1990

Modeling and analysis of an inner diameter slicing blade

George Steven Mazur
Lehigh University

MODELING AND ANALYSIS OF AN INNER DIAMETER SLICING BLADE

by

George Steven Mazur

A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

Mechanical Engineering

Lehigh University

1989

This project is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

Sept 7, 1989

(date)

Robert A Lucas

Professor in Charge

F Erdogan

Chairman of Department

ACKNOWLEDGEMENTS

The author expresses his gratitude to Professor Robert Lucas and Professor Dean Updike for their invaluable advice and guidance in this study.

My thanks are also due to Professor Arturs Kalnins for the use of his Kshel computer program.

TABLE OF CONTENTS

		Page
	Abstract	1
	Symbols	2
I.	Introduction	3
II.	Slicing Operation	5
III.	Kshel Capabilities	13
IV.	Model	25
V.	Results	42
VI.	General Conclusions and Remarks	48
VII.	Appendices	
	1. Grinding Interface Length	49
	2. Fourier Series for Normal Force ...	51
	3. Transverse Point Load	52
	4. Verification of Rotation Analysis .	53
	Figures	55
	Tables	70
	References	74
	Vita	77

LIST OF FIGURES

Page

1. STC Model 2200 Wafering System 55
2. SMI ID Slicing Blade 56
3. Tensioning Hydraulic and Mechanical 57
4. Negative and Positive Blade Deflection . 58
5. Autosort Free State Wafer Plot 59
6. Boundary Condition Coordinate Directions 60
7. Cross Section of Blade Mount and Back Plate 61
8. Direction of Grinding Force Components . 62
9. Direction of Prestress Forces 63
10. Kshel Plot of Radial Displacement Due to a Tensioning Value of .069 inches vs. Radius of Blade 64
11. Kshel Plot of Stresses Due to a Tensioning Value of .069 inches vs. Radius of Blade 65
12. Kshel Plot of Rotational Stresses vs. Radius of Blade 66
13. Analytical Plot of Rotational Stresses vs. Radius of Blade 67
14. Blade Deflection Monitor Printout 68
15. Plot of Axial Blade Deflection vs. Displacement of Inner Diameter Due to a .7934 lb. Point Load at the Inner Edge of the Blade 69

LIST OF TABLES

		Page
1.	Radial Displacement and Stress	70
2.	Natural Frequency vs. Wave Numbers...	71
3.	Natural Frequency vs. Prestress	72
4.	Length of Grinding Interface	73

ABSTRACT

An inner diameter slicing blade is used for the grinding of silicon single crystal ingots into thin slices. These slices, called wafers, are the basic material for the manufacturing of semiconductors.

A modeling and analysis of an inner diameter slicing blade is undertaken is this study. The blade's operating parameters of prestress, rotational speed, grinding forces, and temperature and their influence on the blade's stresses, deflection, and frequency are evaluated. Kshel, a computer program, is used to model the ID blade as a one dimensional axisymmetric shell and provide the analysis of the slicing parameters.

It is determined from this analysis that the blade tension and the transverse grinding force component are the slicing parameters which significantly affect the deflection of the blade as it slices through the ingot.

SYMBOLS

a = Inner radius of blade

b = Outer radius of blade

σ_θ = Stress in theta direction

σ_r = Stress in radial direction

u = Radial displacement

p = Mass density

Fn = Force in normal direction

Ft = Force in tangential direction

Fa = Force in transverse direction

r = radius of blade

T = Temperature

v = Poisson's ratio

E = Young's modulus of elasticity

P = Power

w = Angular velocity of blade

ε_θ = Strain in theta direction

ε_r = Strain in radial direction

I. INTRODUCTION

In the microelectronics industry most semiconductors are fabricated by placing metallized layers on a thin silicon substrate. Cylindrically ground, monocrystalline ingots of silicon are sliced into wafers to form the substrate on which the semiconductors are built. Critical to the overall manufacturing quality of the semiconductors is the dimensional uniformity , flatness, and cleanliness of the silicon wafer that results from the ingot slicing operation.

As the technology of semiconductors advance, circuit designs are using finer line widths in the metallization process. This in turn requires the silicon substrate to have better flatness, minimum taper, lower warp and bow.

Wafer cost is another important consideration in the manufacturing process. In addition to manufacturing the wafer's dimensional quality, material loss from the slicing of the silicon ingot must be maintained at a minimum. The material removed by the slicing operation represents a loss in the product available for further process.

There are several different methods employed to slice the silicon ingots. One technique is to use outer diameter blades. In this technique a circular wheel having a fixed abrasive on its outside diameter is used to grind slices off the silicon ingot. This method requires a relatively thick blade for the slicing operation which results in a large kerf or loss of the ingot material and is therefore a costly procedure.

