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THE FLYCUTTING OF GLASS

A Thesis in

Mechanical Engineering

By

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We approve the thesis of Jamie Leigh Beattie.

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Abstract

The goal of this research is to obtain preliminary information in the flycutting of glass to optical quality. Previous research has focused on the diamond turning of glass rather than flycutting. During the diamond turning of glass, the tool remains in constant contact with the glass workpiece. The diamond absorbs heat during the cutting process resulting in rapid tool wear. The theory proposed is that the intermittent contact of the tool with the workpiece during flycutting will lengthen the life of the tool by allowing the diamond to cool between cuts. In this research, the flycutting of glass to optical quality will be investigated, and the problem of significant diamond tool wear will then be addressed.

Experimental modal analysis of the tool holder, air-bearing spindle, workpiece chuck, and mounting plate will be used to determine the system parameters of the structural loop from the frequency response function curve-fit. The results of these modal tests will provide parameters such as feed and optimum spindle speed for use in experimental cutting tests. Also, tool rake angle and nose radius variations will be noted during several flycutting tests.

A preliminary effort in dry flycutting of a BK7 (borosilicate) glass sample has generated several promising results including: (1) evidence of ductile regime material removal with conventional (0^o rake) diamond tools, (2) good surface finish and form accuracy, and (3) better tool life than previously noted under diamond turning.

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Acknowledgments

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Chapter 1
Introduction to Glass Cutting Research

1.1 Introduction

In the glass cutting industry, opticians have been cutting glass for decades mainly by brittle fracture—taking large depths of cut. The problem encountered has been that the surface finish of the glass cut by brittle fracture is not of optical quality and contains unacceptable sub-surface damage. Optical quality is a necessity in the making of lenses for precision optics and defense applications.

Historically, glass was finely ground to the desired shape, for example spherical lenses, and then polished to optical quality. Glass has been routinely ground using diamond wheels, yet has proven difficult to machine by single point cutting because of tool wear. The possibility of a one-step process of cutting the glass to optical quality and to the appropriate shape without the extra step of polishing, would increase efficiency and decrease cost. Presently, better methods are being developed and implemented.

Ultra-precision machining methods of cutting glass to eliminate these extra steps have been investigated. In this work, single point machining of glass is attempted with the benefit of three features: (1) flycutting (as opposed to turning), (2) highly accurate depth of cut (nanometer infeed), and (3) high sensitivity cutting force sensor (instrumented work holder).

In the diamond flycutting of glass, a single crystal diamond tool is used to machine the glass specimen, taking nanometer depths of cut [1]. This small depth of cut allows for a transition from brittle to ductile material removal, enabling the optician to cut to optical quality.

Flycutting glass with synthetic diamond tools is similar to diamond turning. During diamond turning the tool remains in constant contact with the workpiece, but in flycutting, the tool does not. Figure 1.1 illustrates diamond turning, while Figure 1.2 displays diamond flycutting. In turning, the workpiece generally rotates and the tool remains rigid during the cut; however, during flycutting the tool generally rotates and the workpiece remains fixed. With turning, the tool absorbs heat and wears quickly. Short tool life is a significant problem in diamond turning.

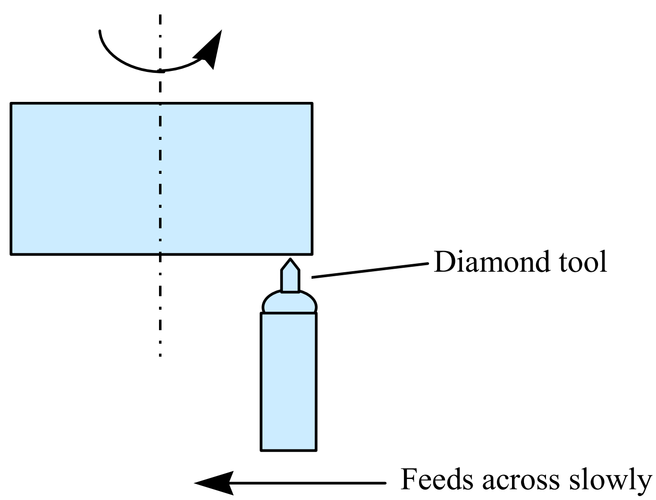

Figure 1.1 Sketch of diamond turning

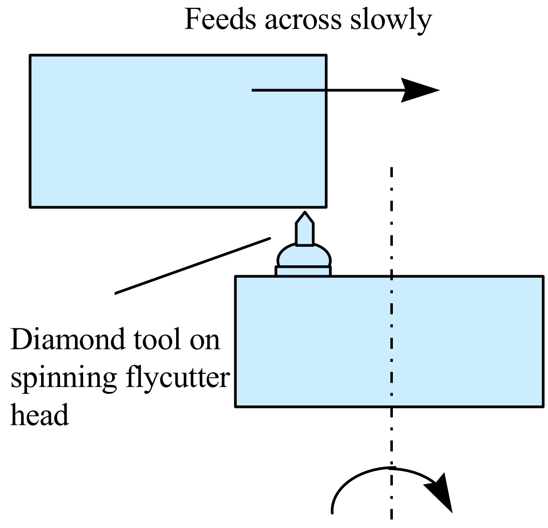

Figure 1.2 Sketch of diamond flycutting

A set of experiments is performed to explore the feasibility of flycutting as an alternative to diamond turning and a possible solution to tool life problems. Early results are encouraging and are attributed to the three features outlined above. For example, the high resolution of both infeed position and grinding/cutting force allows measurement of the limit of ductile regime material removal. Furthermore, the discontinuous nature of flycutting offers the diamond tool a chance to dissipate heat. This reduction in heat is likely to improve surface quality and form accuracy, and increase the life of the diamond. This research becomes critical in the flycutting of brittle substances such as glass where the diamond wears out within seconds.

Also, after experimental tests have been completed, the test specimens can be inspected under a microscope and optical flats to determine the form accuracy of the glass surfaces. The goal of this research work is to achieve nanometer form accuracy.

The experimental flycutting setup used in these tests does not allow constant force machining. Instead, a high structural loop stiffness (8.57E-9 meters/Newton compliance) is used in hopes of reaching an acceptable compromise for efficient material removal.

Structural loop stiffness and natural frequency parameters can be obtained via modal analysis of the tool holder and spindle, and the workpiece chuck and mounting plate (work holder). Using the results obtained during the modal analysis, the optimum spindle speed and other machining parameters may be determined. These parameters can be incorporated into a simulation model. A numerical model simulating the displacement of the tool during the interrupted cut of flycutting can be developed.

1.2 Review of the Literature

Most of the literature available on glass cutting is on the single point diamond turning of glass rather than its flycutting. The literature documents several unsuccessful attempts to turn glass using diamond tools. The problems encountered during the diamond turning of glass have been that optical quality surfaces could not be achieved, or that significant wear of the diamond tool occurs within seconds. In retrospect, several reasons for the undesirable results could be that: (1) the synthetic diamond is not of high quality, (2) touch-off of the diamond to the workpiece surface was not accurately identified and a larger depth of cut was taken than expected, (3) depths of cut were larger than the critical depth of cut during the flycutting experiment, or (4) tool wear was too rapid.

Past experiments include single groove tests accomplished by loading a pyramidal Vickers indenter, carried out by Puttick, Rudman, and Smith [2]. These single groove tests consisted of using the flat face of a Vickers indenter, generally used for hardness tests, as the cutting face. The indenter was used to cut a rotating soda lime microscope slide. Approximately 100 passes were taken, creating a single groove by constant force machining. A 5.0 gram weight provided a 0.05 N downward force on the soda lime slide. This setup is an example of a soft machine, having an unknown depth of cut but a controllably fixed load. From this setup, brittle fracture material removal resulted with some evidence of plastic flow and bouncing of the tool. These results prompted the researchers to design a hard machine to determine and control the depth of cut—a more realistic design for a machine used in industry. This hard machine would be one having a rigidly fixed tool and a high structural loop stiffness. Puttick, Rudman, and Smith conducted testing where no diamond tool wear was evident; however, this lack of wear may be the result of constant force machining [2].

