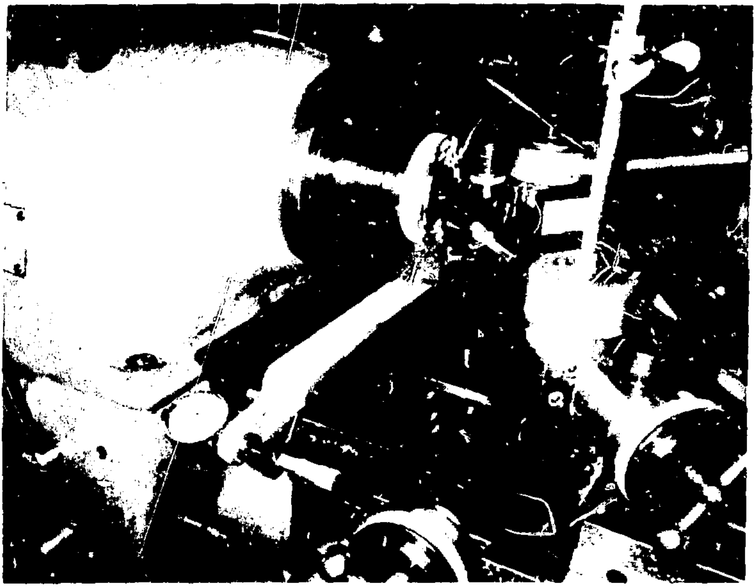


Fig. 2. Collet setup for machining disks.

Test Procedure

The basic procedure followed in evaluating the turning capabilities of various tool materials on beryllium was as follows.

FACING CUTS - PRELIMINARY TESTS

The beryllium test log was mounted in a four-jaw chuck in the test lathe, and the diamond tool was held in an Aloris tool holder as shown in Fig. 2. A center hole was drilled in the test specimen to overcome problems of establishing exact set-height. The tool was fed radially outward from the center of the test specimen. A Port-A-Tak was used to get exact spindle rpm, and a stopwatch was used to check the cross-slide feed rate. In most instances a 0.001-in. (0.0254-mm) depth of cut was used with a feed rate of approximately 0.001 in./rev. (0.0254 mm/rev.).

During the initial cut, the diamond-turned surface appeared to be of marginal success. However, we observed that significant tool wear had occurred during the cut. As a result of this and several other test face cuts, we decided that a series of cuts should be taken on the periphery of the workpiece to maintain a constant surface feed and to evaluate the tool wear rates at various cutting speeds. We used Freon TF cutting fluid on the final test face cut to reduce temperature and friction, and it proved to be helpful in achieving a better finish.

LONGITUDINAL TURNING CUTS - WEAR TESTS

These cuts were made to maintain constant surface speeds for establishing tool wear rates. The turning test involved operating the lathe at various speeds from 30 to 2000 rpm. Feed rates were selected to maintain 0.001 in./rev. (0.0254 mm/rev.). To minimize the difficulty of accurately maintaining the low feed rates at low spindle rpm's, we added a special variable-speed drive to the carriage. This consisted of a gear-reduction Bodine motor driven by a Miniark variable-speed control unit. The carriage was driven through a double O-ring belt-drive system.

FACING OF DISK SPECIMENS

To provide a series of historical samples, 0.25-in.-thick (6.35-mm-thick) specimens were parted off from the 3-in. (76.2-mm) test log, and a special soft-jaw collet chuck was used to hold them (Fig. 2). It was on these specimens that the effects of various tool materials were investigated.

Preliminary tests showed it to be unnecessary to feed at rates of less than 0.001 in./rev. (0.0254 mm/rev.). The minimum feed the machine drive system could produce was 0.130 in./min (3.302 mm/min). At 100 rpm this would achieve 0.0013 in./rev. (0.033 mm/rev.), a suitable feed rate for these tests.

Test Data and Discussion of Results

FACING CUTS - PRELIMINARY TESTS

Test Cut No. 1

For the first cut, the beryllium test log was mounted in a four-jaw chuck. The test log was drilled with a No. 2 center drill, the face was cleaned up with a carbide tool, and the edge was chamfered. Moore diamond tool #L-44 was mounted in the Aloris tool holder. The spindle speed was set at 900 rpm, the feed rate at 0.00035 in./rev. (0.009 mm/rev.), that is, 0.320 in./min (8.128 mm/min), and the depth of cut at 0.001 in. (0.0254 mm). This should provide a 0.5-μin. (0.0127-μ) peak-to-valley (P/V) theoretical finish.

During the first portion of the cut, out to about a 1-in. (25.4-mm) diameter, the machined surface was reflective. The remainder of the machined surface was torn. The tool was removed and examined by microscope. Approximately 0.002 to 0.003 in. (0.0508 to 0.0762 mm) flank wear land was present (Figs. 3a, 3b, and 3c).

Test Cut No. 2

The work was then re-inserted into the chuck, and a second pass was made at 0.130 in./min (3.302 mm/min) feed rate and at 375 rpm. The intent of this second cut was to help ascertain the predominant failure mode on the diamond tool (i.e., did the thermal mode or the abrasive mode predominate?). A surface profile trace of the test log face was made revealing the rapid diamond wear rate. During the first 25 revolutions of the cut, the surface roughness was in the 3- to 5-μin. (0.07- to 0.127-μ) range, but rapidly deteriorated to a rough, torn surface appearance. This trace is shown in Fig. 4.

The microscopic examination of the workpiece surface is shown in Figs. 5a and 5b. Figure 5a was taken at the beginning of the cut and Fig.

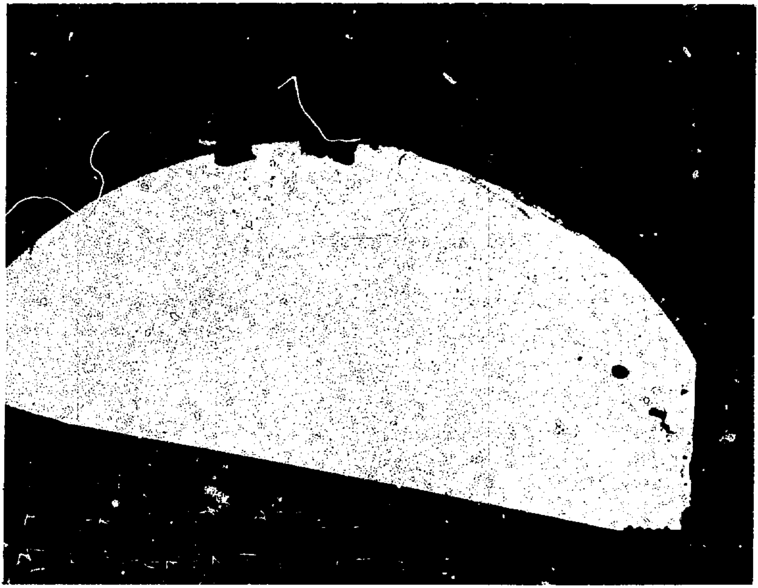


Fig. 3. Moore diamond tool #L-44. (a) Top view, 121X.

5b was taken 0.125 in. (3.175 mm) from the end of the cut. Figure 5a confirms the 3- to 5-μin. (0.07- to 0.27-μ) P/V roughness shown on the profile trace, while Fig. 5b shows a severe form error due to excessive tool wear and pressure. The tool was also examined under the microscope and revealed a series of parallel grooves in the wear flank. These grooves, known as "Pekelharing grooves," have a spacing between them approximating the feed rate (Fig. 3d). The mechanism of tool failure is not known at this time, but it appears to be primarily an abrasive type wear.

Test Cut No.3

Tape was placed over the first end to protect it for later microscopic examination, and the workpiece was reversed in the chuck. A new

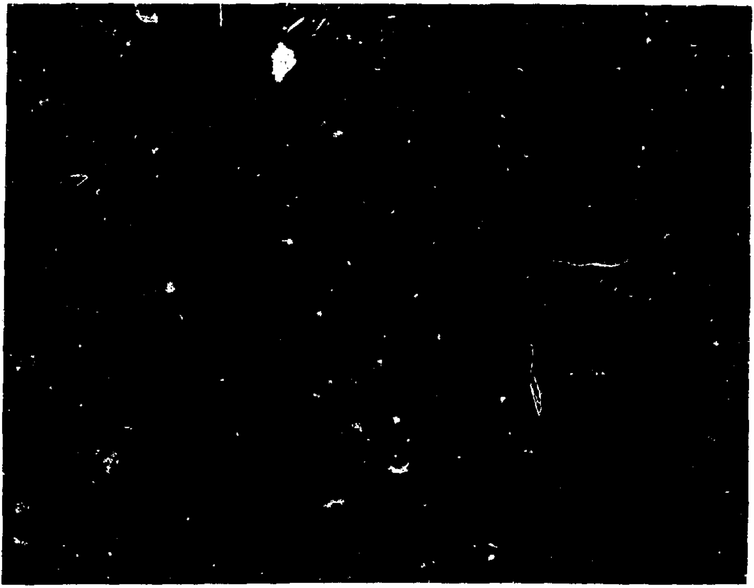


Fig. 3. Moore diamond tool #L-44. (b) Front view showing flank wear, 337X.

center hole was drilled and a cleanup cut was taken with a carbide cutting tool. A new diamond tool was used (Moore #L-'?). Feed rate was 0.130 in./min (3.302 mm/min), speed 375 rpm, and depth of cut 0.001 in. (0.0254 mm). The intent of this cut was to ascertain repeatability of the test using a new diamond tool.

Following this test the specimen was examined under the microscope, and photomicrographs of the specimen were taken. Clevite surface finish analyzer readings were also taken for both ends of the specimen and correlated with the interferometric photographs. This test definitely confirmed the repeatability of the tool failure mode. (Figs. 6a, 6b, and 7).

After some discussion we decided that both cutting temperature and abrasiveness of the workpiece may

Fig. 3. Moore diamond tool #L-44. (c) Wear land caused by first pass, 611X.

be the cause of rapid tool wear. A series of experiments was set up in which it was felt important to reduce speed, apply cutting fluid, and check the effects of tool temperature and abrasiveness.

Test Cut No. 4

A cut was made using carbide grade 907 to compare the wear rates of carbide tools with that of diamond. Two cuts were taken, one on each end of the workpiece. These were later evaluated, and we found that a finish of 30 to 40 µin. (0.76 to 1.01 µ) P/V was obtained. This finish, while good, was not of optical quality. Wear rate on the carbide was approximately one-half that of the single-crystal diamond. Cutting conditions for the carbide tool were

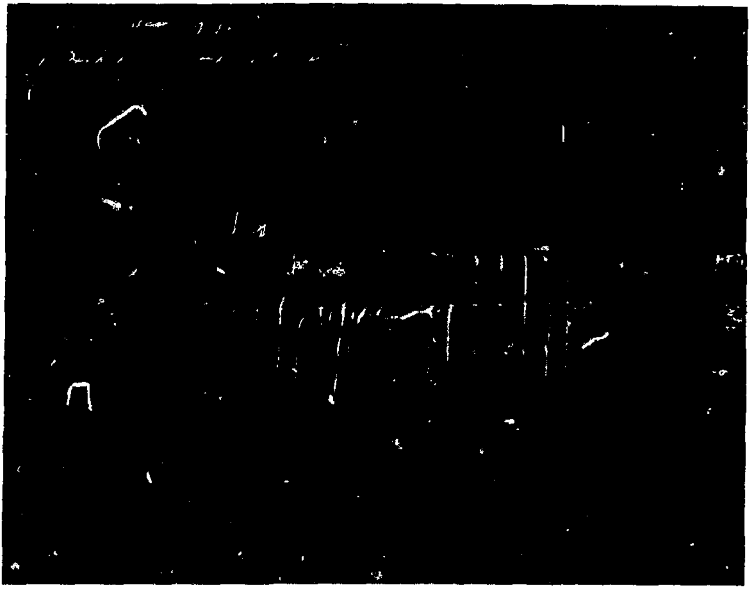


Fig. 3. Moore diamond tool #1-44. (d) Wear land caused by second pass, 611X.