Another method is to use a wire saw. In this method a wire , with either a fixed or a free abrasive, is made to travel through the ingot thereby grinding a cut through the material. This method works well for small ingot diameters. As ingot diameter increases, the wire saw method creates considerable taper in the silicon wafer.

The third method, ID (inner diameter) slicing, employs a thin circular steel blade with a central hole. The blade, which is tensioned on the outside diameter by means of a blade tensioning ring, has an abrasive fixed to the inner diameter to form its cutting edge. This arrangement allows the blade to have a thinner kerf while maintaining axial stiffness. It is this configuration for wafer manufacturing that this study will evaluate. After a brief description of the parameters that compose this operation a specific blade geometry will be evaluated by modeling the blade as a plate.

The ID slicing saw used for this study is an STC Model 22 Wafering System [1]. See Figure 1. This slicing saw is capable of slicing up to 125 mm diameter ingots using a 22 inch outer diameter slicing blade.

II. SLICING OPERATION

The slicing of a silicon ingot into wafers is one of the most critical operations in the processing of silicon substrates. In this investigation, the slicing operation studied is performed by the manufacturing process known as ID slicing. The blade, driven at a constant rotational speed throughout the cutting operation is plunged through the silicon ingot in a radially pivoted guillotine type motion. The plunge speed is controlled throughout the cut to provide a constant force on the cutting surface. The cutting operation proceeds from the inside ID outward.

A thin stainless steel plate is used as the core material for the saw blade. The core or inner diameter of the blade is plated in the shape of a teardrop with a Ni-Diamond matrix uniformly deposited around the entire inner circumference. The matrix is plated electrolytically from a slurry using a plastic chamber to form the teardrop shape. The diamonds are held in place by the pinning action of the surrounding electrodeposited Ni atoms. See Figure 2.

This blade is then placed in tension by stretching its outer diameter. This tensioning is performed by one of the following methods:

1. Hydraulic tensioning system (see Figure 3a)

The blade is placed on three equally positioned dowel pins on the lower clamping ring. The upper clamping ring, which contains the tensioning ring, is fastened to the lower clamping ring by forty-eight (48) 5/16-24 American National fine thread series screws torqued to a 250 in-lb specification. The screw torquing sequence is to first torque the screws adjacent to the three dowel pins, then torque the remaining screws in succession.

An expansion gage is placed on the inner diameter of the saw blade. The expansion gage is a fixture which stradels the inner diameter of the blade. At one end of the gage there is a dial indicator which contacts the inner edge and indicates any displacement in the dimension of the inner diameter.

Hydraulic fluid is pumped through a grease fitting into a sealed channel behind the tensioning ring. This operation applies a uniform pressure around the outer portion of the blade. The hydraulic fluid is pumped in until the desired stretch, indicated by the expansion gage, of the inner diameter is achieved. This system does not require much setup time, but it does not allow for the blade's material variation in the transverse and parallel rolling direction.

The stainless steel material used for the inner diameter saw is manufactured by cold rolling stainless steel sheets until the desired thickness is obtained and then annealed. When the metal is rolled, it passes and is squeezed between two revolving rolls. The grains are elongated by this process in the direction of rolling, and the material emerges at a faster rate than it enters. The metal is returned to near its original state by annealing. Annealing heats the metal above its recrystalline temperature to reform and relax the grains. Since the grains are still slightly elongated in the rolling direction, the material properties of the stainless steel vary in the directions parallel and perpendicular to the rolling direction. This variation under the uniform pressure used to tension the outer diameter of the blade, results in the inner diameter being displaced out-of-round causing an noncontinuous or elliptic cutting edge.

2. Mechanical tensioning system (see Figure 3b) Again the blade is mounted between a lower and upper clamping ring. In this system the tensioning ring applies pressure to the blade by means of tensioning screws located on one inch centers around the circumference of the upper clamping ring. By adjusting the tension individually on these screws the tensioning ring is controlled to selectivity apply pressure to the blade. As pressure is applied

to the tensioning ring, the inner edge of the blade is monitored with a roller dial indicator to determine which screws need to be adjusted to apply the proper pressure to maintain a concentric inner edge. By this method, the blade can be stretched to the desired inner diameter expansion, while retaining the concentricity and roundness of the inner diameter. This system requires a greater setup time, but results in a blade with a continuous cutting edge. It is important to maintain the continuous cutting edge so that the blade is grinding with the entire inner edge, thus causing more uniform forces and wear on the blade.

The silicon ingot is mounted onto a graphite beam using a slow cure epoxy. The ingot is mounted on graphite to allow the blade to slice through the entire diameter of ingot, while leaving the sliced wafers attached to the graphite beam until a number of wafers are sliced and then removed. This mounted ingot is secured into the ingot box of the saw. After the blade grinds through the ingot, creating a wafer, the blade returns to its up or home position. A stepper motor then drives a leadscrew which indexes the ingot a programmed distance through the inner diameter of the saw blade.