Another series of diamond turning tests were performed by Sanger and Baker using a 12-in.-capacity precision facing machine and round nose diamond tools [3]. The goal of Sanger and Baker's research was to determine the feasibility of diamond turning glass surfaces resulting in excellent surface finish and form accuracy. The primary glass sample used in this set of testing was SF-6. Transparent, smooth, and clear surfaces were obtained by the researchers during turning. The parameters used to achieve these surfaces on SF-6 glass were: (1) high negative rake angles, (2) very low cutting speeds, and (3) low depths of cut. Tests were also conducted on fused silica, ULE, Zerodur®, and BK7 (borosilicate glass sample), but only data on the SF-6 samples were reported. Heptyl alcohol (heptanol) was used as the coolant. The main challenge encountered in this work was the problem of significant diamond tool wear. The researchers determined that a worn diamond tool cut a uniform surface suggesting that tool shape must be taken into consideration, even more so than the cutting speed [3].

The research work done by Blough was carried out to identify significant cutting parameters and material properties in the ductile machining of glass [4]. This research incorporated a nano-positioning tool holder, the testing of this tool holder, and the single point diamond turning of glass. One aspect of the tool holder testing was that the tool holder positioning accuracy had to be less than the critical depth of cut. Blough's research consisted of a closed-loop feedback system, incorporating a capacitance gage to detect touch-off.

Two glasses were thoroughly investigated— Zerodur® and BK7. Cutting tests were also performed on LAKN14, SK16, and PSK53A. Traditional zero degree rake angle diamond tools along with negative rake angle tools were used during the testing. Odorless mineral spirits was the coolant selected. A signature crescent shaped wear marking was present in the diamond tools used. Blough encountered touch-off problems on the glass surfaces. A lack of material removal was noticed, where the diamond would actually rub instead of cut the glass, leading to tool wear. This finding was originally blamed on a lack of compliance in the structural loop, but it later appeared to be that the surface of the glass elastically deformed [4].

Blough also investigated tool wear. He limited the causes of tool wear down to three categories: mechanical, chemical, and thermal. An example of mechanical wear would be chipping of the diamond, but no evidence of chipping was seen in these experiments. Chemical wear usually occurs during the machining of ferrous materials, not glass. Blough noted that diamonds have a very high thermal conductivity and that glass has a very low thermal conductivity. Therefore, thermal factors appeared to be the cause of tool wear in these experiments. [4].

During cutting experiments, the diamond draws heat away from the glass, causing oxidation and/or graphitization [4]. This conclusion was used to explain diamond tool wear in most of the previous tests. Jim Bryan has suggested that flycutting may provide the diamond tool a chance to cool between cuts to lengthen tool life [5].

Blough found that as the tool edge wore, a larger area of contact formed between the tool and glass workpiece, which dispersed heat and resulted in a lower temperature overall. This theory explained the nature of the high wear rate of the diamond at the beginning of the cut and eventually little to no wear later in the cut. Research was conducted to eliminate oxygen at the tool tip, by flooding it with a non-oxygen gas. These attempts, as well as the experimentation with coolant, did not solve the problem of tool wear [4].

Of the variations of cutting parameters tried by Blough, none wore successful in the diamond turning of BK7. However, diamond turning of FCD-1 was possible without instantaneous wear of the diamond tool [4].

Some other types of glass that have been used in turning experiments are SF58, SF5, K-Na-SiO_2, F2. Previous research work consisted of changing variables such as nose radius and rake angle of the diamond tool, or trying non-diamond tools. Other researchers have also changed parameters such as cutting speed, feed, and the type of coolant used.

Several additional coolants have been used during testing to determine their effect on machinability of glass: hydrofluoric acid, water, sodium hydroxide, sodium metasilicate, and ammonium bifluoride [3]. Silicon oil is another coolant that has been investigated in the diamond turning of glass [4].

There have been a few inconsistencies in previous research and several tests have not achieved satisfactory repeatability. Extensive efforts have been made to investigate the diamond turning of glass varying the cutting parameters and tool parameters, but researchers have met with mixed results. Very little is known about the flycutting, instead of the turning, of glass using diamond tools. Previous researchers' trials with diamond turning can now be related to the flycutting experiments described in this work.

1.3 Research Objective

The goal of this research is to obtain some preliminary information on flycutting, and to determine if flycutting of glass to optical quality is feasible.

Because of the high thermal conductivity of the diamond leading to wear of the tool, the theory proposed is that during flycutting, the diamond will have a chance to cool between cuts. Therefore, the tool should not show significant wear as quickly as in turning, where the tool is in constant contact with the workpiece. By observing the tool with a microscope before and after the cutting test, qualitative characteristics of wear can be detected.

During experimental testing, dry cutting tests along with tests involving coolant can be compared. Tool and cutting parameters can be varied during experiments to determine ideal conditions for flycutting to optical quality; for example, tool nose radius and tool rake angle can be varied for several cutting tests.

Next, experimental modal analysis provides stiffness and natural frequency information. These stiffness and natural frequency values can be used in creating a numerical model simulating the displacement of the tool. Optimal cutting parameters such as spindle speed, feed, and depth of cut can be determined by varying these values during simulation runs.

Finally, touch-off problems on the glass sample can be investigated with the initial calibration and selection of the capacitance gage mounting locations.

Chapter 2
Preparation and Experimental Setup

2.1 Diamond Flycutting Setup

The experiments are carried out using a Moore No. 3 Jig Grinder base and a Professional Instruments Twin-Mount air bearing spindle. The Moore base features plain ways with high stiffness and repeatability. An overall view of the flycutting test setup can be seen in Figure 2.1.

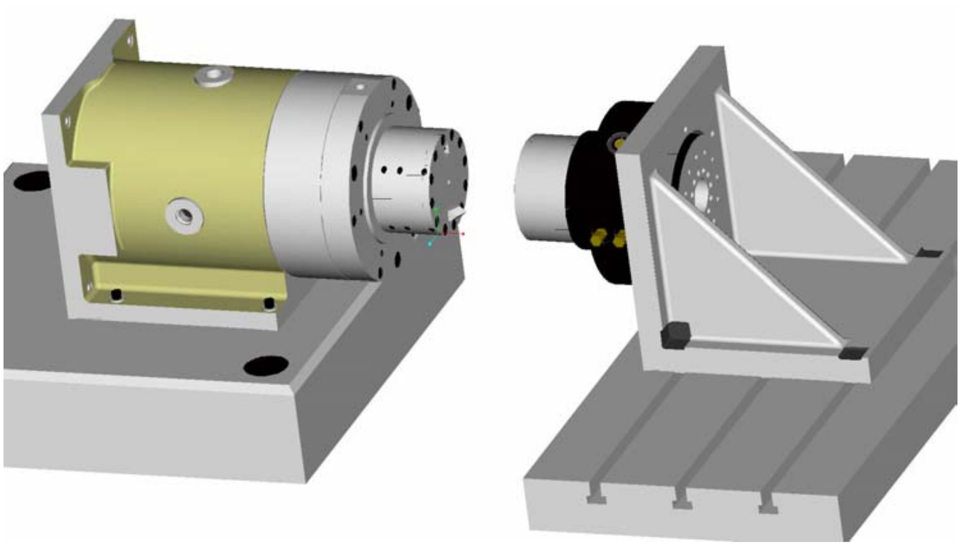

Figure 2.1 Overall view of flycutting and work holding spindles

The Professional Instruments Twin Mount uses a four inch BLOCKHEAD with axial compliance of 2.855E-9 meters/Newton and nanometer error motions. Error motion refers to the spindle's deviation from the centerline when rotating. Figure 2.2 shows this setup. Figure 2.3 is a photograph of the flycutter head and work holder. The glass sample is rigidly mounted with epoxy in a steel or bronze chuck bolted to a second BLOCKHEAD spindle (work holder) that does not rotate.