750 rpm speed and 0.600 in./min (15.24 mm/min) feed rate. No cutting fluid was used with this cut. Tool flank wear was 0.0016 in. (Figs. 8 and 9b).

Test Cut No. 5

The next cut was made to ascertain the combined effects of temperature- and friction-reducing methods on diamond turning as indicated previously. A slow rpm with a coolant was used. The speed was 100 rpm, the feed rate was standardized at 0.130 in./min (3.302 mm/min), and a Moore diamond tool (#E-4) was used. The depth of cut was approximately 0.0005 in. (0.0127 mm). The cutting fluid Freon TF was used. The specimen and the diamond tool were examined for flank wear after the cut. Flank wear

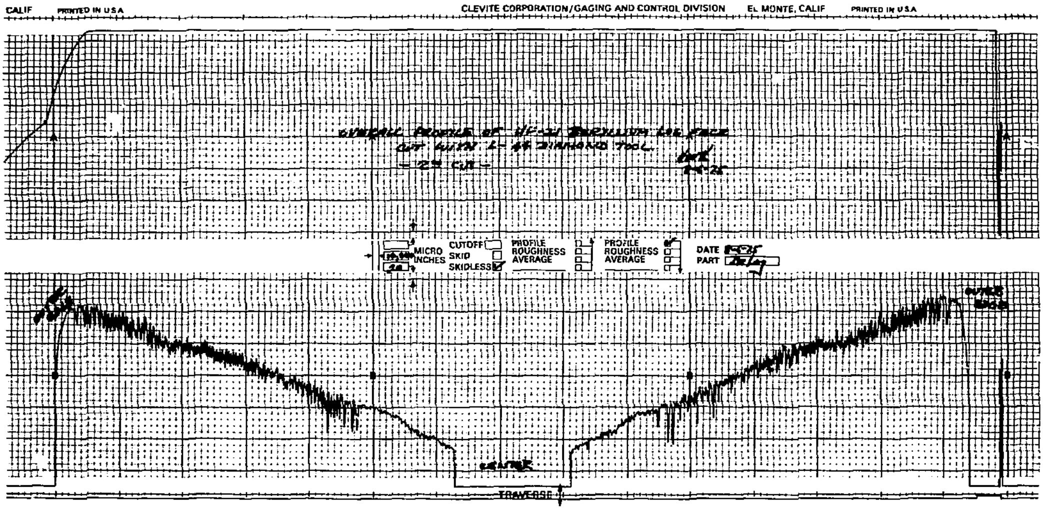


Fig. 4. Trace of face cut with tool #L-44: second pass, no coolant.

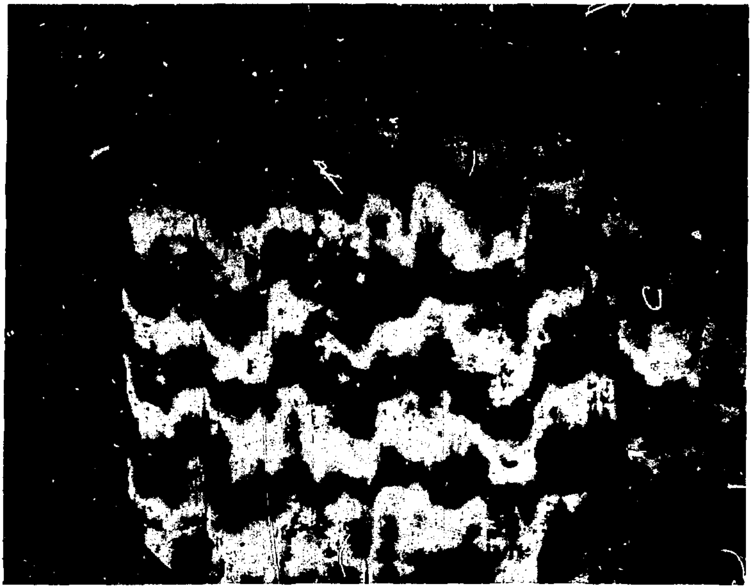


Fig. 5. Interference photomicrographs of Test Cut No. 2. (a) Finish at start of cut, 337X.

was found to be about 0.0018 in. (0.04572 mm), and a 2- to 30-μin. (0.05- to 0.76-μ) P/V surface finish was achieved (Figs 9a, 10a, 10b, 11a, 11b, and 12).

Test Cut No. 6

We learned from Bill Pope of the Megadiamond Corporation that diamond begins to graphitize at approximately 1200°C or below. We also learned that beryllium acts as a catalyst in promoting graphitization. This, along with information on grinding steel with diamond tools,[3-5] led to the formulation of the theory that the failure mechanism when machining beryllium is graphitization. The diamond wear surface appeared to graphitize, after which it was rapidly abraded by hard particles and the beryllium chip. Consequently, tests were made at reduced temperatures to help reduce the rate of diamond graphitization and flank wear.

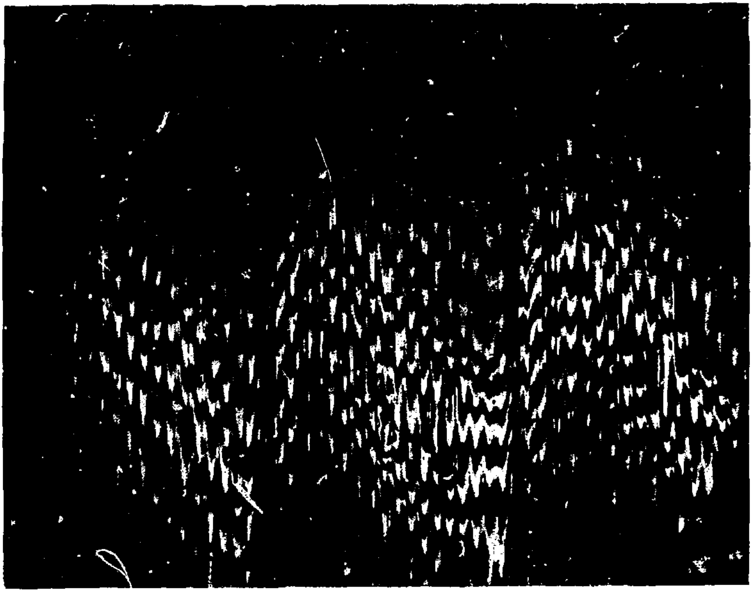


Fig. 5. Interference photomicrographs of Test Cut No. 2. (b) Finish 0.125 in. from end of cut, 337X.

One attempt to reduce graphitization was to use a bonded polycrystalline diamond, anticipating that the bonding agent would enhance heat conductivity and consequently keep the tool temperature lower. A Megadiamond tool (#2-A) was held in the negative rake tool holder, spindle speed was set to approximately 100 rpm, and feed rate was 0.130 in./min (3.302 mm/min) with a depth of cut of 0.001 in. (0.0254 mm). Freon TF was used as a cutting fluid. The nose radius was small on this tool, approximately 0.007 in. (0.1778 mm). Because of the poor radius of the unlapped tool and the resulting poor surface finish, an effort was made to obtain polycrystalline diamonds with a lapped face. Several specimens were provided for the experiment by Megadiamond Corporation.

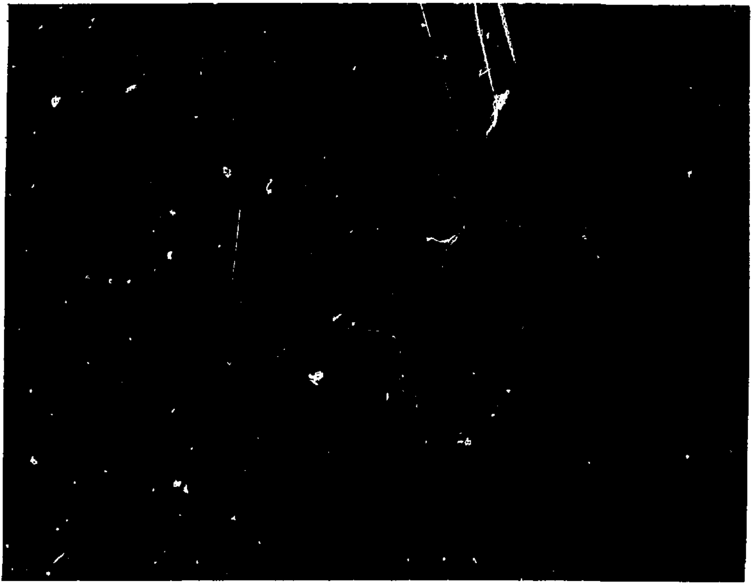


Fig. 6. Moore diamond tool #L-42. (a) Top view, 121X.

A comparison of the results of the facing cuts is given in Table D-1 in Appendix D.

LONGITUDINAL TURNING CUTS - WEAR TESTS

Following the receipt of the lapped Megadiamond inserts, we made a series of longitudinal turning cuts at constant surface speed to ascertain the tool wear rate at various cutting speeds. These tools had a 0.015-in. (0.381-mm) nose radius and consequently required smaller feed rates than those for the single-crystal diamond tools to achieve the same theoretical surface finish. The coolant used was Freon TF. Cutting conditions were standardized at a depth of cut of 0.001 in. (0.0254 mm), and feed rate was set at 0.105 in./min (2.667 mm/min).

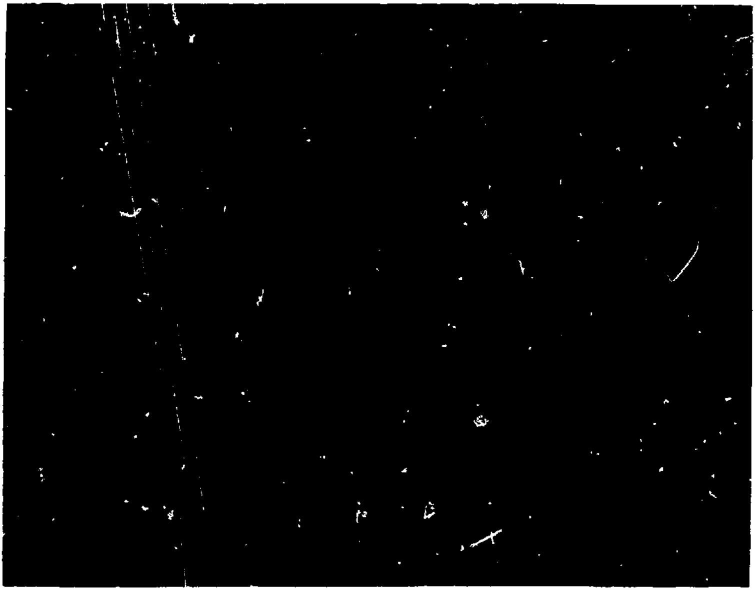


Fig. 6. Moore diamond tool #L-42. (b) Front view showing flank wear, 337X.