The primary variables involved in the inner diameter slicing operation are:

1. Blade pretension. To achieve the maximum stiffness of the material.

2. Coolant. Applied to the blade in three different places. One coolant nozzle is positioned on the inner edge of the blade at the entrance of the cutting area, another nozzle is positioned on the inner edge of the blade at the exit of the cutting area, and a third is positioned at the back of the blade near the outer edge to be used as a backwash to help rinse away the slurry, composed of silicon chips, diamond chips, epoxy, graphite, and nickel wear. The rate of these three flows as well as the positioning of the nozzles is important to effectively rinse away the slurry and maintain a new grinding surface.

3. Plunge speed. The rate at which the saw blade travels through the ingot on its grinding stroke.

4. Blade speed. The revolutions per minute at which the tensioned blade rotates.

5. Temperature. Developed at the blade tip.

6. Condition of cutting edge. Determined by dressing or cleaning of the diamond edge to create an effective grinding surface.

7. Grinding forces. Developed as blade travels through ingot.

The output or control parameter for the slicing operation is the deflection of the blade as it slices through ingot. To monitor the blade deflection, a non contact probe is positioned on the front of the blade near the inner diameter and attached so that the deflection normal to the blade at the inner diameter of the blade is measured throughout the slicing cycle. This probe uses eddy currents to detect any axial movement of the blade. The probe's signal is amplified to drive an ink pen which traces the deflection of the blade as the blade slices through the ingot. The monitor/controller stops the next slicing cycle if blade has deflected beyond preset limits.

The blade can deflect in either of two directions, toward the ingot or toward the wafer. See Figure 4. Deflecting towards the ingot is referred to as negative bow and deflecting towards the wafer is referred to as positive bow. When the deflection is positive, the blade's path on the return stroke will cause the blade to rub against the convex face of the ingot. Since the ingot is fixed in the ingot box and can not move, this rubbing causes damage to the blade's core material and creates grind marks on the ingot face. When deflection is negative, the blade's path on the return stroke will cause the blade to rub against the convex face of the wafer. Since the sliced wafer is only fixed by the epoxy at the bottom of the cut, the wafer will lean away from the blade as the blade attempts to rub the wafer's convex face, thus avoiding any damage due to rubbing.

Blade deflection during the slicing cycle produces both a bow and a warp in the wafer. Bow is defined as the free state variation of the center of the wafer to the outer edge of the wafer, and warp is defined as the maximum free state variation of any two points on the wafer. Figure 5 shows the bow and warp of a 125mm wafer as determined by Autosort, a commercial surface analyses instrument. Autosort uses a laser to reflect off the wafer surface. From the angle of the reflected laser beam, an algorithm determines the corresponding shape of the wafer.

When the blade deflects out of preset limits during the plunge stroke, dressing of the blade is required to recondition the grinding surface of the inner edge and thereby reduce the axial deflection of the blade. Dressing is used to clean up the grinding edge of the blade by removing any build up of slurry or epoxy thus exposing the diamond grinding surfaces, and to create new diamond grinding surfaces by fracturing the worn diamonds. The dressing procedure uses a one half (1/2) inch square, medium hardness, six (6) inch long, aluminum oxide or a silicon carbide stick, which is presented to the blade in the direction or method needed to correct the out-of-limit condition.

There are three main dressing methods. The first is a plunge dress. In this method the blade is plunged straight through the dressing stick, in order to "dress" the inner edge of the blade. The second method is a pull. In this method the blade is plunged part way into the dressing stick, then the dressing stick is pulled horizontally away from the blade in order to "dress" the back of the blade. The third method is a push. In this method the blade is plunged part way into the dressing stick, then the dressing stick is pushed towards the blade in order to "dress" the front of the blade.

As the blade travels through the ingot, the inner edge will tend to travel towards the direction of clean or free grinding and away from the direction of obstructed grinding. Therefore, the dressing method required is the one which will best clean the obstructed portion of the blade.

III. KSHEL CAPABILITIES

The KSHEL Programs are for the stress analysis of shells of revolution. A personal computer version of the KSHEL Programs is used for this study. The minimum PC configuration required to run this program is an IBM compatible PC, with 512K bytes of memory, a math coprocessor, one 360K byte floppy disk drive, and DOS version 2.10 or later.

1. MATHEMATICAL MODEL

KSHEL Programs analyze thin Shells of Revolution. They use what is commonly called "Classical Shell Theory". The mathematical model of this theory regards a shell as a two-dimensional surface, called the Reference Surface, and assumes that if the deformed Reference Surface is known, then the location of every point in the deformed shell wall is also known. The thinner the shell, the more accurate are the answers. The algorithm that is used for the solutions of boundary value problems by all KSHEL Executives, and its application to shells of revolution, can be found in reference [2].