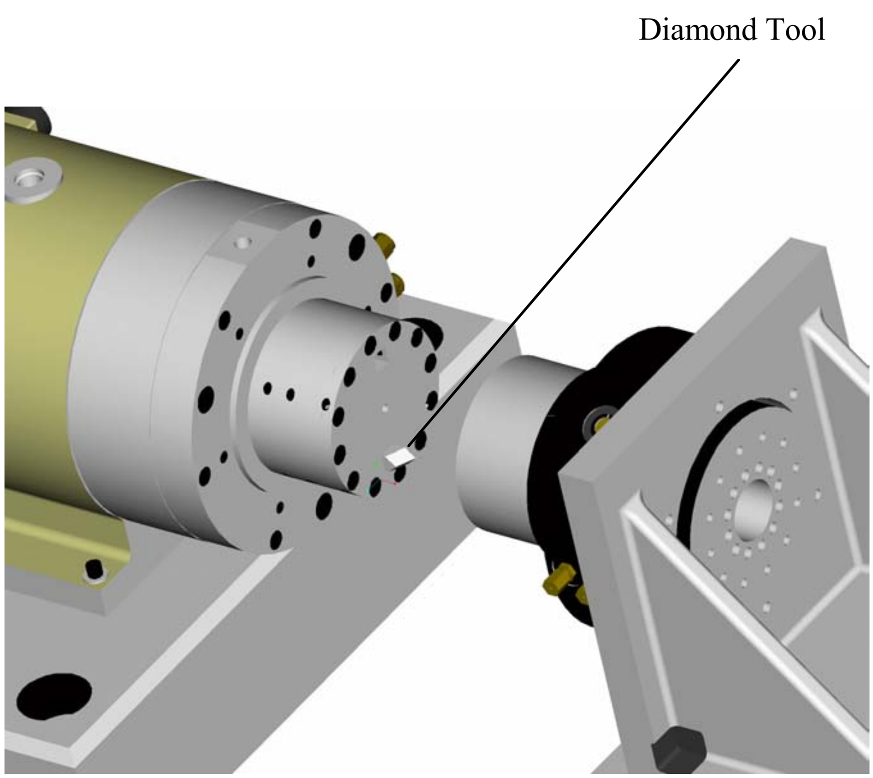

Figure 2.2 Close-up view of diamond tool flycutter head and workpiece chuck

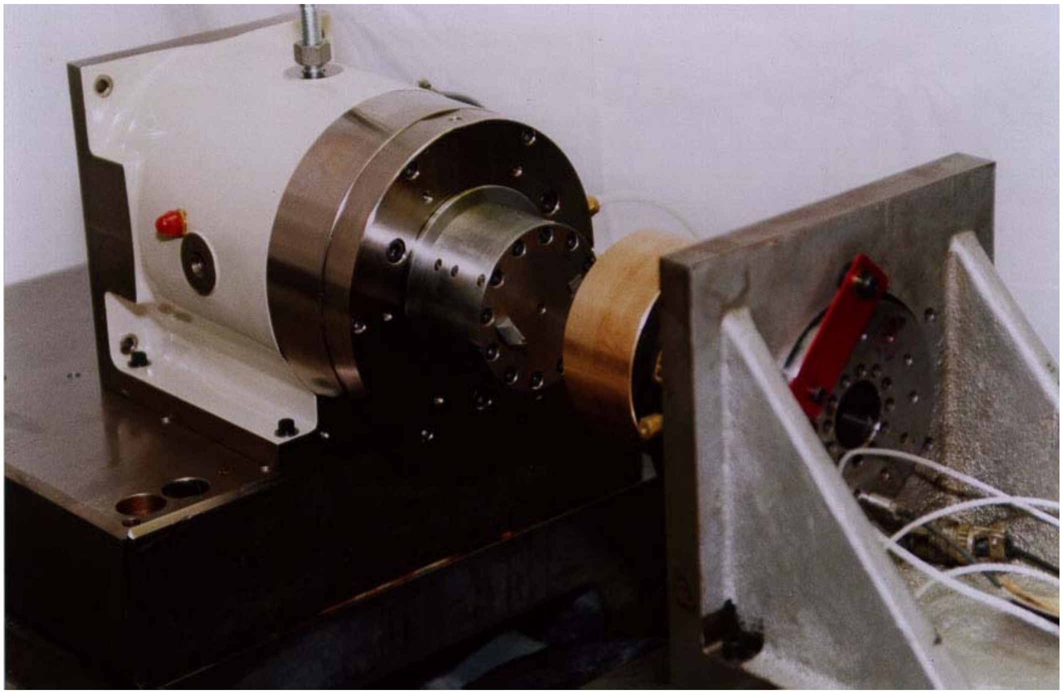

Figure 2.3 Photograph of the diamond tool flycutter head and workpiece chuck

The motivation for using the second air bearing spindle as a work holder is that not only does it contribute to the high stiffness of the structural loop, but also a slight axial growth can be achieved by varying the spindle supply pressure. The work holder air bearing grows axially by 1.8E-12 meters/Newton/meter^2 of supply pressure. Therefore, an infeed of 2.54E-8 meters can be repeatable by increasing the work holder supply pressure by two psi. The work holder air bearing has a second design feature: a high-sensitivity Lion Precision capacitance gage to detect the contact of the tool and workpiece. Figure 2.4 shows this capacitance gage imbedded in the work holder.

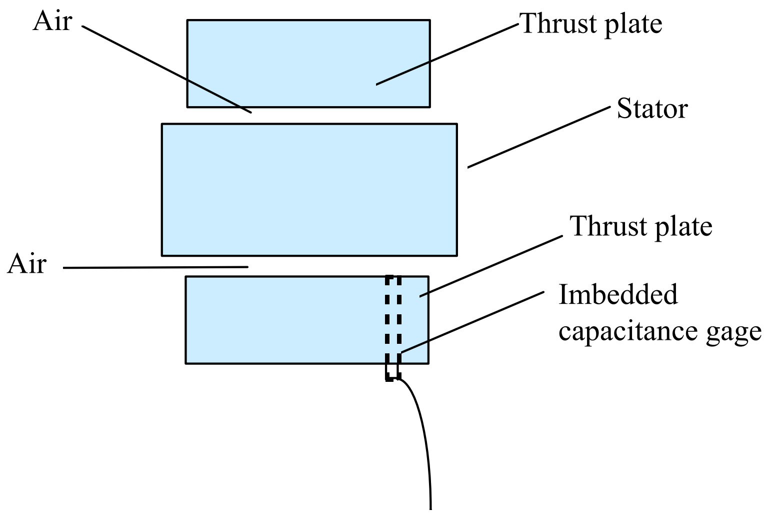

Figure 2.4 Sketch of capacitance gage imbedded in work holder

During testing, the flycutting spindle is run at either 200 or 1000 RPM. These speeds yield cutting velocities of approximately 0.635 and 3.175 meters/sec. The cross axis feed is 3.81E-5 meters per spindle revolution. The workpiece chuck and work holder can be seen in Figure 2.5. A photograph of the bronze workpiece chuck can be seen in Figure 2.6, and a close-up photograph of the steel chuck can be seen in Figure 2.7.

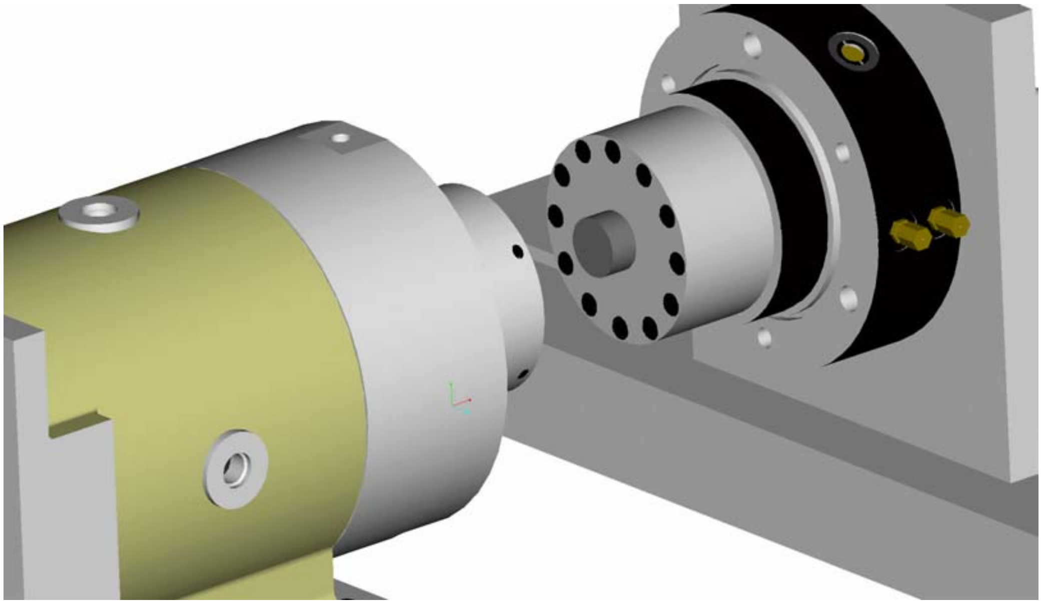

Figure 2.5 Close-up view of workpiece chuck and the capacitance gage-instrumented BLOCKHEAD