Flank wear was measured using a Bausch and Lomb Stereozoom Microscope with a 20X eyepiece and 0.7 to 3.0X zoom lens. An eyepiece reticle was used for measuring flank wear. A stopwatch was used for accurately measuring cutting time, and tests were run at total lapsed times of 10, 20, 50, 100, 200, and 500 s. Data from these tests were plotted and are shown in Figs. 13 through 20. A log/log plot for the tool-life curve of diamond tool wear is shown in Fig. 20. This plot shows that diamond tool life follows the general Taylor Relationship.

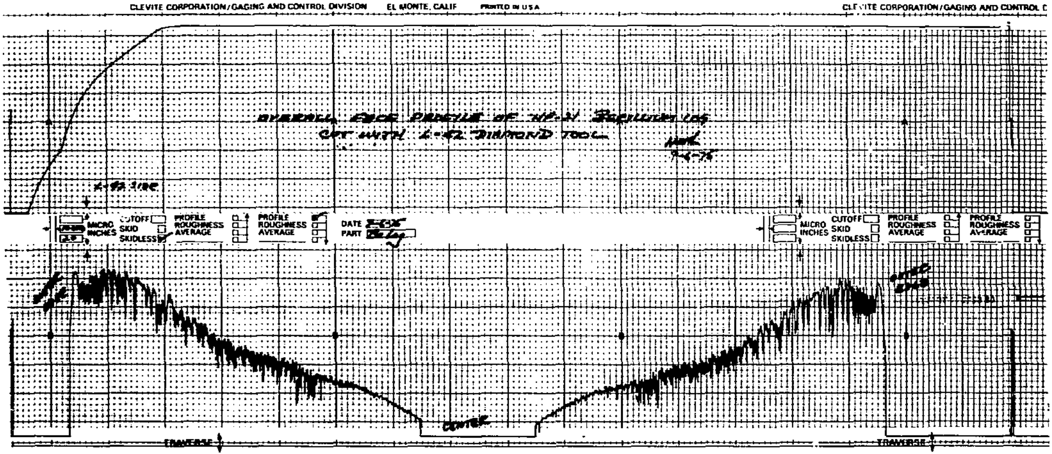


Fig. 7. Trace of face cut with tool #L-42: no coolant.

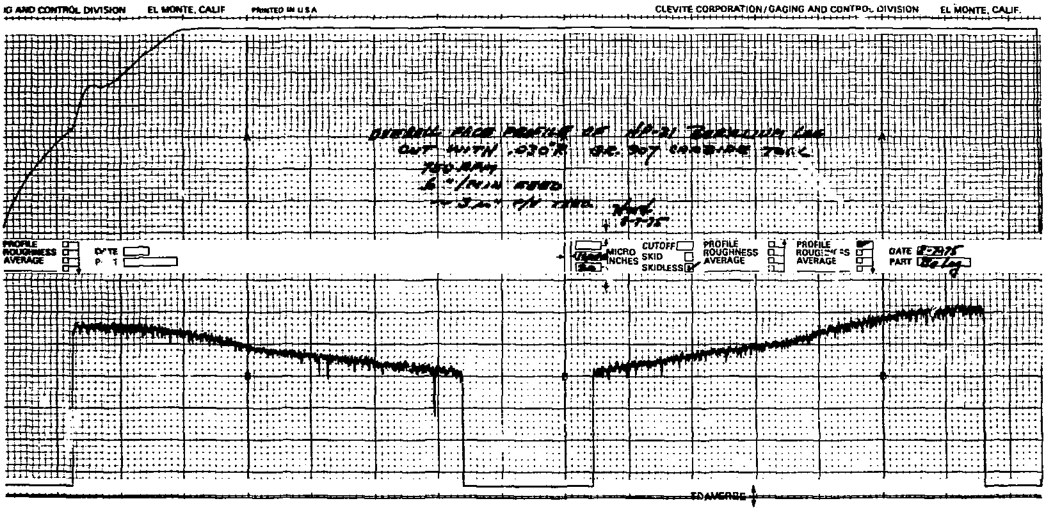


Fig. 8. Trace of face cut with 907 grade carbide: no coolant.

Fig. 9. Surface photographs. (a) Diamond turned with Moore tool #E-4, 3X. Pencil shows reflectivity.

Fig. 9. Surface photographs. (b) Cut with 907 grade carbide tool, 3X.

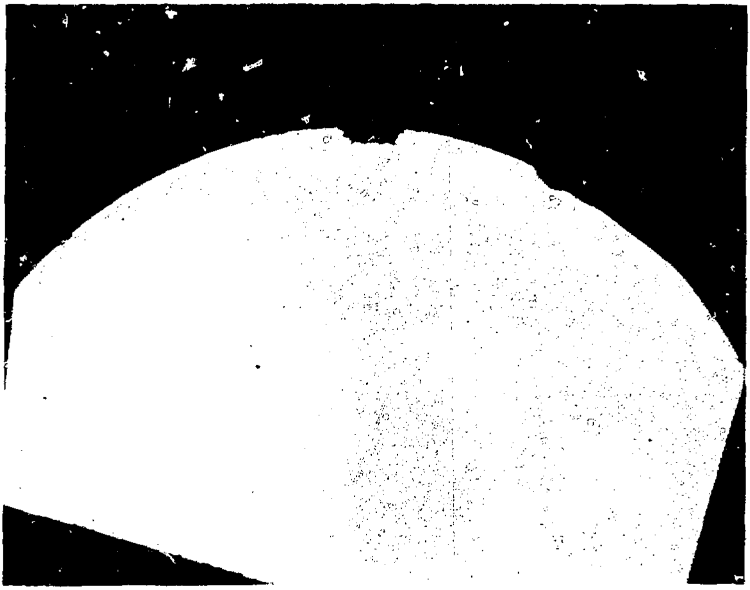


Fig. 10. Moore diamond tool #E-4. (a) Top view, 121X.

Fig. 10. Moore diamond tool #E-4. (b) Front view showing flank wear, 337X.

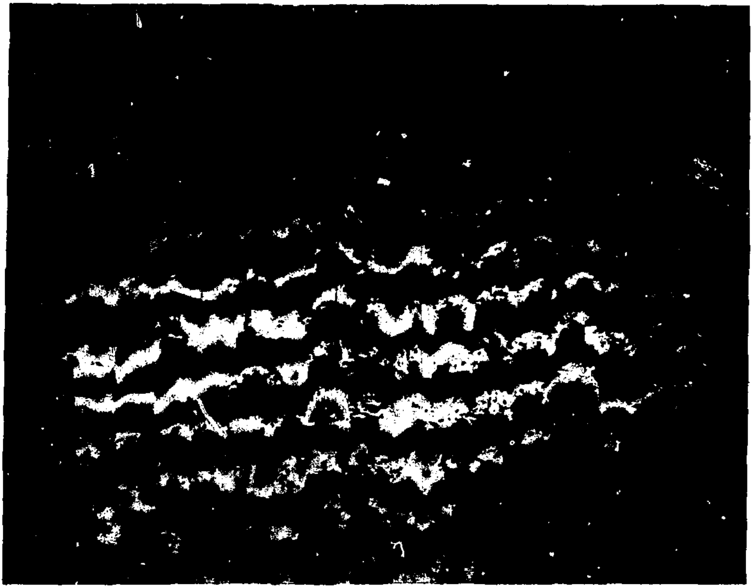


Fig. 11. Interference photomicrographs of Test Cut No. 5. (a) Finish at start of cut, 337X.

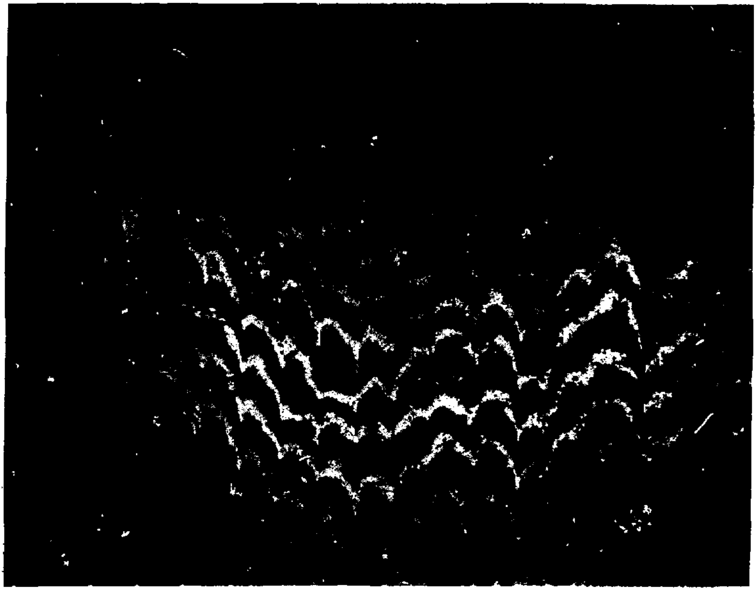


Fig. 11. Interference photomicrographs of Test Cut No. 5.
(b) Finish at end of cut, 337X.

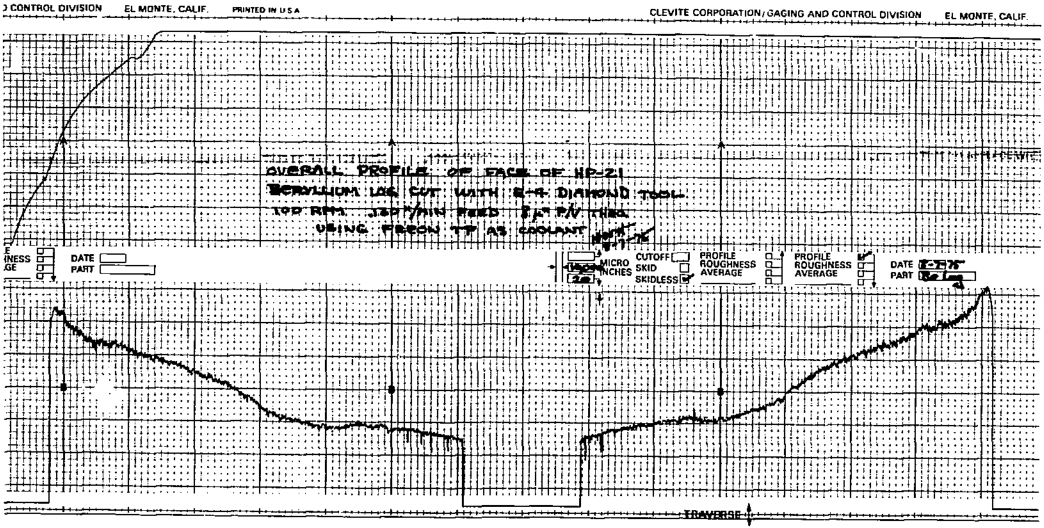


Fig. 12. Trace of face cut with Moore tool #E-4: Freon TF coolant.