2. GEOMETRY

The Reference Surface is generated by drawing a plane curve, called Meridian, and revolving it about a straight Axis of Symmetry. All intersections of the Reference Surface by a plane that is perpendicular to the Axis of Symmetry must be Circles. The property of axial symmetry of the shell includes the condition that the wall thickness, springs, elastic foundations, and material parameters do not vary when going around the Circles. However, the wall thickness, elastic foundation, and material parameters can have arbitrary variations along the Meridian.

3. ELASTIC STRESS ANALYSIS

KshelPC does Elastic stress analysis. Surface, Edge, and Ring Loads can have arbitrary variation around the Axis of Symmetry. All loads can have harmonic (sine or cosine) time dependence. If the loads vary around the Axis of Symmetry, then they must be expanded in a Fourier Series by FKShel.

4. GEOMETRICALLY NONLINEAR ANALYSIS

KshelPC, KshelPL, and KshelCR can do geometrically Nonlinear Stress Analysis. It is applicable for axisymmetric loads only. It assumes a nonlinear membrane strain-displacement relation and satisfies force and moment equilibrium of the shell in its deformed state. A nonlinear analysis is needed if the maximum deflections are of the order of the thickness. It is required for Snap-through Instability problems. The algorithm that is used for the solution of all nonlinear boundary value problems executed by KSHEL Executives, and its application to shells of revolution, can be found in reference [3].

5. HEAT CONDUCTION

KshelHC does Heat Conduction in a shell of revolution. It uses an original algorithm, developed by Dean P. Updike and Artuŕs Kalnins, for treating through-the-wall and along-the-Meridian variations of internal heat fluxes and temperatures. It finds the heat flux across the Bounding Surfaces of the shell, the Resultant Flux and a weighted average temperature along the Meridian, and the temperatures at 9 points per layer through the wall. The input consists of thermal conductivities of the wall, divided in up to 4 layers, ambient temperatures, film coefficients, and Radiation Fluxes at the Bounding Surfaces; prescribed Resultant Fluxes, average temperatures, film coefficients, ambient temperatures, and Radiation Fluxes at the shell edges. Conductivity can vary with temperature. Film coefficients, ambient temperatures and Radiation Fluxes can vary along the Meridian. KshelHC is also capable of finding time-transient thermal states between given sets of input variables. KshelHC and KshelPC use a common Data File, with some parts used by both, some only by KshelPC, and some only by KshelHC. The Data File is written with the same Preprocessor, IKShel, and the output processed with the same Postprocessor, PKShel. For a thermal stress problem, KshelHC is run first, and a Temperature File is written. This File is then used as input for KshelPC.

6. FREE VIBRATION

KshelFV does Free Vibration of a shell of revolution. In the absence of any externally applied loads, the shell can undergo Free Vibration. The vibration is started by some initial conditions: given displacements and velocities at every material point of the shell at some initial time. During the vibration, the shape of the shell is the sum of the Normal Modes of Free Vibration. KshelFV calculates Natural Frequencies and the solutions of Normal Modes. Axisymmetric and non symmetric modes can be obtained. The latter are identified by their Fourier Wave Numbers. The algorithm that is used for the solution of boundary value problems of Free Vibration of shells of revolution can be found in reference [4].

7. BUCKLING

KshelBU does Buckling of a shell of revolution. It is applicable to buckling that is produced by axisymmetric loads. If the loads produce compressive in-plane membrane stresses, then the shell can buckle if such loads reach sufficiently large magnitudes. KshelBU calculates Prestress Multipliers by which these loads must be multiplied in order to bring the shell to its Stability Limit. The lowest of the Multipliers times the magnitudes of the applied axisymmetric loads give the Critical Buckling Loads of the shell. The development of a theory of buckling of shells, and its connection to vibration, can be found in reference [5].

8. TIME-TRANSIENT ANALYSIS

KshelFV and either TKShel or PKShel are required to do Time-transient analysis. This refers to a case in which all loads are multiplied by one function of time, say F(t). The solution is expanded in a Series of the Normal Modes of Free Vibration. The first step is to calculate a number of consecutive Normal Modes with KshelFV, starting with the one with the lowest Natural Frequency. The Surface Loads must be specified when the Normal Modes are calculated with KshelFV. In addition to the solution of each Mode, KshelFV also calculates certain integrals that are needed for the construction of the transient response. These solutions and the Mode Integrals are written on the Postprocessor File. The actual response is obtained by two of KSHEL Postprocessors: PKShel and TKShel. PKShel gives the transient solution for the shell at specified times. TKShel gives the time variation of a specified output variable at a specified point on the shell. A derivation of the governing equations that are used by TKShel, and their application to a spherical shell, can be found in reference [6].