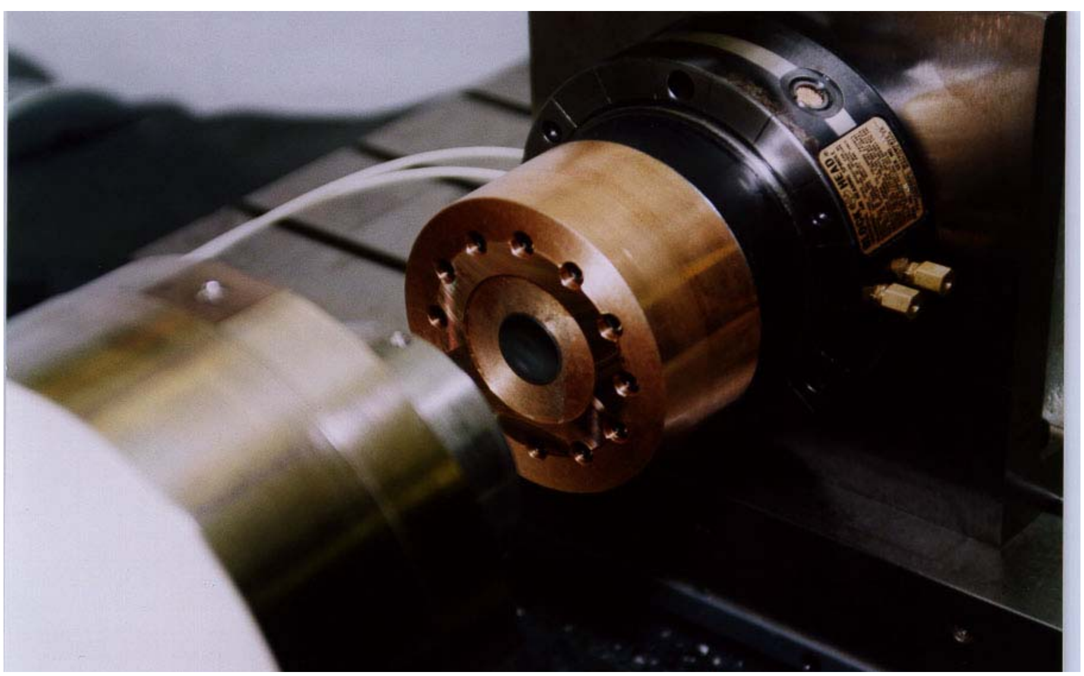

Figure 2.6 Photograph of bronze workpiece chuck

Figure 2.7 Close-up photograph of glass mounted in steel chuck

Edge Technologies' single crystal, synthetic round-nosed diamond tools are used in the flycutting of the BK7 glass samples. A Pro/ENGINEER drawing of the setup is displayed in Figure 2.8.

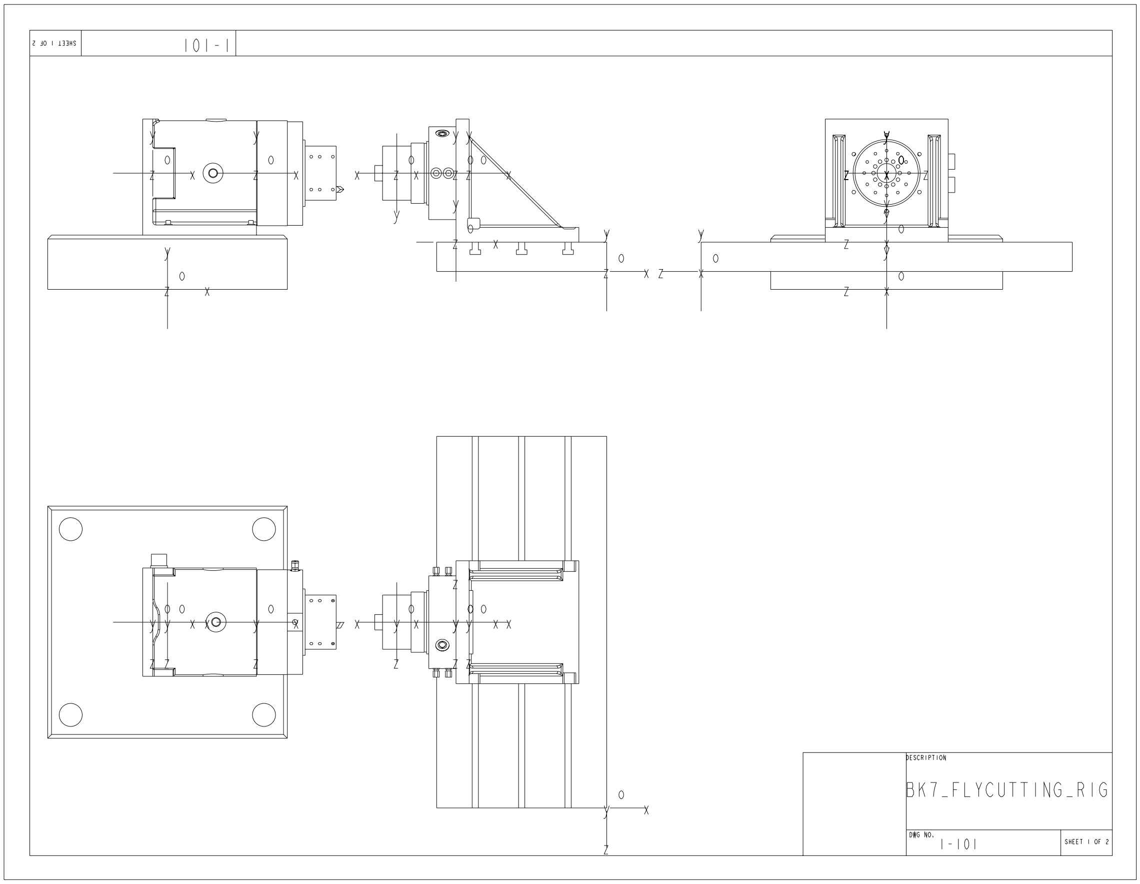

Figure 2.8 Pro/ENGINEER drawing of flycutting and work holding spindles

2.2 Measurement of Structural Loop Stiffness and Natural Frequencies

Experimental modal analysis of the Twin Mount and instrumented work holder is performed to determine information regarding the system's natural frequencies and damping. The frequency response function is determined by impacting the mass of the spindle and work holder with an impact hammer and measuring the response with an accelerometer. A roving accelerometer is placed at several locations around the bolt circle of both the flycutter head and the workpiece chuck and instrumented work holder. Measurements are taken in the axial direction of the two spindles. STAR Modal program results of the drive point along with a curve-fit plotted in Matlab can be seen in Figure 2.9.