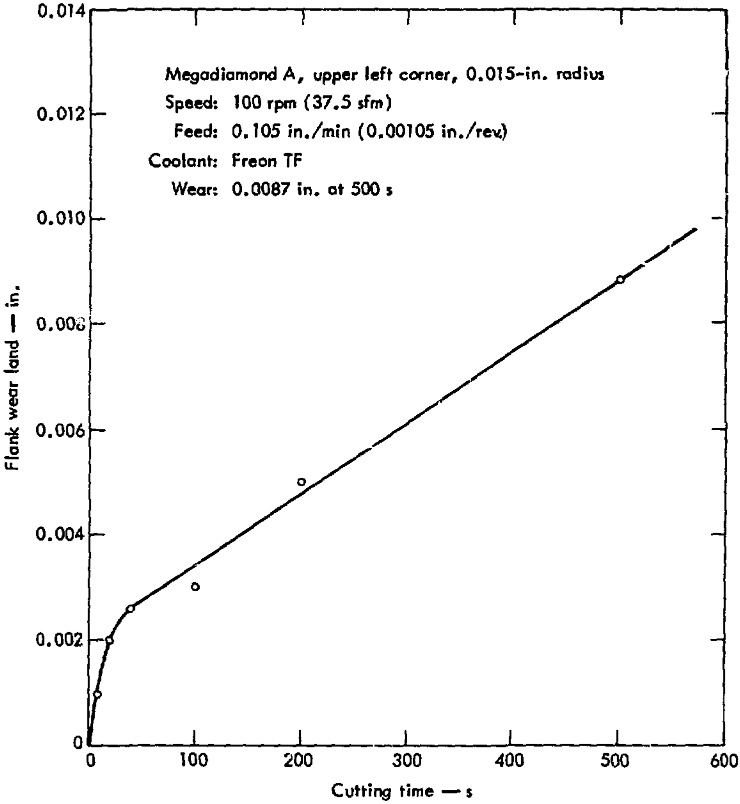


Fig. 13. Plot of tool wear for Megadiamond A, Wear Test No. 1.

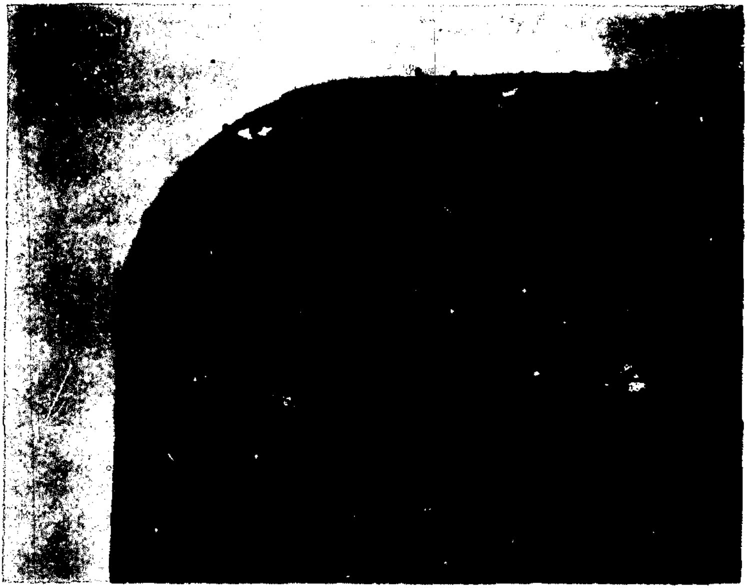


Fig. 14. Megadiamond A after Wear Test No. 1. (a) Top view, 121X.

Fig. 14. Megadiamond A after Wear Test No. 1.
(b) Front view showing flank wear, 121X.

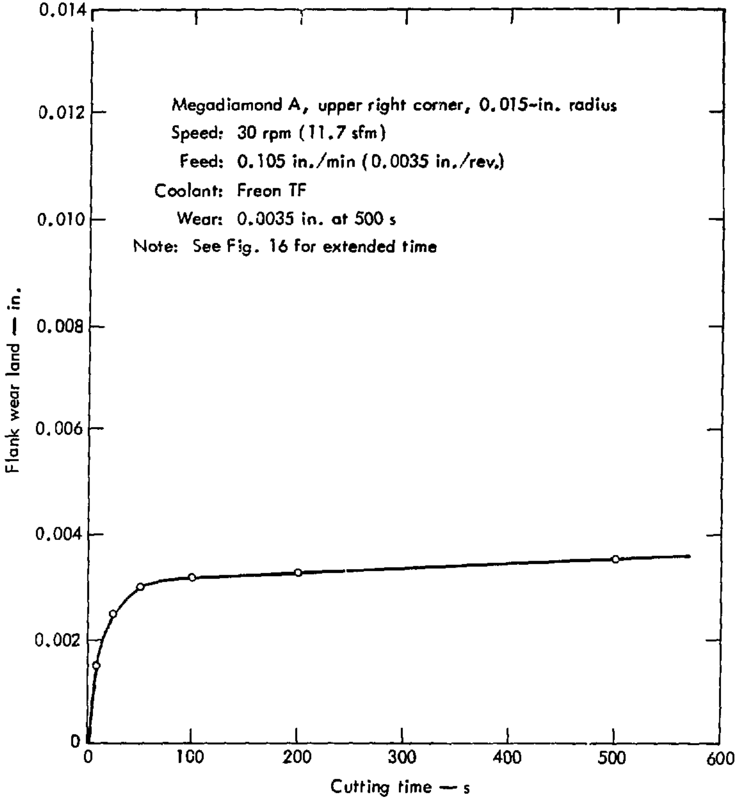


Fig. 15. Plot of tool wear for Megadiamond A, Wear Test No. 2.

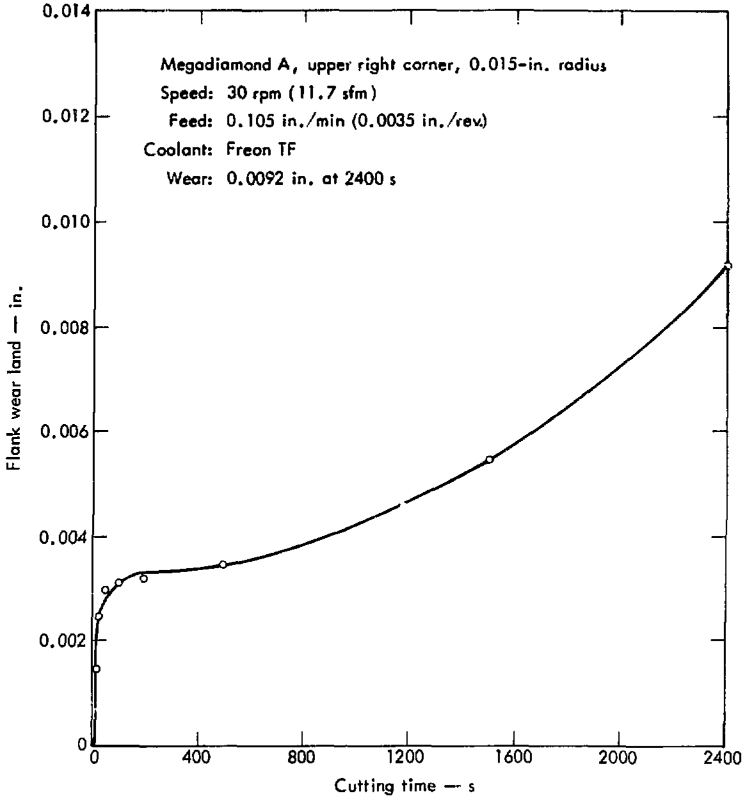


Fig. 16. Plot of extended-time tool wear for Megauiamond A, Wear Test No. 2.

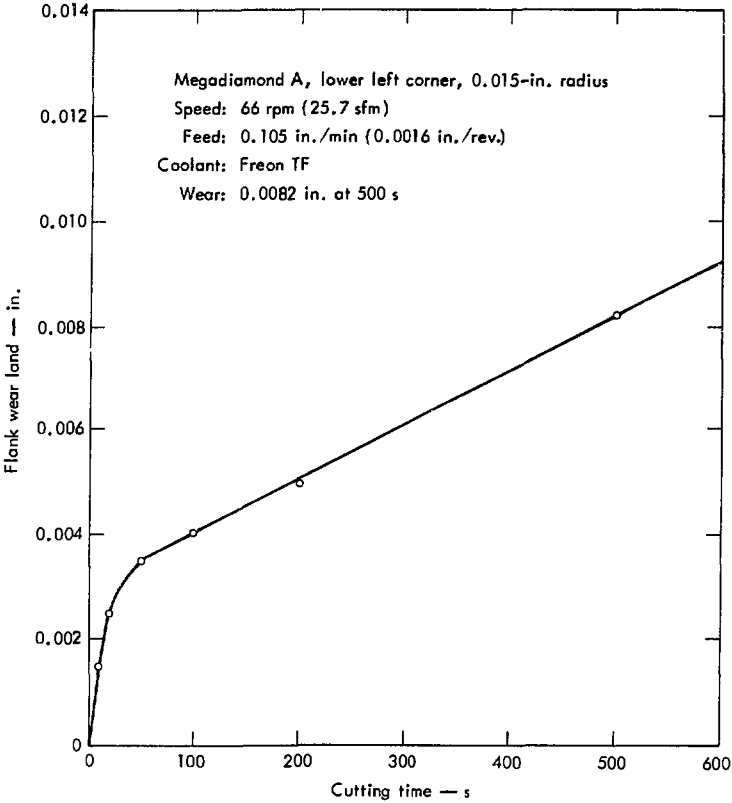


Fig. 17. Plot of tool wear for Megadiamond A, Wear Test No. 3.

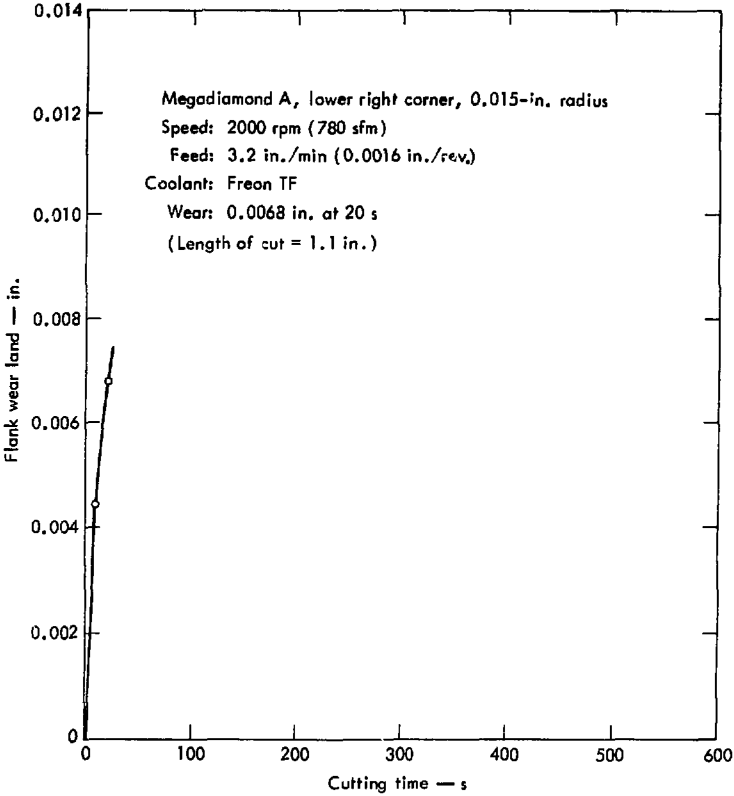


Fig. 18. Plot of tool wear for Megadiamond A, Wear Test No. 4.