9. SEISMIC ANALYSIS

KshelFV and PKShel are required to do Seismic Analysis. A number of Normal Modes must be calculated with KshelFV, the Surface Loads specified, and the solutions written on the Postprocessor File. The seismic response is obtained by PKShel. It requires the Peak Velocity of ground motion that must be obtained from a response spectrum for a given frequency. Based on the data that is on the Postprocessor File and the Peak Velocity, PKShel gives an estimate of the seismic response of the shell. An application of seismic analysis to a containment shell of a power plant can be found in reference [7].

10. PLASTICITY AND CREEP

KshelPL does Incremental Plasticity and Creep. This analysis option has been developed and its copyright is owned by Dean P. Updike. It is applicable to axisymmetric loads only. It models a sequence of instantaneous plastic effects that can be followed by creep in time. In the plastic range, the stress-strain relationship can be either bilinear (linear strain hardening), or taken from an arbitrary curve that relates stress with plastic strain. The stress-strain relationship can be for either true stress versus natural strain or nominal stress versus nominal strain. It can also vary with temperature. This variation is taken from a Table File written by MKShel. The initial yield condition may be either that of Tresca (maximum shear stress) or von Mises (octahedral shear stress). Isotropic or kinematic strain hardening, or a combination of the two, can be modeled. The loading history can be made to follow specified paths in load magnitudes and time. The increments in load produce instantaneous plastic strains, and the increments in time produce creep strain increments. Both may occur simultaneously. A restart feature is available, which means that, if a solution is stored on a Restart File, then it can be continued in another Run at a later time. The Restart File retains the current material history. It can do loading and unloading, find Limit Loads, execute cyclic loading paths, and determine the amount of plastic strain per cycle. An application of this analysis can be found in reference [8].

11. CREEP ANALYSIS

KshelCR does Creep Analysis in time. The difference between the creep in KshelCR and that in KshelPL is that the time increments in KshelPL are specified constants over Load Paths and every time increment can be accompanied by a load increment, while in KshelCR the time increments are selected automatically by KshelCR for optimum convergence and the loads in one Subcase are kept constant. KshelCR is applicable to axisymmetric loads only. KshelCR calculates creep deformations in the Secondary Creep Zone. An exponential power law expressing the creep strain rate in terms of stress is used. The material parameters of the law can vary with temperature. This variation is taken from a Table File written by MKShel. An application of this analysis can be found in reference [9].

12. SNAP-THROUGH ANALYSIS

KshelPC does Snap-through Analysis. Shells that differ slightly from a developable surface (flat plate or a conical shell) can have a snap-through instability. The most common example is a shallow spherical cap that snaps through under pressure. The instability appears as a Limit Point (zero slope) on the plot of the applied load vs. some relevant displacement. Snap-through analysis requires a nonlinear analysis and is therefore limited to axisymmetric loads. Most common snap-through problems occur when the material behaves elastically. However, if a shell snaps through elastically, at a critical load P, then it also snaps through in creep at a lower load than P, provided that sufficient time has elapsed. This is shown in reference [9].

13. PLASTIC BUCKLING

KshelPL and KshelBU working together can do Plastic Buckling. KshelPL calculates a number solutions at specified load increments that have brought the shell material into the plastic range. Relevant parts of these solutions are written on the Prestress File. This File is then used by KshelBU to determine at which load increment the shell is at its Stability Limit.

14. TEMPERATURE-DEPENDENT MATERIAL PROPERTIES

The KSHEL Executives accept material properties that vary with temperature. The variation is read from Table Files written by the Preprocessor MKShel. MKShel receives a point-by-point input of the material parameters vs. temperature and produces the Table Files.

15. KSHEL EXTERNAL FILES

15.1. Postprocessor File. This file contains those solutions that are to be printed for output. It is written by all KSHEL Executives. It is used by the Postprocessors PKShel for postprocessing, CKShel for contour maps, and HKShel for history plots.

15.2. Table FileIt contains Tables that list material parameters versus temperature. It is written by the Preprocessor MKShel. It is used by all KSHEL Executives to read temperature-dependent material parameters.

15.3. Temperature FileIt contains the temperatures of all solutions of heat conduction. It is written by KshelHC and used by KshelPC, KshelPL, and KshelCR as an input file that specifies the temperature input for the shell.

15.4. Restart FileIt contains the history of the material behavior at the last Load Point that has been calculated. It is written and used by KshelPL and KshelCR only, for Plasticity and Creep Options. It is used to continue a plasticity or creep process in a later Run.

15.5. Prestress FileIt contains the Prestress States of the solutions of Load Points. It is written by all KSHEL Executives. It can be used to include the effect of Prestress on the bending stiffness of the shell, which is of importance mainly in the calculation of Buckling Loads.

15.6. Run Summary FileIt contains a summary of what happened in the run. It is written by all KSHEL Executives. It is used by the user to get a quick overview of the status of the Run.