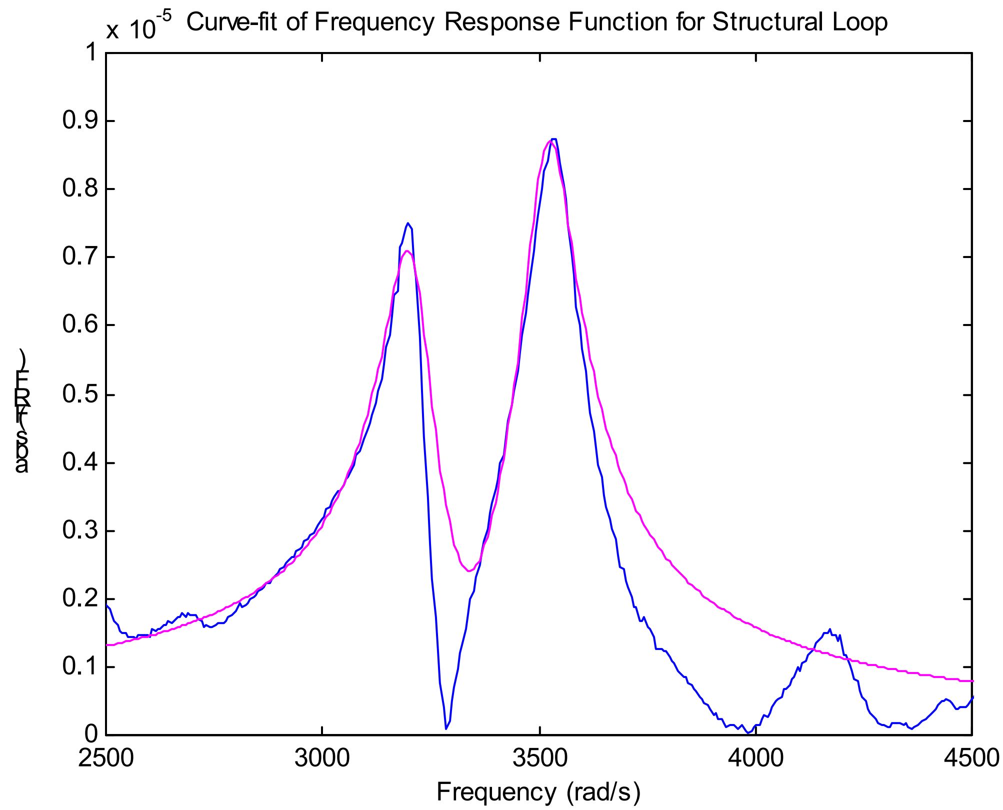

Figure 2.9 Curve-fit of FRF in Matlab

Observing the peaks at 3200 and 3525 rad/s gives valuable information about optimal spindle speed and cutting parameters. Identification of these resonances allows for avoiding these values when considering the optimal spindle speed. The equation for the total computation of the loop dynamic compliance shown in Figure 2.10 is expressed as follows:

$$FRF = \frac{X_1}{F_1} + \frac{X_2}{F_2} + \frac{X_1}{F_2} + \frac{X_2}{F_1} \tag{2.1}$$

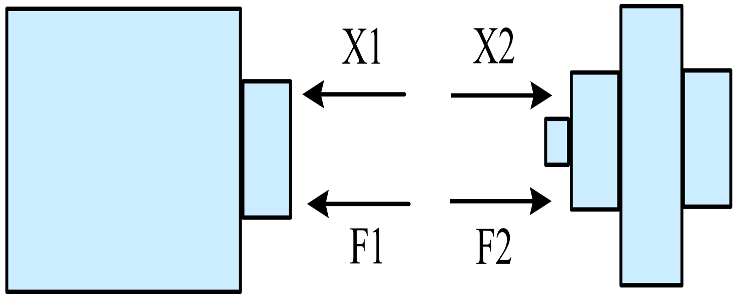

Figure 2.10 Sketch for loop dynamic compliance calculation

Obtained from the loop dynamic compliance and experimental modal analysis, the resulting parameters can be used to create a numerical model for simulation of the tool displacement. A numerical model for flycutting has been created in the Matlab Simulink program implementing fifth order Runge Kutta numerical integration. The numerical model can be used to solve for the tool displacement and chip area. The chip area calculation uses equations for the current tool position and the previous tool path history [1].

The initial condition for the position of the tool is the initial depth of cut. The initial condition for the velocity of the tool is zero because there is no previous tool history.

The inputs to the model for flycutting are the tool nose radius, the depth of cut, the cross axis feed rate, and the spindle speed. The interrupted nature of the cut is approximated by taking an average of several passes of the tool through the workpiece, determining the arc when the tool is in contact with the workpiece. Figure 2.11 displays the Simulink model for flycutting.

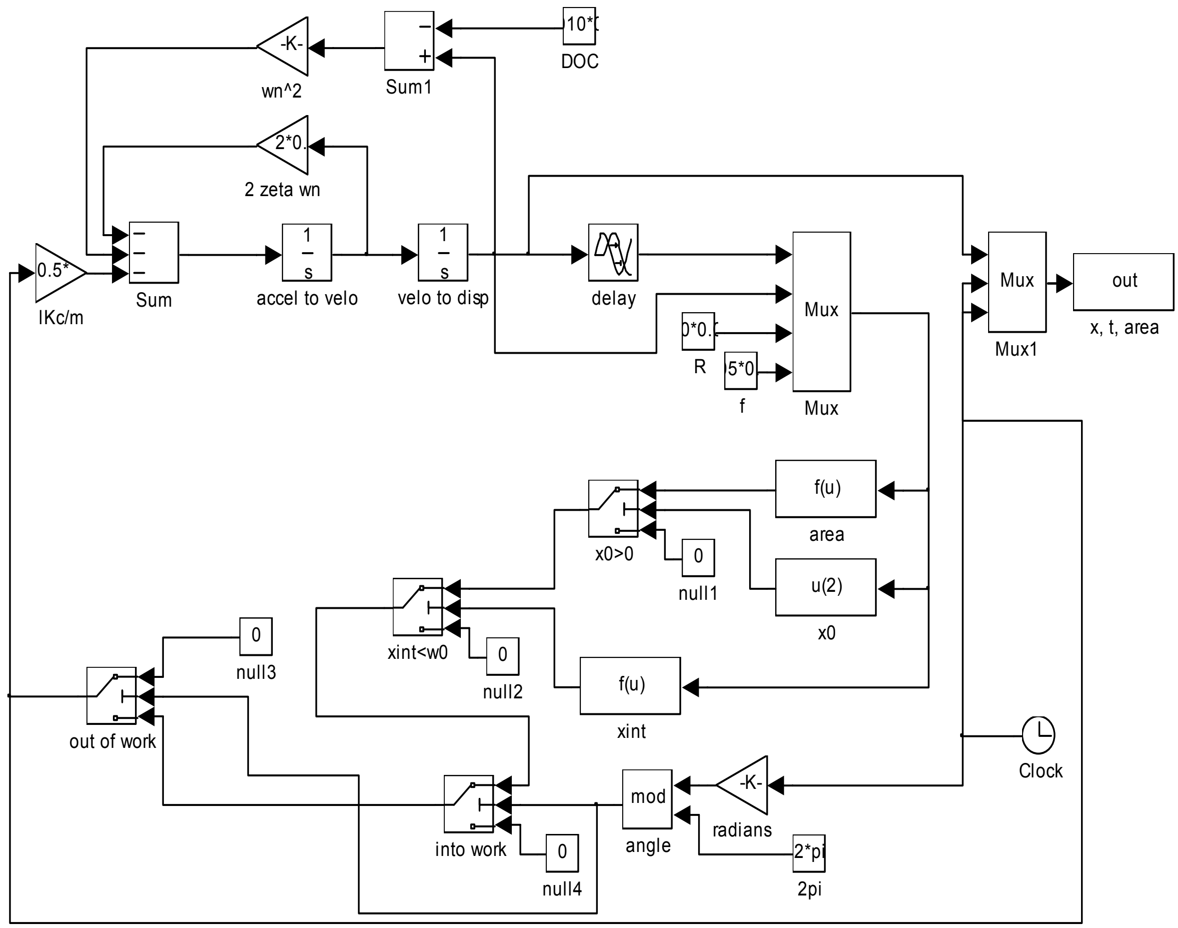

Figure 2.11 Numerical model for flycutting using Simulink

Schaut gives a detailed explanation of the calculations involved in a diamond turning simulation [1]. The following equations can also be applied to a flycutting simulation model.