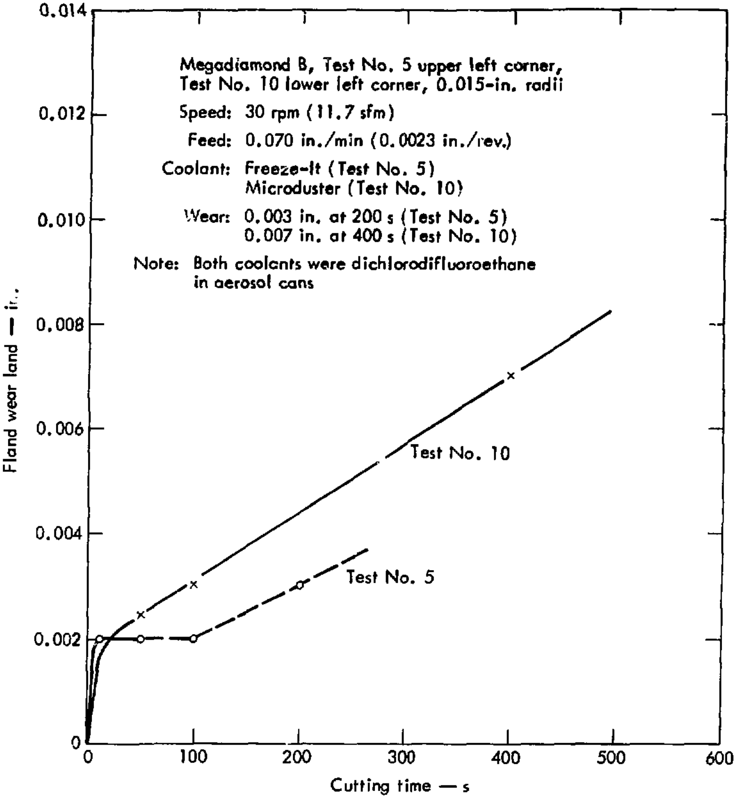


Fig. 19. Plot of tool wear for Megadiamond B, Wear Test Nos. 5 and 10.

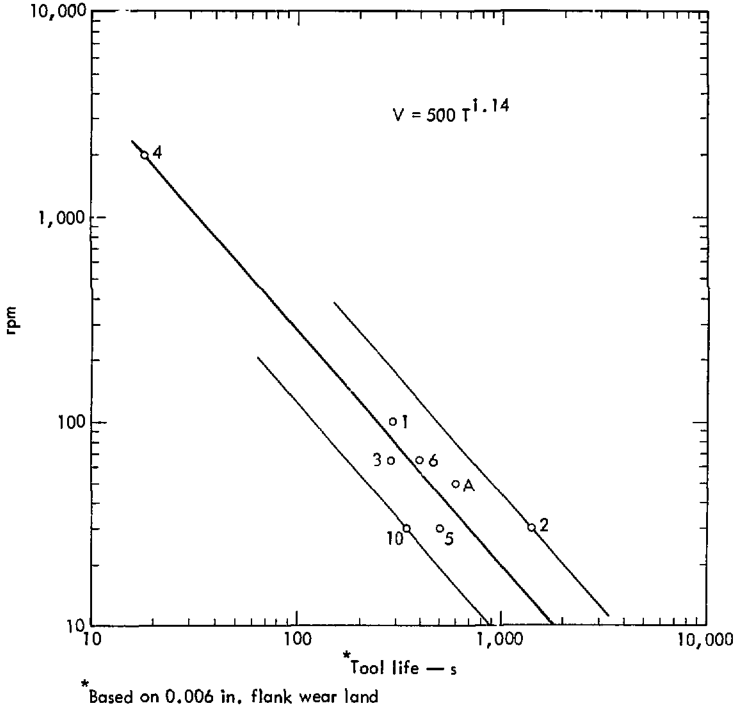


Fig. 20. Tool-life plot, log/log, Wear Test Nos. 1, 2, 3, 4, 5, 6, 10, and A.

Wear Test No. 1

Wear Test No. 1 was a cylindrical cut on a beryllium log. The tool used was Megadiamond A, upper left corner, with a nose radius of 0.015 in. (0.381 mm). The cutting speed was 100 rpm, equivalent to 39 surface ft/min. The feed rate was 0.105 in./min (2.667 mm/min), and the coolant used was Freon TF.

The total length of time on this cut was 500 s, with the tool removed and inspected for wear at total lapsed times of 10, 20, 50, 100, 200, and 500 s. The total wear was 0.0087 in. (0.2210 mm). The data taken from the different test times are plotted in Fig. 13, and the tool used is shown in Figs. 14a and 14b.

Wear Test No. 2

Wear Test No. 2 was also a cylindrical cut using Megadiamond A, upper right corner. The cutting speed was 30 rpm, and the feed rate was 0.105 in./min (2.667 mm/min). The coolant used was Freon TF.

The slower speed allowed us to cut for a considerably longer period of time, and the data taken were extended through a time period of 2400 s. At the end of the 2400-s cutting period, the tool wear measured 0.009 in. (0.2338 mm). The data from this cut are plotted in Figs. 15 and 16. Figure 16 shows wear beyond the 500-s time period.

Wear Test No. 3

Wear Test No. 3 was a cylindrical cut using Megadiamond A, lower left corner. The cutting speed for this test was 66 rpm, equivalent to 25 surface ft/min (7.62 m/min). The feed rate was 0.100 in./min (2.54 mm/min), and the coolant used was Freon TF. The duration of cut was a total of 500 s, and tool wear at the end of this time was 0.0082 in. (0.2083 mm). Data for this test are plotted in Fig. 17.

Wear Test No. 4

Wear Test No. 4 was conducted with Megadiamond A, lower right corner, at a speed of 2000 rpm in an effort to help ascertain the effect of high temperature on graphitization. Freon TF was used as a cutting fluid, and the cut was run for 20 s, after which the flank wear was found to be 0.0068 in. (0.1727 mm). This provided an additional point on the tool-life curve and was found to fit well into the previous data (Fig. 18).

Wear Test No. 5

Wear Test No. 5 was conducted using Magadiamond B, upper left corner, at 30 rpm and a feed rate of 0.070 in./min (1.778 mm/min). "Freeze-It" cutting fluid, supplied by Aervoe Products, was used in this test. The Freeze-It solution was sprayed over the tool to reduce its temperature to -50°F (-46°C).

We observed a very low wear rate on the polycrystalline diamond during the 200 s it was used in the test. Flank wear land was 0.0028 in. (0.0711 mm) (Fig. 19). A repeat of this test using "Microduster," another Freon spray, for a longer time period is also shown in Fig. 19 for comparison.

Wear Test No. A

Wear Test No. A was initially a cleanup cut for the workpiece, but was timed at 21 min; the flank wear after 21 min was 0.0103 in. (0.2616 mm). This test also provided an additional point on the tool-life curve (Fig. 20).

Wear Test No. 6

Wear Test No. 6 was a best-finish effort with polycrystalline diamond. The cutting speed was 66 rpm with a cutting time of 400 s. Freon TF was used as the cutting fluid. The theoretical surface finish was 14 μin. (0.35 μ) P/V. The actual surface finish achieved was in the range 25 to 80 μin. (0.635 to 1.65 μ) P/V. This was an unsatisfactory finish and may be partially attributed to the poor finish on the tool nose.

Wear Test No. 7

Wear Test No. 7 was the same as test No. 6, but we used a single-crystal diamond, Moore tool #E-3. Cutting conditions were the same except that the depth of cut was 0.00075 in. (0.0191 mm) instead of 0.001 in. (0.0254 mm). The surface finish was measured in the range 15 to 100 μin. (0.381 to 2.54 μ) P/V as compared to 25 to 80 μin. (0.635 to 1.65 μ) for the polycrystalline diamond. During the initial phases of the test, the single-crystal diamond produced a much better surface than did the polycrystalline diamond, but the single-crystal-diamond finish deteriorated more rapidly.

Wear Test No. 8

In Wear Test No. 8 a facing cut was made to determine if, using the information we gathered on cutting speeds and fluids, a surface finish of optical quality could be obtained. Moore single-crystal-diamond tool #E-3 was used. For this test the cutting speed was 66 rpm, and the feed rate was 0.024 in./min (0.6096 mm/min). This should have given us a theoretical finish of 0.5 μin. (0.0127 μ) P/V. The coolant used was Freon TF.

Because of the exceedingly slow feed rate and because wear is a factor of time, the tool wore to the point where tool pressure was finally high enough to break it. This occurred at approximately 17.5 min in cutting time. The finish was then evaluated and charts made.

It is interesting to note that although the theoretical finish was set at 0.5 μin. (0.0127 μ), the actual finish was not that good on the piece, partly because of the machine capability; the finish was apparently no better than would have previously been achieved with a coarser feed rate. For this reason all subsequent machining on beryllium was done at about a 0.001-in./rev. (0.0254-mm/rev.) feed rate.

Wear Test No. 9

Wear Test No. 9 was not documented because of the problem encountered with the diamond tool breaking in the previous cut. It is noteworthy that here an attempt was made to use liquid nitrogen as a coolant to further lower cutting temperatures. We found it very difficult to cool sufficiently using liquid nitrogen, because unless the material to be cut were at the ambient temperature of the liquid nitrogen, the coolant would tend to splatter off the surface and not effectively cool at all. Another problem was in trying to maintain a steady flow of liquid nitrogen. Freeze-It aerosol spray was far more effective in cooling the bar quickly.

Wear Test No. 10

In Wear Test No. 10 a cylindrical cut was taken at 30 rpm and a feed rate of 0.070 in./m (1.778 mm/min) with a cutting depth of 0.001 in. (0.0254 mm) using Microduster. By inverting the can, the freezing application that we had obtained previously with Freeze-It was duplicated.

The purpose of this test was to extend what had been done in Test No. 5 to a total time of 400 s to help plot the previous test and determine what the wear rate really would be. This was done, and there was flank wear of 0.007 in. (0.1778 mm) at the end of 400 s cutting time. This correlated well with the information obtained earlier (Fig. 19).

Wear Test No. 11

Wear Test No. 11 was a cylindrical cut using a carbide grade 907 tool at 400 rpm with a 1.1-in./min (27.94-mm/min) feed rate, and a 0.001-in. (0.0254-mm) depth of cut. This was cut dry and was merely a cleanup cut, but it was timed and the flank wear on the tool was checked. The length of the cut was approximately 1.5 in. (38.1 mm). The cutting time was 95 s. Flank wear was measured at 0.002 in. (0.0508 mm), considerably less than expected with a diamond tool.

Wear Test No. 12

Wear Test No. 12 was a facing cut using a 907 grade carbide tool with a 0.130-in. (0.762-mm) nose radius. The cutting speed was 100 rpm, and the feed rate was 0.130 in./min (3.302 mm/min). The depth of cut was 0.001 in. (0.0254 mm), and the cutting fluid was perchloroethylene, commonly called "perk."

The object of this test was to determine whether or not perk was a better cutting fluid than Freon TF. Tool flank wear was measured on this test at 0.003 in. (0.0762 mm). Because of the slow feed rate and speed the tool failed at a diameter of approximately 0.6 in. (15.24 mm). The reason for this cut at this speed and feed was to compare the carbide tool to the diamond tool at the same cutting parameters described in Wear Test No. 13.