16. PREPROCESSING AND POSTPROCESSING

The standard KSHEL Processors are IKShel, PKShel, FKShel, and MKShel. Other Processors are available for special purposes.

16.1. IKShel

IKShel is a complete Preprocessor used for all KSHEL Executives. It writes data for all cards that are described in this manual. It can be used in two modes:

(1) to create a new Input File; (2) to Update an old Input File. The Update Mode makes changes in an old Input File and produces a new Input File. It is useful for complicated shells with many datacards. Portions of the Input File can be written during one session at the terminal and then continued in another session.

16.2. PKShel

PKShel is a complete Postprocessor used for all KSHEL Executives. For one shell geometry, KSHEL Executives can produce a number of solutions. After the solutions for all loading conditions have been calculated, they can be written on a Postprocessor File. PKShel takes the solutions from the Postprocessor Files and adds them in various combinations. It can print and plot the added solutions. As long as the solutions are produced from the same geometry, the solutions of more than one Postprocessor File can be included in the addition.

16.3. FKShel

Loads that vary around the Circumferential Circles must be expanded in a Fourier Series and its Coefficients used as input for the Loads. FKShel is a Preprocessor that receives a point-by-point input of the variation of the loads and outputs the Fourier Coefficients.

16.4. MKShel

All KSHEL Executives accept material properties that vary with temperature. The variation is read from Table Files that the user must write with MKShel before the KSHEL Executive job is submitted. MKShel is a Preprocessor that receives a point-by-point input of material parameters vs. temp. and writes Table Files.

17. THEORETICAL BASIS OF KSHEL ALGORITHM

The algorithm that formed the basis of the KSHEL programs can be found in reference [2].

IV. MODEL

In order to study and evaluate the effect of the various operating parameters as described previously on the ID slicing blade grinding characteristics, the blade is modelled as a thin plate. The particular blade considered is manufactured by SMI (Semiconductor Material Inc.), reference [10]. It has a 22 inch outer diameter with a 8 inch inner diameter. The core material is .006 inches thick 301 stainless steel. Natural diamonds grit/size 325/400 are electroplated in the Ni matrix on the inner diameter. The Ni-diamond matrix is .016 inches thick on the inner edge and tapers off in the radial distance of .110 inches to the thickness of the core material. The concentration of diamond is dependent on the electroplating parameters used by the blade manufacturer.

Because of this blade's axisymmetric geometry, thinness, and loading types to be investigated in this study, the Kshel Program is employed for the modelling and analysis procedure. The Kshel model for the geometry of the blade is made in two parts; the first part representing the nickel plated diamond inner edge with a radial length of .110 inches and a thickness of .016 inches. The second part representing the stainless steel core material with a radial length of 10.89 inches and a thickness of .006 inches.

The material properties assumed for the calculations are: Young's modulus of elasticity for the stainless steel core, 28,000,000. psi; Poison's ratio of .3; stainless steel density of .733E-03 lbs/inch*inch; and ambient temperature at 0 degrees Fahrenheit.

The following boundary conditions can be assigned to the inner and outer diameter edges. See Figure 6.

1. QPHI - resultant force along axial vector, measured in lbs/inch.
2. NPHI - resultant force along normal vector, measured in lbs/inch.
3. MPHI - bending moment, about tangent of circumferential circle, measured in inch*lbs/inch.
4. NFTH - resultant force along tangent of circumferential circle, measured in lbs/inch.
5. W - displacement along axial vector, measured in inches.
6. UPHI - displacement along normal vector, measured in inches.
7. BPHI - angle of rotation of normal, about tangent of circumferential circle, measured in radians.
8. UTHETA - displacement along circumferential vector, measured in inches.

OPERATING PARAMETERS - BOUNDARY CONDITIONS

Using the above quantities and definitions as the specific Kshel model for analysis the determination, engineering estimates, and assumptions used for the evaluation of each operating parameter follows. A 125 mm or 5 inch diameter monocyrstalline ingot will be the assumed workpiece for this ID blade analysis.

1. TENSIONING

The operating parameter which establishes the operating stiffness of the blade is referred to as the blade tensioning. Blade tensioning is measured by the amount of increase in the inner diameter of the blade, indicated by an ID expansion gage, as the outer edge of the blade is tensioned by either hydraulic or mechanical tensioning.

For the Kshel model, the inner diameter of the blade is assumed constrained through the boundary conditions by the forces NPHI, QPHI, NFTH and moment MPHI, equal to zero and unconstrained in displacement. The outer diameter boundary conditions for W, BPHI, UTHETA is specified to be 0.0. Also the outer diameter boundary condition, UPHI, is incremented to determine at which value the outer diameter displacement results in the greatest blade stiffness. From this, one can determine the corresponding optimal inner diameter displacement required for maximum blade stiffness.