The calculation of the chip area is accomplished by determining the equation of motion describing the tool displacement normal to the workpiece. The equation of motion for the lumped parameter model is:

$$m\ddot{y} + c\dot{y} + k(y - h) = -\lambda K_c A \tag{2.2}$$

where, m = mass (kg),
k = stiffness (N/m),
c = damping (Ns/m),
h = desired depth of cut (m),
λ = fraction of the cutting force transmitted to the tool in the x-direction,
K_c = specific cutting energy (N/m^2),
A = instantaneous chip area removed (m^2).

The chip area profile for a single tool pass is,

$$y(x) = \sqrt{R^2 - x^2} - (R - h) \tag{2.3}$$

where R is the radius of the tool, but using a parabolic approximation for the round nosed geometry of the tool, equation 2.3 becomes,

$$y(x) = h - \frac{x^2}{2R} \tag{2.4}$$

The chip area using this approximation is the following:

$$A = \frac{4}{3} h \sqrt{2hR} \tag{2.5}$$

Two passes of the tool are as follows:

$$y_0 = h_0 - \frac{x^2}{2R} \tag{2.6}$$

$$y_1 = h_1 - \frac{(x+f)^2}{2R} \tag{2.7}$$

By equating these two equations, the point of intersection can be determined.

$$x_{\text{int}} = \frac{R(h_1 - h_0)}{f} - \frac{f}{2} \tag{2.8}$$

The chip area can be calculated through integration of the following equation:

$$A_{total} = \int_{x_{\text{int}}}^{w_1 - f} (y_0 - y_1)\, dx + \int_{w_1 - f}^{w_0} y_0 \, dx \tag{2.9}$$

then obtaining,

$$A_{total} = \frac{f}{2}(h_0 + h_1) + \frac{2}{3}(h_0 w_0 - h_1 w_1) + \frac{R}{2f}(h_0 - h_1)^2 - \frac{f^3}{24R} \tag{3.0}$$

where w_0 and w_1-f refer to the half chip width for the current and previous passes of the tool, and

$$w = \sqrt{2hR} \tag{3.1}$$

Introducing δ, one can define the difference between the current and previous paths' depth of cuts.

$$\delta = h_0 - h_1 \tag{3.2}$$

To determine when the tool leaves the workpiece,

$$\delta_c = h_0 - h_1 = -\frac{f^2}{2R}\left(1 + \sqrt{\frac{8hR}{f^2}}\right) \tag{3.3}$$

And no chip area is removed if $\delta < \delta_c$. Therefore, the simulation model checks for this condition. The model checks that the depth of cut is greater than zero and that the depth of cut is greater than the critical depth of cut.

Finally, determination of whether the tool is in the arc of contact with the workpiece for the interrupted cut must be achieved. The angle is determined by

$$\theta = \omega t \tag{3.4}$$

where,

$$\omega = \frac{2\pi}{T} \tag{3.5}$$

2.3 Capacitance Gage Calibration

A calibration for the high-sensitivity capacitance gage imbedded in the work holder is obtained using two 1 volt/thousandth inch Lion Precision capacitance gages of known calibration mounted on the bolt circle of the instrumented work holder. The instrumented work holder is moved by changing the supply air pressure. The calculated calibration factor for the imbedded capacitance gage is determined to be approximately 175 volts/thousandth inch (6.89E6 V/m). Table 2.1 shows the data used for the calculations, and Figure 2.12 displays the data in graphical form.

Table 2.1 Table of calibration for the instrumented work holder

TEST 2 (psi)	Instr. Workholder (millionths)	gage 1 (millionths)	gage 2 (millionths)
35.00	-7.57	-3.40	-1.88
42.50	-5.79	-1.65	0.64
49.10	-4.19	-0.61	2.56
57.00	-2.28	1.22	4.64
63.20	-0.82	2.62	6.22
68.40	0.35	3.50	7.30
73.40	1.41	4.59	8.45
78.50	2.54	5.86	9.57
83.00	3.47	6.80	10.40
88.50	4.60	8.10	11.31
94.00	5.75	9.25	12.45
98.50	6.63	10.15	13.04

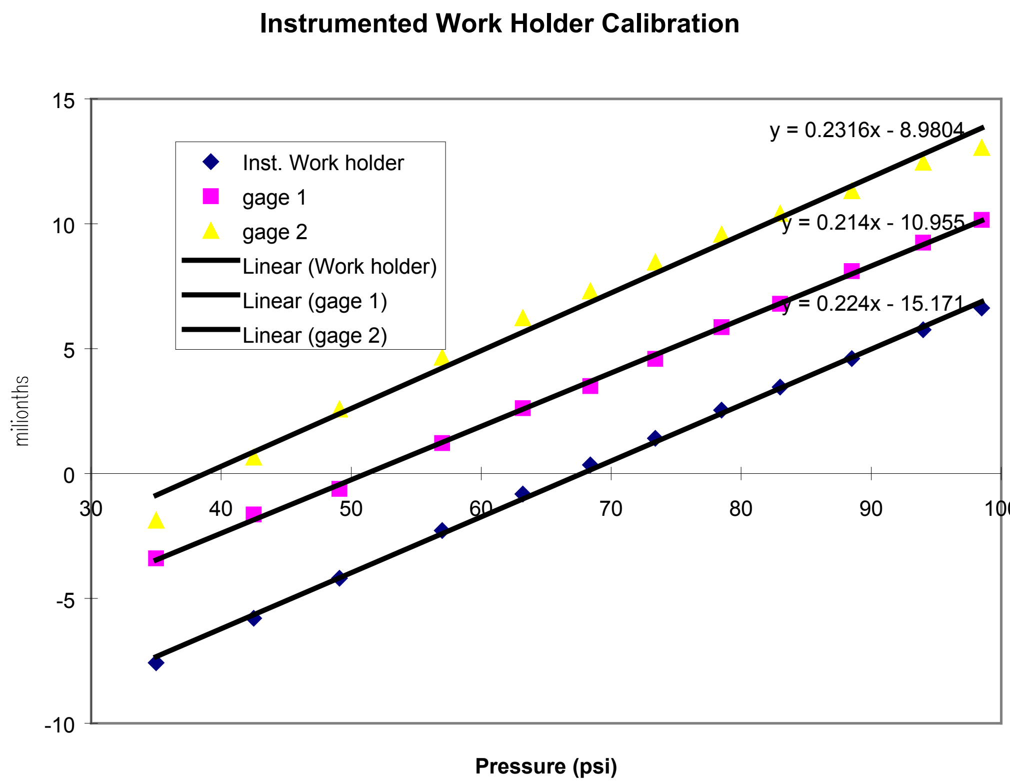

Figure 2.12 Calibration results for instrumented work holder capacitance gage

Chapter 3
Experimental Testing and Results

Several flycutting tests have been made on a BK7 glass sample. The chapter will be divided up into sections corresponding to a few of these tests. In each of these sections, the actual test will be discussed, describing the wear of the tool, the surface finish and form accuracy of the BK7 glass sample, the variation of parameters used, problems encountered, and steps taken to improve the next test.

3.1 The First Flycutting Test

In the first flycutting test, a 25 millimeter diameter BK7 glass sample is mounted in a steel chuck and dry flycut. The diamond tool that is used has a 762 micrometer nose radius and a zero degree rake angle. The spindle speed is set to 200 rpm for this flycutting test, and the cross axis feed is 38 micrometers/spindle revolution. A Lion Precision capacitance gage temporarily mounted to the Twin Mount spindle is used to measure infeed while another capacitance gage in the instrumented spindle detects the cutting. The capacitance gage senses the charge across the gap between the tip of the gage and a conducting target surface [1]. Due to cross talk between capacitance gage amplifiers, only one capacitance gage can be used at a time. Figure 3.1 displays a sketch of what the cut in the workpiece actually looks like when viewed by the naked eye.

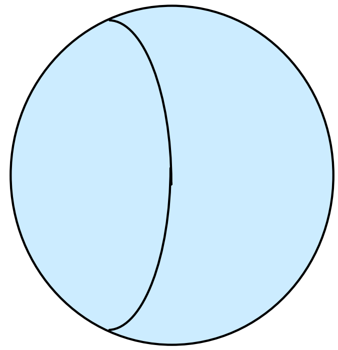

Figure 3.1 Sketch of one cut in workpiece

In this first round of testing, the glass sample is tilted in the chuck so that the tool does not make contact with the entire face of the workpiece. Only a crescent-shaped wedge of material is removed in one pass of the tool over the entire workpiece. The size of the wedge increases with each subsequent pass over the workpiece until eventually the entire surface is faced.