Wear Test No. 13

Wear Test No. 13 was a facing cut also using perk as a cutting fluid. We used a Moore diamond tool #L-44 located on a fresh tool edge. The cutting speed was 100 rpm, the feed rate 0.130 in./min (3.302 mm/min), and the depth of cut 0.001 in. (0.0254 mm). The flank wear was measured at 0.0059 in. (0.1499 mm).

The finish on the piece was not as good as that obtained with Freon TF. This piece was parted off the end of the log as a disk 0.25 in. (6.35 mm) thick and 1.5 in. (38.1 mm) in diameter. This disk was then studied under the scanning electron microscope, and a microanalysis of the material was performed.

A comparison of the results of the wear tests is given in Table D-2 in Appendix D.

FACING CUTS ON DISK SPECIMENS

To document more completely the attempts to achieve an optical finish on beryllium using diamond tools, we decided to supply the requestor of this report with samples of the actual turned surfaces. This was accomplished using a carbide parting tool to part off disks approximately 0.25 in. (6.35 mm) thick and 1.5 in. (38.1 mm) in diameter. The disks were held in the aluminum soft-jaw collet in the Hardinge spindle (Fig. 2). This facilitated the easy removal and replacement of disks to maintain parallelism and allowed us to take a series of facing cuts when necessary.

In the process of cutting these disks, two trial cuts were made using ceramic tools. These cuts proved that the ceramic tool not only wore to the extent of diamond tools, but produced an unacceptable finish in terms of optical quality. The data received from these tests can be seen in Table D-3 (Appendix D), but will not be included in the sample disks provided.

Disk A

Disk A was a brass disk face cut to show the maximum machining capability of the Hardinge Lathe on a material that can be diamond turned to optical surfaces. Because brass can be readily diamond machined to optical quality surfaces, it was selected to give a reference as to what the machine could produce.

Disk A was placed in the collet, faced with a preliminary facing cut with a carbide tool, and Moore diamond tool #L-23 was inserted into the Aloris holder. The spindle speed for this cut was 400 rpm, the feed rate was 0.130 in./min (3.302 mm/min), and a 0.001-in. (0.0254-mm) depth of cut was taken. Kerosene was used as a cutting fluid.

The theoretical finish for which we set the machine spindle speed and feed rate was 0.5 μin. (0.0127 μ) P/V. The disk was then checked on the Clevite analyzer and found to have an actual surface finish of from 2 to 5 μin. (0.0508 to 0.127 μ) P/V, not including flaws in the material (voids and pits). This is the best finish that we achieved on the Hardinge Lathe.

Disk B

Disk B was also a brass disk used for establishing a surface standard. The cutting parameters used were the same as those used for all the diamond turning of the beryllium disk samples. The cutting speed was 100 rpm, and the feed rate was 0.130 in./min (3.302 mm/min). The theoretical finish of this feed rate and speed is 7 μin. (0.1778 μ) P/V. The depth of cut was 0.001 in. (0.0254 mm), and again kerosene was used as the cutting fluid.

Moore diamond tool #L-23 was again used; it had not been worn on the Disk A cut. Disk B was also checked with the Clevite analyzer and had a surface finish of 5 to 8 μin. (0.127 to 0.203 μ) P/V, excluding material flaws. The overall finish proved to be very close to the theoretical 7-μin. (0.1778-μ) P/V finish.

Disk C

Disk C was a HP-21 beryllium disk. It was cut with a 907 grade carbide tool and was included to show the surface to which all disks were cut prior to the diamond-turning cut - described as a basic surface. Disk C was provided to show the type of finish normally achieved on beryllium with standard manufacturing techniques. The cutting speed was 460 rpm, and the feed rate was 0.500 in./min (12.7 mm/min).

This should have created a 5-μin. (0.127-μ) P/V theoretical finish. The carbide tool radius is the same as that of diamond tools, i.e., a 0.030-in. (0.762-mm) radius. The beryllium was cut dry in this test. It is interesting to note that the flank wear from this cut on the carbide tool was 0.001 in. (0.0254 mm), considerably less than that noted on diamond tools in the subsequent tests.

The finish on Disk C was checked on the Clevite analyzer and found to be from 20 to 90 μin. (0.508 to 2.413 μ) P/V. The disk flatness was within 100 in. (0.00254 mm) of the capability of this machine when compared to those cuts previously made on the brass disks. The concavity of the carbide-turned face did not result in a significant increase in depth of cut for subsequent diamond-tool cuts.

Disk D

For the Disk D test a diamond tool manufactured by Moore (#L-45) was used. This tool had a 0.030-in. (0.762-mm) nose radius. The cutting speed was 100 rpm, and the feed rate was 0.130 in./min (3.302 mm/min). This was intended to give a surface finish comparable to the brass Disk B, 7 μin. (0.1778 mm) P/V. The depth of cut was 0.001 in. (0.0254 mm), and Freon TF was used as a cutting fluid.

By visual inspection we found a deterioration of finish with tool wear as it goes across the cut. The finish at the center of the disk measured 5 μin. (0.127 μ) P/V and compares well to the finish achieved on brass; however, as the tool progressed across the piece and neared the end of the cut, the P/V value is 95 μin. (2.413 μ), or approximately that achieved with carbide tools on this same material. The flank wear on the diamond tool measured 0.0047 in. (0.1194 mm).

Disk E

This cut on a beryllium disk was made using a diamond tool from a different manufacturing source - Citco Diamond Tool Company. It was a single-crystal diamond with a 0.030-in. (0.762-mm) radius and was the same geometry as the tool used on Disk D. Orientation of the diamond was not known.

The cutting parameters were also the same as Disk D. The cut was made and the tool was inspected for wear. The flank wear measured 0.0059 in. (0.1499 mm). The disk was also inspected on the Clevite analyzer and found to have a finish of from 10 to 95 μin. (0.254 to 2.413 μ) P/V. This tool did not give a finish as good as that of the Moore tool, and flank wear was slightly greater. Differences in these results might be explained by differences in diamond orientation. It is well known that diamond has strong directional properties.

Disk F

The Disk F cut was made using a Megadiamond that had a lapped radius of 0.015 in. (0.381 mm). Because this radius is one-half that of the single-crystal diamonds, the theoretical finish was approximately 14 μin. (0.3556 μ) P/V. The same cutting parameters were used once more. The flank wear on the tool at the end of the cut was measured at 0.0076 in. (0.1930 mm).

This disk was also inspected on the Clevite analyzer, and the surface profile was from 35 to 70 μin. (0.889 to 1.778 μ) P/V. The finish was never as good as the theoretical finish, attributed to the edge shape and smoothness of the Megadiamond insert. However, the tool did give a slightly better finish at the end of the cut than did the single-crystal diamonds. We believe this occurs because as the tool wears, new diamond particles are constantly being introduced that in effect give a sharper edge even though the tool has worn. Single-crystal diamond does not have this advantage.

Disk G

Disk G was chemically milled 0.005 in. (0.127 mm) off each face to remove any surface impurities possibly causing major tool wear. Because of uncertainty as to the depth that etching could remove impurities, a minimum depth cut was taken to clean the surface. The back side of the disk was faced using a diamond tool until parallel to the front. The piece was then turned in the collet, and the uncut face was checked for run out and found to be less than 0.0002 in. (0.0051 mm). A cut 0.0005 in. (0.0127) deep was taken on the freshly etched surface.

Disk G exemplifies the greatest success in achieving an optical surface with diamond turning. The finish values ranged from 5 to 35 μin. (0.127 to 0.889 μ) P/V. This was perhaps the most encouraging information we had received to date. The flank wear on the Moore diamond tool #E-5 was measured to be 0.0025 in. (0.0635 mm). Photomicrographs of the surface are shown in Figs. 21a and 21b.

Disk H

Disk H provided a comparison in machining a purer grade of beryllium. As can be seen in Appendix C, the history of analysis of this material showed it to have a purity of 99.8% with very small amounts of beryllium oxide and other hard impurities. The disk was parted from a bar 2 in. (50.8 mm) in diameter and approximately 12 in. (304.8 mm) long. It was faced using carbide tools and drilled to relieve the center area.

For this test the Moore diamond tool #E-5 used on Disk G was again used by moving to a fresh portion of the tool. Prior to the finishing cut, a diamond roughing cut was made to remove any surface impurities introduced by the carbide tool. A Moore diamond tool #L-23 was used with a 0.001-in. (0.0254-mm) depth of cut. This tool was measured to have 0.0024 in. (0.06096 mm) flank wear. The surface of this disk was measured on the Clevite analyzer and found to have from 10 to 90 μin. (0.254 to 2.286 μ) P/V and was not as reflective as the chemically milled HP-21 disk.

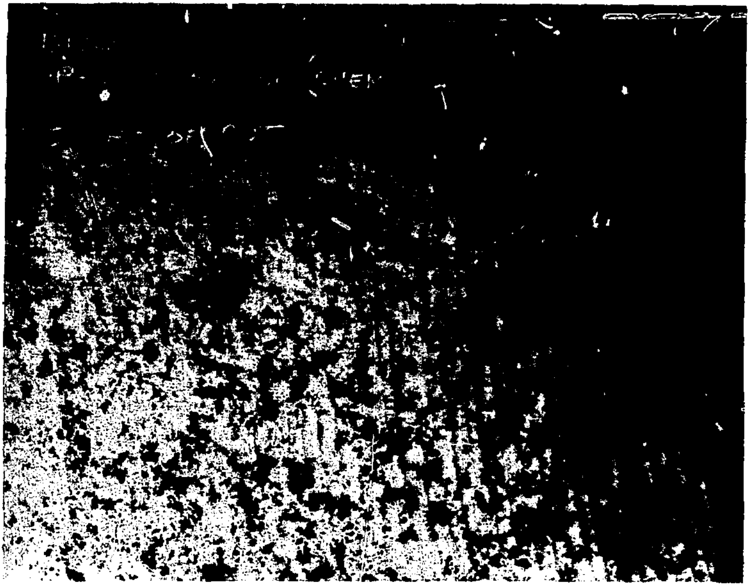


Fig. 21. Disk G surface photomicrographs. (a) Start of cut, 121X.

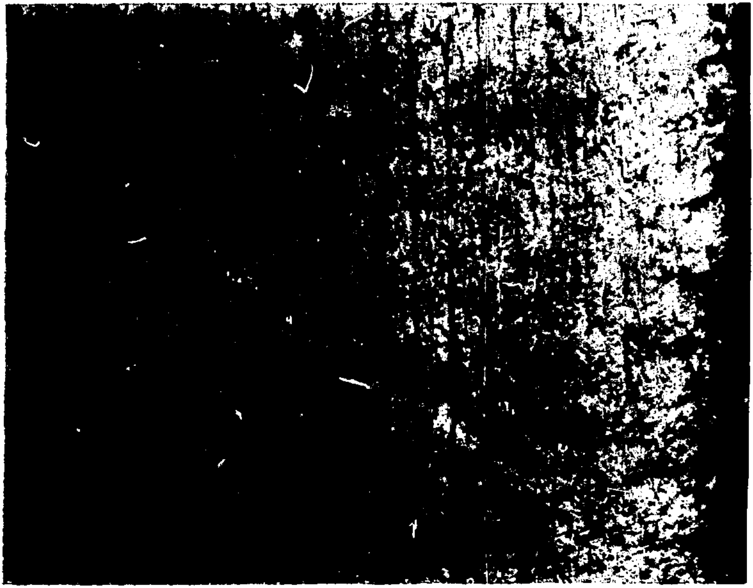


Fig. 21. Disk G surface photomicrographs. (b) End of cut, 121X.