2. ROTATION

Blade rotation is the rotational velocity of the blade about its axis of symmetry. This blade rotation is supplied by a 2 hp DC motor and monitored by a tachometer. The DC motor maintains the blade at a constant rotational speed through a feed-back-loop in its controller as the blade grinds through the ingot. The speed for the grinding of monocrystalline silicon as specified by the blade manufacturer [10] is 3400 - 3600 feet/minute grinding speed. For the ID blade modelled in this analysis, the manufacturers specification results in a rotational speed of 1600 rpm.

The blade rotational parameter requires two considerations in the slicing process. The first is the stress applied to the blade from the inertial forces. In order to analyze the rotational affects on the blade, the additional loading contribution of the blade mount and back plate need to be taken into consideration.

The blade is clamped between the upper and lower clamping rings of the blade mount, and this blade mount assembly is then fastened to a solid back plate attached to the spindle drive as seen in Figure 7. A Kshel analysis of the inertial forces and displacements was performed on a blade mount / back plate model rotating at the operating speed of 1600 rpm's. The results of this analysis showed that the back plate provided sufficient stiffness to constrain the blade mount so as to cause negligible displacements radially. Given this result, it was assumed that the blade mount / back plate provided no addition loadings on the blade and therefore, the rotational effects on the blade could be determined by a model of the blade alone.

The boundary conditions assumed for this operating parameter consists of the established blade geometry model with inner edge boundary conditions constraining the forces, QPHI, NPHI, and NFTH to zero and the moment, MPHI, equal to zero. The outer edge boundary condition assumes all the displacements except UPHI to be zero. UPHI is allowed to be free. From this model, the Kshel program uses the operating rotational speed of 1600 rpm as an input to determine the stresses and displacements resulting from the inertial forces.

A second consideration is the effect the blade's rotational speed has on the grinding mechanics of the ID blade edge and the silicon workpiece. As reported previously, the blade manufacturer's [10] specified grinding surface speed is 3400 - 3600 feet/minute for ID slicing of silicon, this grinding surface speed is used as a constant in this study. The effect various grinding surface speeds have on the slicing operating parameters should be a topic for further research.

3. GRINDING FORCE

The grinding force acting on the blade is considered to act in three cartesian component directions. The three component forces are defined as the normal, Fn, acting along radial direction in the plane of the blade, the tangential, Ft, acting tangent to any point on the circumference of the blade, and the transverse or axial, Fa, acting normal to the blade and parallel to the axis of symmetry of the blade. See Figure 8.

One method for determining the actual force components developed during grinding is to use a multicomponent dynamometer. See reference [11]. A typical dynamometer uses compression-sensitive quartz rings to measure the force component Fa. Shear-sensitive quartz rings measure the components Fn and Ft. Quartz rings are used in pairs with a common electrode between them, yielding double sensitivity. Two pairs of shear rings for Fn and Ft and one pair of compression rings for Fa, assembled in a single housing, constitute a three-component force transducer. The amplifier converts the electrical charge, and thus indirectly the measured force, into a proportional voltage.

The three force components are acting on the blade along the length of the grinding path interface. This interface length, which varies with the plunge depth, is calculated in Appendix 1. Since the three components of the grinding force are nonsymmetric, meaning they only act on a portion of the inner diameter as defined by the interface length, the force components must be expanded in a Fourier Series approximation for input into Kshel. The Fourier Series approximation is in the form:

F = A0 + A1*cos(theta) + A2*cos(2*theta) + ...

where An is a Wave Number, theta is the circumferential angle, and F denotes the grinding force component.

Kshel requires the coefficients, F′ and F′′, as input. Fkshel determines these coefficients for a series that matches the prescribed grinding force component distribution within an accuracy of .01 lbs. Appendix 2 shows the calculation to determine the Fourier Series wave number coefficient for the normal grinding force component. For the blade being analyzed in this study, the values of the force components were taken from several publications. See references [12, 13, 14, and 15]. Since the maximum grinding path interface occurs when the blade is grinding in the middle of the ingot, the force components at this point were assumed to be at their maximum values.

3.1 Normal Grinding Force Component

In this Kshel analysis of the blade model, the wave number coefficients for the normal force component, determined from the Fkshel program, are input as the inner edge boundary condition, NPHI. The force boundary conditions, QPHI and NFTH and the moment boundary condition, MPHI, are constrained to be zero on the inner edge of the blade. The outer edge of the blade is constrained by W, UPHI, BPHI, and UTHETA to be zero. Separate Kshel programs are executed for each value of the normal force component at 0.5 inch intervals of plunge depth through the ingot. The maximum normal component of force, occurring at the middle of the ingot, is estimated from a three dimensional plot of normal force versus blade rotation of 1600 rpm and a plunge speed of 2 inch/min. in references [12, 13, 14, and 15] to be 5.0 lbs.