During cutting, traces from the high-gain work holder capacitance gage are captured. Figure 3.2 shows the gage output at 0.1, 0.2, 0.4, 0.8, and 0.16 micro-meters depth of cut (4, 8, 16, 32, and 64 micro-inches) depths of cut.

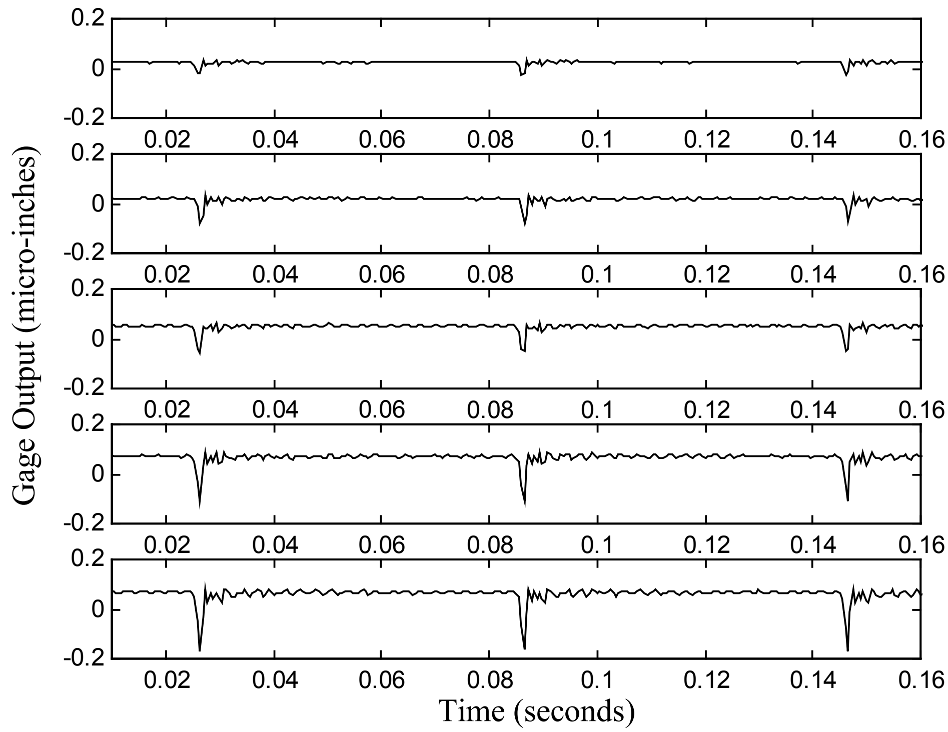

Figure 3.2 Five traces of capacitance gage output in micro-inches showing 160 milliseconds of intermittent contact with workpiece at 1000 RPM for depths of cut of 4,8,16,32, and 64 micro-inches respectively

Each trace shows 160 milliseconds of cutting data at 1000 RPM. From the top, the traces show the intermittent contact with the workpiece at depths of cut of 0.1, 0.2, 0.4, 0.8, and 0.16 micro-meters. In totality, about eighty passes over the workpiece are completed. Of these, forty are at 0.1 micro-meters depth of cut. Approximately twenty passes are taken at 0.2 micro-meters, 10 at 0.4 micro-meters, and a few are taken at 0.8 and 0.16 micro-meters. During the fourth 0.16 micro-meters cut, deep scratches are found in the workpiece. Evidence of wear appears in the diamond tool.

3.2 The Second Flycutting Test

In the second flycutting test, a 25 millimeter diameter BK7 glass sample, mounted in a steel chuck, is ground flat with a 400 grit diamond wheel. This grinding step is taken to square up the workpiece. Figure 3.3 shows a photograph of the grinding setup.

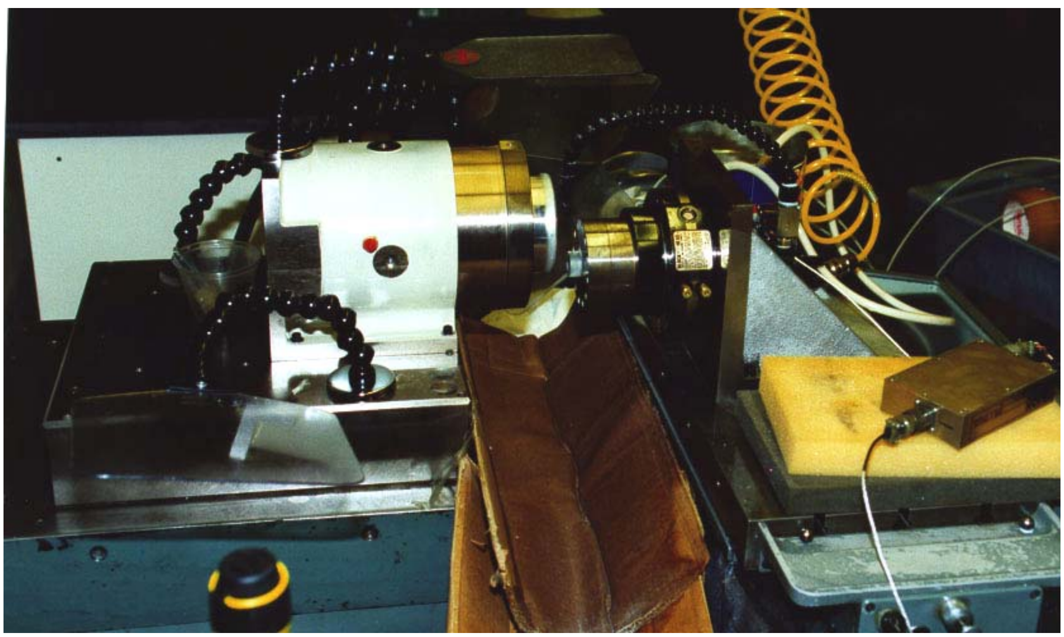

Figure 3.3 Photograph of grinding setup

Approximately 254 micrometers of stock are ground from the glass sample in 5 micrometer passes. VHP E320 Chemical Emulsion Concentrate is used as the coolant during grinding, leaving a surface finish that is only faintly cloudy to the unaided eye. Microscopic inspection of the surface at 50x magnification reveals a pitted surface that leads to the slight cloudiness.

The workpiece is then dry flycut. The diamond tool used has a 0.002 meter nose radius and a zero degree rake angle. The spindle speed is set to 1000 rpm for this flycutting test, and the cross axis feed is 38 micrometers/spindle revolution.

Despite the diamond grinding, a slight tilt in the work holder captures the transition from ductile to brittle regime material removal during the cut as described below. This serendipitous result is very encouraging.

Because of the tilted orientation of the workpiece to the flycutter, the transition from not cutting to ductile cutting to brittle cutting is illustrated in the three distinct regions in the upper two-thirds of the figure. Although the ground surface appears pitted under magnification, a single pass of flycutting diamond removes almost all of these pits and left a nearly clear finish, and visible grooves under magnification. Near the end of the cut, where the depth of cut is highest, a poor surface results. This abrupt transition presumably marks the limit of the ductile regime--approximately 0.127 micrometers). Figure 3.4 pictures the BK7 glass surface as viewed under 50x magnification.

Figure 3.4 BK7 sample under 50x magnification showing the transition from ductile to brittle material removal

The transition occurs at a few nanometers depth of cut, but is not yet accurately known. During ductile regime cutting, the slight cloudiness of the ground surface is removed, leaving an apparently specular finish.

The cutting action (motion) is completely recorded by the instrumented work holder. Figure 3.5 shows the brief contact of fifteen passes of the tool over the workpiece.