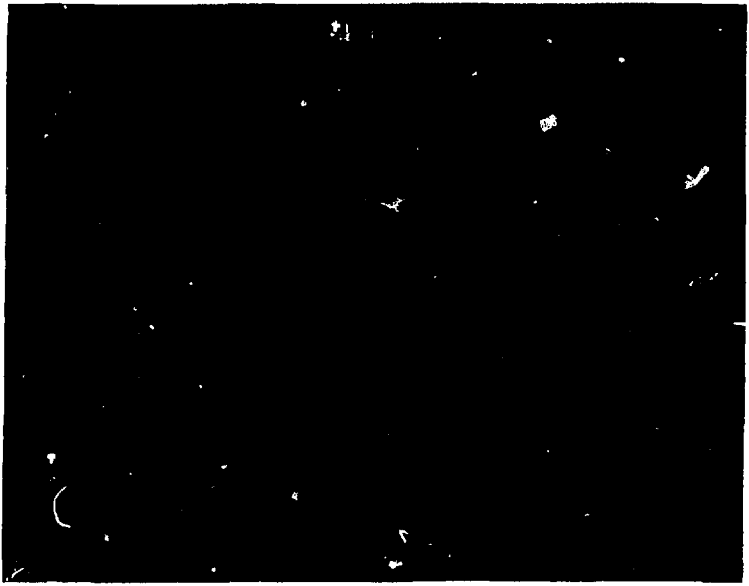


Fig. 22. Disk H surface interference photomicrographs. (a) Start of cut, 121X.

Disk H also is an example of the problems inherent in achieving an optical finish on materials made by powder metallurgy. It was assumed that the high-purity material would cause less tool wear and result in a better surface. However, the results indicated that the absence of impurity elements did not improve tool life or surface finish. Figures 22a and 22b show the surface at a higher magnification. Specifications and the radiograph report are in Appendix C.

The disk test data are given in tabular form as Table D-3 in Appendix D.

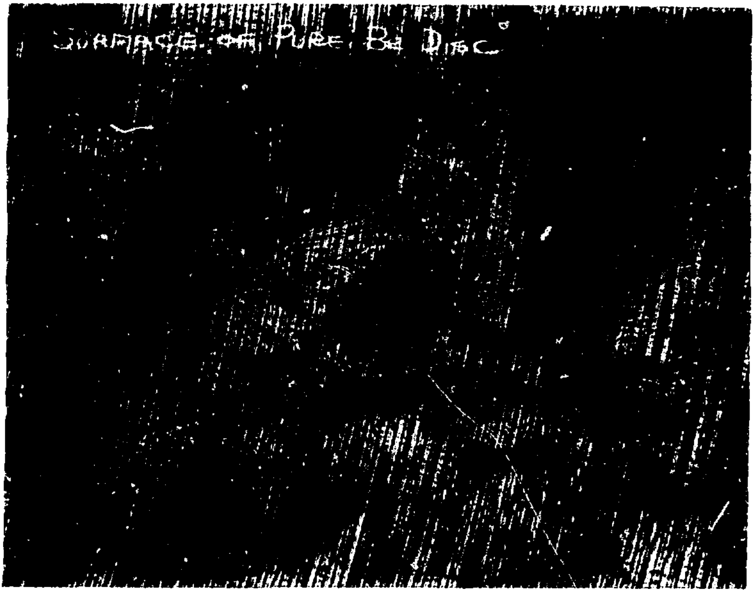


Fig. 22. Disk H surface interference photomicrographs. (b) Typical surface (note grain boundaries), 121X.

Conclusions

Before making conclusions it is necessary to make a few comments regarding the test procedures.

It is Lawrence Livermore Laboratory practice to use theoretical P/V values to roughly predict surface finish. The relationship between tool nose radius and feed per revolution determines the theoretical finish desired. The formula used is

$$P/V = \frac{(\text{feed/revolution})^2}{8 \times \text{tool nose radius}} .$$

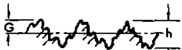
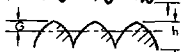
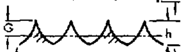
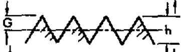
Where feed is 0.0013 in./rev. and tool nose radius is 0.030 in., for example,

$$P/V = \frac{(0.0013)^2}{8 \times 0.030} = \frac{1.69 \times 10^{-6}}{0.24}$$

$$\cong 0.00000704 \cong 7\ \mu\text{in.}$$

Peak-to-valley surface finish can be checked directly on a Clevite analyzer to determine whether the theoretical value has been achieved. Assuming a uniformly random waveform, the AA value is 0.2 times the P/V value (Fig. 23).

An air-bearing lathe was not used in these tests because of contamination problems. Because neither diamond-turning machine is presently used for cutting contaminated material, the time and cost involved in

Waveform: h = 1		M_L*	M_M*	AA	rms	h/AA	h/rms	G/h	G/AA	rms/AA
Uniformly random		---	---	0.2	0.25	5.0	4.0	0.5	2.5	1.25
Round crested parabolic		0.523	---	0.256	0.298	3.91	3.36	0.333	1.29	1.16
Sharp crested parabolic		0.770	---	0.256	0.298	3.91	3.36	0.667	2.60	1.16
Sinusoidal		0.678	0.612	0.318	0.353	3.14	2.83	0.5	1.57	1.11
Saw tooth		0.630	0.578	0.25	0.289	4.0	3.46	0.5	2.0	1.16
Square		1.0	1.0	0.5	0.5	2.0	2.0	0.5	1.0	1.0

*$h_{eL} = M_L h$; $h_{eM} = M_M h$.

Fig. 23. Average height values for various waveforms. This figure shows the relationship between P/V values and AA and rms values.

adapting these machines for contaminated material cutting was considered excessive unless it were established that additional accuracy was needed.

Freon TF was used as a coolant because it was found to be successful in other machinability tests performed here at Lawrence Livermore Laboratory. It was found to be as good a cutting fluid as carbon tetrachloride, which was banned because of health hazards. Freon TF does not promote oxidation on the surface of the beryllium, as does water, and leaves the surface clean and free of contamination. It also prevented the built-up edge from forming on the diamond tool and provided considerable cooling. The pieces were chilled to the touch at the end of each cut from the rapid evaporation of the Freon.

The finish on the brass disks was not of the surface quality that could be obtained on the diamond-turning machine with the air-bearing spindle. However, the finish was good enough to determine whether or not diamond turning was feasible. It is noteworthy that when the slower feed rates were used to obtain a 0.5-μin. (0.127-μ) P/V theoretical finish, the diamond tools were unable to make a cut all the way across the face of the beryllium disk without early failure. Tool wear was in all cases the governing factor, except on the brass-disk cuts.

It is generally not good practice to use form error as an indicator of tool wear because such things as chucking influences and machine travel errors can also affect form. By comparing the flatness of the sample disks it is possible to estimate the differences of wear rates, verify the earlier findings, and correlate flank wear. The form errors and finishes of the disks cut with Megadiamond can then be compared with those cut with a single-crystal diamond. It is seen that although the Megadiamond wears slightly faster, it tends to cut longer because it is continuously exposing fresh diamond to the cutting surface as the tool wears. It is also noteworthy that the carbide tool produced the least form error.

The conclusion that can be drawn based on these tests may be simply stated: diamond tools cannot presently provide optical finishes on beryllium. This must be qualified somewhat because there was marginal success for very short distances in achieving theoretical finishes. Surface finish at the start of the cut was often the theoretical value to which the machine had been set. However, because of tool wear, most of the finishes had sufficiently degraded by the time the end of the cut was reached to be no better (and often worse) than the finish provided by a carbide tool.

The most successful cut obtained was on Disk G, which had been chemically milled 0.005 in. (0.127 mm) off each face. We first thought that the reason for the success was that purer beryllium resulted from etching. However, the next test on Disk H served to disprove this theory. Disk H was of a higher purity and showed no high-density inclusions in the radiograph (Appendix C), yet caused tool wear equal to that caused by the HP-21 beryllium disks. The chemically milled beryllium seemed to smear as the tool dulled and appeared to give a better finish throughout the cut. Close observation of this surface under a microscope tends to verify this (Figs. 21 and 22).

Recommendations

It is recommended that, money and time permitting, the study of wear mechanics on diamond tools be continued. The satisfactory turning of an optical finish on beryllium would be only one valuable result. Other materials not previously machinable with diamond tools, i.e., steel and other ferrous materials, may be successfully finished also.

In these tests, the theory of graphitization was neither proved nor disapproved. (See Refs. 3, 4, and 5 for discussion of this theory.) Although the tests tend to confirm the theory, the mechanics of wear are still really unknown. It would be beneficial to all forms of machining using diamond-turning techniques to know what the wear mechanics are and whether or not it is possible to somehow eliminate the cause of wear or prepare or modify the material to make diamond-turning feasible.

References

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KLC/grw

Appendix A. HP-21 Log Analysis

KAWECKI BERYLCO INDUSTRIES, INC.
POST OFFICE BOX 429
HAZLETON, PENNSYLVANIA 18201

QUALITY CONTROL MATERIAL TEST REPORT

CUSTOMER: Honeywell, Inc.
CUSTOMER LOCATION: Lexington, Mass.
CUSTOMER P. O. NUMBER: IX-81699

DATE: May 23, 1975
BERYLCO ORDER NO. 58-8941
SPEC. NUMBERS: HP-21

DESCRIPTION
1 Pc. Kawecki Berylco Be metal Rod 1½" Dia. x 3" long.

K.B.I. UNIT# 571P

K.B.I. FILM# HSH-9098

NUMBER	571P
Be Assay	98.60
BeO	1.63
C	.077
Fe	.130
Al	.028
Mg	.010
Si	.026
All other metallic impurities	.04 Max.
	FT
U.T.S.	54,900
.2% Y.S.	39,100
% El.	5.80
DENSITY	1.848 g/cc

REMARKS Penetrant and radiographic inspection conforms to the above specification.
One (1) Pack of film enclosed with shipment.

KAWECKI BERYLCO INDUSTRIES, INC.
P.O. BOX 429, HAZLETON, PA. 18201

By J. A. Dzuiba
J.A. Dzuiba
Title Q.C. Foreman

HQC-1A

Appendix B. HP-21 Radiograph and Nondestructive Test Report

Interdepartmental letterhead

Mail Station L- 415

Ext: 7601

MEMORANDUM - September 8, 1975 Reference No. 27805

TO: Jim Bryan

FROM: Nondestructive Testing Section
Materials Engineering Division

SUBJECT: Beryllium Specimen

Radiographic Inspection

No evidence of any abnormality is detected either by dye penetrant or radiographic inspection.

The sample contains an estimated 120 high density inclusions, the largest about .23mm in diameter.