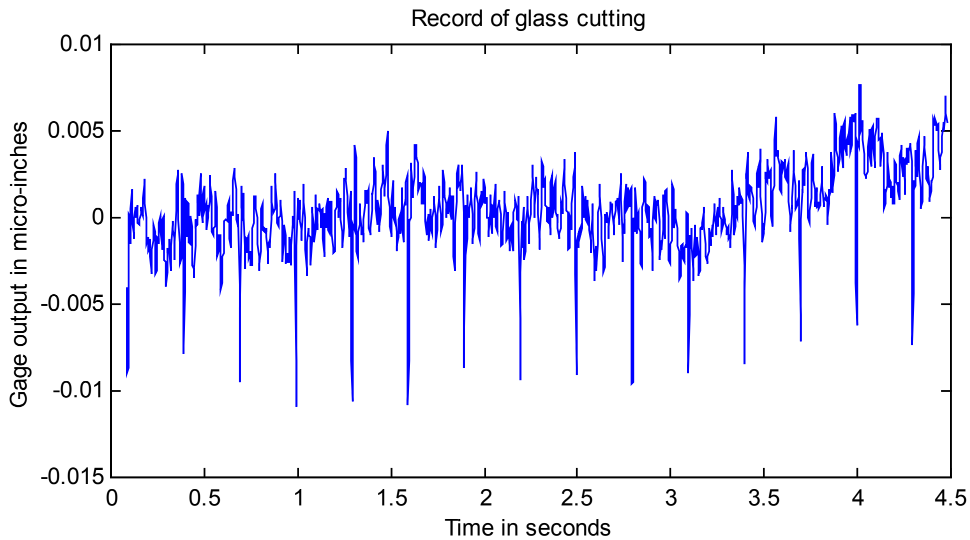

Figure 3.5 Instrumented work holder output showing contact of the diamond tool with the BK7 workpiece

This second test is very encouraging, displaying two small triangular areas of optical quality glass to the unaided eye; however, wear of the tool is evident, showing a crescent shaped wear marking. Figure 3.6 shows a photograph of the diamond tool before flycutting as seen under 50x magnification, and Figure 3.7 shows the tool with the crescent shaped wear marking evident after flycutting. During these initial two tests, the tedious task of touch-off becomes apparent. As other researchers had experienced, there appears to be a lack of material removal when the tool is thought to be in contact with the glass. Analysis of the diamond tool shows flank wear along with evidence of melted glass on the tool. No coolant is used in the flycutting itself.

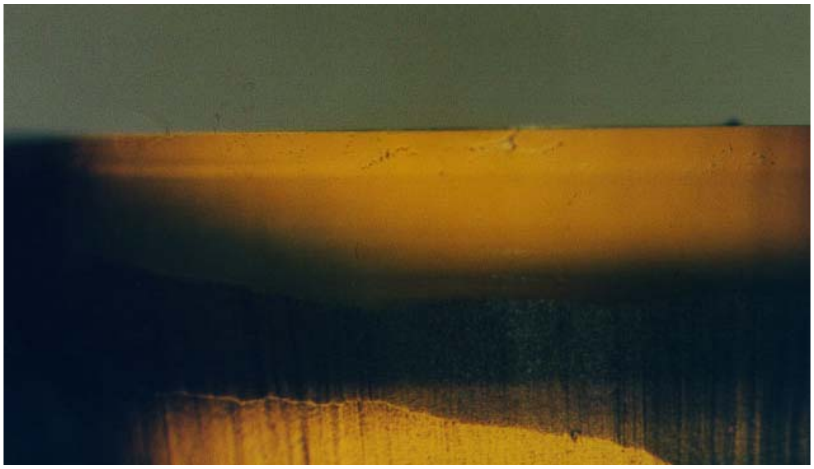

Figure 3.6 Photograph of the diamond tool before flycutting

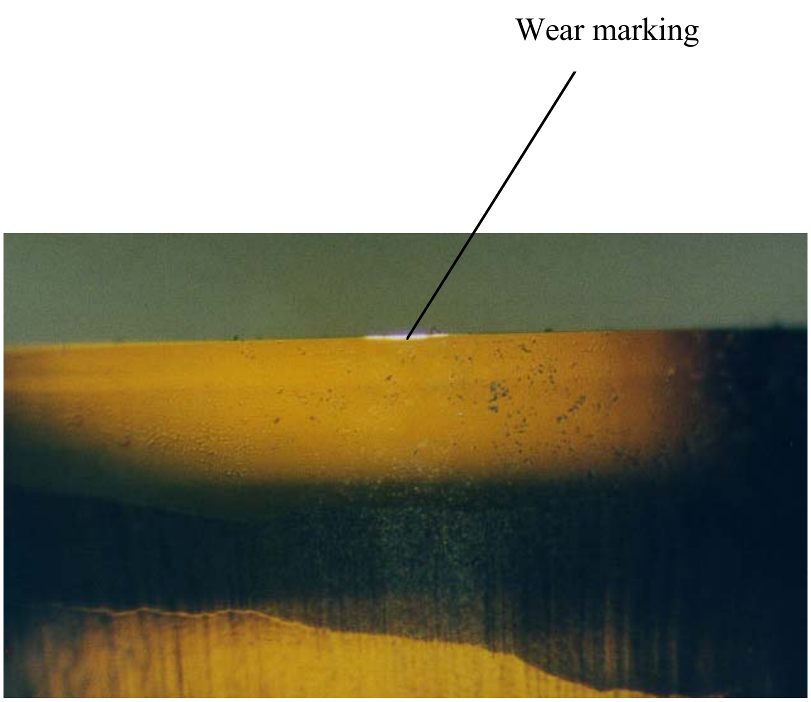

Figure 3.7 Photograph of the diamond tool after flycutting showing the crescent shaped wear marking

3.3 The Third Flycutting Test

The third test involves a 25 millimeter diameter BK7 glass sample mounted in a bronze chuck. The glass workpiece is then ground flat and flush with the bronze chuck using the 400 grit diamond wheel. This preparation stage is used to improve the touch-off methods used in the first two flycutting tests. By touching-off on a soft ductile material such as bronze, the diamond tool is not damaged. Noting the location of the tool's initial contact with the bronze, will provide more accurate glass touch-off. A 0.001 meter nose radius, zero degree rake angle tool is used with a spindle speed of 1000 rpm and a feed rate of 38 micrometers per spindle revolution. VHP E320 Chemical Emulsion Concentrate is used as the coolant for both grinding and flycutting. This flycutting test resulted in a cloudy surface, and damage to the diamond tool.

The main problem encountered in this test is that the coolant interfered with the reading from the capacitance gage, so an alternative place of mounting may be considered in future tests.

Chapter 4
Conclusions

Precision flycutting of glass could possibly be a solution to the problem of time consuming, costly polishing stages in industry. The initial success of a near optical quality glass surface is very encouraging, but repeatability of such a surface appears to be challenging. Ductile material removal and optical quality surface finish does still seem possible.

The work described in this report provides exciting results suggesting that it may be possible to flycut glass under practical conditions. Most importantly, significant progress towards the tool wear issue has been demonstrated with the flycutting geometry.

The high quality of the Professional Instruments/Lion Precision/Moore test setup (both its accuracy and resolution) is credited for the new success. Furthermore, the tools from Edge Technologies represent vast improvements over the natural diamond tools available during the first attempts at turning glass.

Although the results are encouraging, a number of questions deserve further investigation.

Chapter 5
Recommendations for Future Work

More flycutting experiments need to be investigated in order to further improve touch-off techniques. Extensive testing will be needed to determine whether flycutting rather than turning is the solution to the time-consuming and expensive methods used in the past. Many questions remain unanswered.

More research should be done on achieving a possible specular surface finish on a large workpiece or on a large surface area of a workpiece. It should be noted what diamond tool parameters can be used to further improve tool life, such as negative rake angles or a particular nose radius dimension.

Another parameter that needs to be investigated in-depth is the range of suitable cutting speeds for the flycutting of glass.

The resolution of the instrumented work holding spindle needs to be determined. It clearly sees the smallest repeatable cuts of the tool, but now it must be determined whether the gage can detect the tool passing over the work with nanometer clearance. Also, the chemistry required in coolant selection must be investigated.

Finally, the experience and the hardware from flycutting glass and coupled with the knowledge of crystalline materials can be used to flycut other materials such as silicon.

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