E. M. Placas

E. M. Placas

EMP:clw

cc: P. Landon

University of California
LAWRENCE LIVERMORE LABORATORY

Appendix C. Specifications and Analysis of Pure Beryllium

CUSTOMER: University of California

CUSTOMER LOCATION: Livermore, California

CUSTOMER P. O. NUMBER: 8305

KAWECKI BERYLCO INDUSTRIES, INC.
POST OFFICE BOX 429
HAZLETON, PENNSYLVANIA 18201
RECERTIFICATION
QUALITY CONTROL MATERIAL TEST REPORT

DATE: May 1, 1975

BERYLCO ORDER NO.: 58-8341

SPEC. NUMBERS: Cast & Extruded from
FF-1 Origin
99.8% Purity

DESCRIPTION

4 Pcs. Kawecki Berylco Be Cast & Extruded Rod 2" Dia. x Random Length.

K.B.I. UNIT# XT-1167 - 1 thru 4

Total Inches 48"

NUMBER Batch Lot	V-031 XT-1167								
Be Assay	99.84								
BeO	.08								
C	.026								
Fe	.010								
Al	< .002								
Mg	.0005								
Si	.006								
Cr	.0006								
Co	.0002								
Cu	.001								
Pb	< .0001								
Mn	.0003								
Mo	< .001								
Ni	.0006								
U.T.S.									
.2% Y.S.									
% El.									
DENSITY									

REMARKS Density & Radiographic inspection conforms to the above specification.

KAWECKI BERYLCO INDUSTRIES, INC.
P.O. BOX 429, HAZLETON, PA. 18201

By L. A. Dettore

Title Q.C. Foreman

HQC-1A

May 30, 1975

X-RAY FLUORESCENCE ANALYSIS

SAMPLES: XF-498 KBI Beryllium rods XT-1167 58-8341

REQUESTOR: Richard Becker

ANALYSIS REQUESTED: Semi-quantitative estimate of impurities present

RESULTS: The only impurities observed are those listed below. With the analysis procedure used, the elements with the approximate Z range of 24-42, plus W, Ta, Pb, and U, would be observed at the trace level. The rods were washed with nitric acid before the analysis to eleiminate surface contaimination.

	Cr	Fe	Ni	Cu	Ni
Rod #1	420 ± 100	195 ± 25	65 ± 10	< 30	195 ± 10
Rod #2	< 50	195 ± 25	80 ± 10	≤ 20	< 5
Rod #3	< 50	220 ± 25	225 ± 20	≤ 20	< 5
Rod #4	< 50	105 ± 20	85 ± 10	≤ 20	< 5

METHOD; Energy dispersive spectrometer, W tube + Sn filter. Quantitation obtained from boron carbide standards, corrected for matrix absorption differences.

Analyst: Richard Ryon

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MEMORANDUM - September 10, 1975 Reference No. 27823

TO: H. W. Hauschildt

FROM: Nondestructive Testing Section
Materials Engineering Division

SUBJECT: BERYLLIUM SPECIMEN
ITEMS: 2

Radiographic Inspection

The one minimal high density inclusion noted is probably surface contamination.

The mottled appearance seen is probably a diffraction pattern resulting from enlarged grain size.

E. M. Placas
E. M. Placas

EMP:clw

cc: P. Landon

University of California
LAWRENCE LIVERMORE LABORATORY

Table D-1. Results of facing cuts.

Test No.	Tool material	Speed		Feed		Depth of cut, in.	Cutting fluid	Flank wear land, in.	P/V surface finish		Remarks
		rpm	sfm[a]	in./min	in./rev.				Theor., µin.	Actual range, µin.	
1	Moore single-crystal diamond #L-44, 0.030-in. radius	900	350	0.320	0.0035	0.001	Dry	0.0021	0.5	2-130	Diamond tool chipped during initial contact
2	Moore single-crystal diamond #L-44, 0.030-in. radius (new position)	375	145	0.130	0.0034	0.001	Dry	0.0027	0.5	5-130	Slower speed didn't help much
3	Moore single-crystal diamond #L-42, 0.030-in. radius	375	145	0.130	0.0034	0.001	Dry	0.0023	0.5	5-130	Repeatability of test with different diamond tool
4	Carbide grade 907	750	290	0.600	0.0008	0.001	Dry	0.0016	3	20-50	Standard precision finish using carbide
5	Moore single-crystal diamond #E-4, 0.030-in. radius	100	39	0.130	0.0013	0.0005	Freon TF	0.0018	7	2-30	Freon TF was of significant value as a cutting fluid
6	Megadiamond, 0.007-in. radius, unlapped corner very rough	100	39	0.130	0.0013	0.001	Freon TF	0.0041	32	60-120	Poor finish probably due to nose-radius quality

[a]sfm = surface ft/min.

Table D-2. Results of longitudinal turning cuts.

Test No.	Tool material	Speed		Feed		Depth of cut, in.	Cutting fluid	Cutting time, s	Flank wear land, in.	P/V surface finish		Remarks
		rpm	sfm[a]	in./min	in./rev.					Theor., μin.	Actual range, μin.	
1	Megadiamond A, upper left corner, 0.015-in. radius	100	39	0.105	0.00105	0.001	Freon TF	10	0.001			Wear Test No. 1, 100 rpm
								20	0.002			
								40	0.002+			
								100	0.003			
								200	0.005			
								500	0.0087			
2	Megadiamond A, upper right corner, 0.015-in. radius	30	11.7	0.105	0.0035	0.001	Freon TF	10	0.0015			Wear Test No. 2, 30 rpm
								25	0.0025			
								50	0.003			
								100	0.003+			
								200	0.0033			
								500	0.0035			
								1500	0.0055			
								2400	0.0092			
3	Megadiamond A, lower left corner, 0.015-in. radius	66	25.7	0.105	0.0016	0.001	Freon TF	10	0.0015			Wear Test No. 3, 66 rpm
								20	0.0025			
								50	0.0035			
								100	0.004			
								200	0.005			
								500	0.0082			
4	Megadiamond A, lower right corner, 0.015-in. radius	2000	780	3.2	0.0016	0.001	Freon TF	10	0.0045			Wear Test No. 4, 2000 rpm, ~1.1-in. length of cut
								20	0.0068			
5	Megadiamond B, upper left corner, 0.015-in. radius	30	11.7	0.070	0.0023	0.001	Freeze-It (spray Freon in aerosol can)	10	0.002			Effect of -50°F cooling (ran out of Freeze-It)
								20	0.002			
								50	0.002			
								100	0.002			
								200	0.003			
A	Megadiamond B, upper right corner, 0.015-in. radius	50	19.5	0.070	0.0014	0.0015	Freon TF	600	0.006			Cleanup cut to obtain constant o.d. on log and obtain additional point on tool-life curve
								1800	0.0103			

[a] sfm = surface ft/min.

Table D-2. Results of longitudinal turning cuts (cont.).

Test No.	Tool material	Speed		Feed		Depth of cut, in.	Cutting fluid	Cutting time, s	Flank wear land, in.	P/V surface finish		Remarks
		rpm	sfm[a]	in./min	in./rev.					Theor., µin.	Actual range, µin.	
6	Megadiamond B, lower right corner, 0.015-in. radius	66	25.7	0.070	0.001	0.001	Freon TF	400	0.0056	8	25-80	Best-finish effort with Megadiamond and slowest possible feed
7	Moore single-crystal diamond	66	25.7	0.070	0.001	0.00075	Freon TF	400	0.006	4	15-100	Comparison of single-crystal diamond to Megadiamond (part showed steep taper on this section)
8 (Facing cut)	Moore single-crystal diamond #E-3	66	25.7	0.024	0.0036	0.001	Freon TF	10,500	See remark	0.5	5-70	Tool failure led to high enough tool pressure that tool broke at 17.5 min
9	Megadiamond B						LN_2					Could not get LN_2 to work correctly; test stopped
10	Megadiamond B, lower left corner, 0.015-in. radius	30	11.7	0.070	0.0023	0.001	Micro-duster inverted to spray Freon at -50°F	10 20 50 100 400	0.002 0.002 0.0025 0.003 0.007			Repeat of test No. 5 to continue time period to 400 s (used 3 cans of spray)
11	907 grade carbide tool, 0.030-in. radius	500	195	1.100	0.0022	0.001	Dry	95	0.002		20-50 not including material flaws	Cleanup cut on log diameter
12 (Facing cut)	907 grade carbide, 0.030-in. radius	100	39	0.130	0.0013	0.001	Perk (perchlorethylene)		0.003	7	15-65	Carbide tool used at diamond tool speeds and feeds; not a success
13 (Facing cut)	Moore single-crystal diamond #L-44, 0.030-in. radius	100	39	0.130	0.0013	0.001	Perk		0.0059	7	10-100	Perk not as good as Freon TF. Parted off 0.25-in.-thick disk for SEM and radiograph. Tool also cut up for SEM

[a]sfm = surface ft/min.

Table D-2. Results of longitudinal turning cuts (cont.).

Test No.	Tool material	Speed		Feed		Depth of cut, in.	Cutting fluid	Cutting time, s	Flank wear land, in.	P/V surface finish		Remarks
		rpm	sfm[a]	in./min	in./rev.					Theor., µin.	Actual range, µin.	
Facing cuts												
14a	Moore diamond tool #L-45, brass log test repeated later on Disks A and B	100	39	0.130	0.0013	0.0005	Perk	-	None	7	7	Proof of machine capability; flatness slightly better than that of disks
14b		400	156	0.130	0.0032	0.001	Perk	-	None	0.5	7-5	
Facing cuts												
17a	Co-6 Ceramic tool, square insert, 0.0[illegible]-in. radius	2000	780	2.000	0.001	0.001	Dry	-	0.0054	2	15-115	Poor quality surface; a lot of smearing
17b		100	39	0.130	0.0013	0.001	Freon TF	-	0.0117	4	20-160	Tool wore worse than high-speed cut

[a]sfm = surface ft/min.

Table D-3. Disk test data.

Disk	Disk material	Tool description	Speed, rpm	Feed in./min	Theor. P/V, μin.	Actual P/V, μin.	Part form, μin.	Tool flank wear, in.	Remarks
A	Brass	Moore single-crystal diamond #L-23, 0.030-in. radius	400	0.130	0.5	2-25, inc. matl. flaws	100, concave	None	Best finish possible on Hardinge Lathe #L-325
B	Brass	Moore single-crystal diamond #L-23, 0.030-in. radius	100	0.130	7	5-65, inc. matl. flaws	110, concave	None	Results of slowest machine feed at 100 rpm for comparative 7-μin. P/V surface to beryllium disks
C	HP-21 beryllium as rec'd	907 grade carbide tool, 0.030-in. radius	460	0.500	5	20-95	200, concave	0.001	Basic surface on which diamond cuts were made
D	HP-21 beryllium as rec'd	Moore single-crystal diamond #L-45, 0.030-in. radius	100	0.130	7	5-95	725, concave	0.0047	Tool failed at ~1 in. diameter typical of initial facing cut surfaces
E	HP-21 beryllium as rec'd	Citco single-crystal diamond #53, 0.030-in. radius	100	0.130	7	10-95	875, concave	0.0059	Test to see effect of different diamond orientation in mounting
F	HP-21 beryllium as rec'd	Megadiamond polycrystalline square insert #C, 0.015-in. radius	100	0.130	14	36-70	620, concave	0.0076	Small nose radius and edge quality result in poorer initial finish
G	HP-21 beryllium chemically milled 0.005-in. off each face	Moore single-crystal diamond #E-5, 0.030-in. radius	100	0.130	7	5-35	725, concave	0.0025	Best finish; appears to have smeared at end of cut when tool got dull
H	KBI 99.8% pure beryllium	Moore single-crystal diamond #E-5, 0.030-in. radius	100	0.130	7	10-90	780, concave	0.0024	Porous appearance