3.2 Tangential Grinding Force Component

In this model, the wave number coefficients for the tangential force component, determined from the Fkshel program, are input as the inner edge boundary condition, NFTH. The force boundary conditions, QPHI and NPHI and the moment boundary condition, MPHI, are constrained to be zero on the inner edge of the blade. The outer edge of the blade is constrained by W, UPHI, BPHI, and UTHETA to be zero. Separate Kshel programs are executed for each value of the tangential force component at 0.5 inch intervals of plunge depth through the ingot. The maximum tangential component of force, occurring at the middle of the ingot, is estimated from a three dimensional plot of tangential force versus blade rotation and plunge speed in references [12, 13, 14, and 15] to be 0.63 lbs.

3.3 Transverse Grinding Force Component

In order to account for the stiffness of the blade in the transverse direction, the analysis requires the blade model be placed in a prestressed condition before the transverse force is applied. The prestressed condition is obtained by first modelling the blade tensioning, as described in Chapter IV.1. The membrane normal stress resultants (force per unit length), NPHI and NTHT resulting from that analysis are then applied as the prestress for the transverse force model. See Figure 9.

In this model, the wave number coefficients for the transverse force component, determined from the Fkshel program, are input as the inner edge boundary condition, QPHI. Also the force boundary conditions, NFTH and NPHI and the moment boundary condition, MPHI, are constrained to be zero on the inner edge of the blade. The outer edge of the blade is constrained by W, UPHI, BPHI, and UTHETA to be zero. Separate Kshel programs are executed for each value of the transverse force component at 0.5 inch intervals of plunge depth through the ingot. The maximum transverse component of force, occurring at the middle of the ingot, has a value of 0.22 lbs. as reported in reference [15].

4. BLADE STIFFNESS

Another method for determining the stiffness of the tensioned ID blade is to use a tool called a force deflectometer. The deflectometer consists of a force gage which applies a constant transverse point load near the inner diameter of the blade. A constant point load of 360 grams or .7934 pounds will be used in this model. This is the general point load value used by many ID blade manufacturers to measure and report the stiffness of their ID blades.

The transverse deflection of the blade resulting from this force is measured by a dial indicator. The blade manufacturer then plots the deflection of the blade from the constant point load for various tensioning values. The manufacturer provides this plot of the blade stiffness to the customer for each lot of stainless steel core material. This plot is one way to quantify the quality and consistency of the blades.

To duplicate this test with the Kshel program, the Kshel model of the blade geometry explained previously is used as the basic model. In order to accountant for the stiffness of the blade in the transverse direction, the analysis requires the blade model be placed in a prestressed condition before the transverse point load is applied.

The prestressed condition is obtained by first modelling the blade tensioning for a specified tension value, as described in Chapter IV.1. The membrane normal stress resultants (force per unit length), NPHI and NTHT resulting from that analysis are then applied as the prestress for the transverse point load model.

In this model, the wave number coefficients for the transverse point load, determined from the Fkshel program, (see Appendix 3) are input as the inner edge boundary condition, QPHI. Also the force boundary conditions, NFTH and NPHI and the moment boundary condition, MPHI, are constrained to be zero on the inner edge of the blade. The outer edge of the blade is constrained by W, UPHI, BPHI, and UTHETA to be zero.

5. TEMPERATURE

Heat generated in the contact area between the wheel and a workpiece causes a deterioration in the dimensional accuracy and finished surface of the workpiece, as well as reducing the useful life of the wheel. Therefore, the temperature at the grinding interface is a significant operating parameter in the analysis of a diamond abrasive grinding blade.

For the STC slicing saw used in this analysis, the grinding interface temperature could not be measured directly but could be estimated from the power requirements of the spindle motor as the blade plunged through the ingot. In order to determine the power increase, a power meter was electrically connected to the saw to measure the power draw on the SCR (silicon controlled rectifier) unit. The SCR is used to convert the AC current into DC current for the spindle motor while it is driving the blade at a constant rotational speed as the blade plunges through the ingot.

Using this power meter, it was determined that 400 watts of power are required to maintain the rotational speed of an unloaded blade. A maximum power increase of 300 watts was recorded as the blade plunged through the ingot. This power increase is the result of the following conditions that occur during the grinding process:

WORK IN :

- -Grinding work done on the workpiece (friction work, deformation and local fracturing of the silicon).
- -Grinding work done on the blade (frictional work, deformation and local fracturing of the diamond nickel matrix).

ENERGY OUT :

- -Kinetic energy of the silicon chips.
- -Heating of the silicon chips.
- -Heating of the workpiece.
- -Heating of the blade.
- -Radiation to the surroundings.
- -Heating of the slurry.
- -Generation of new grinding surfaces.
- -Residual energy remaining in the lattice of the ground surface, grinding matrix, and silicon chips.

Since the percentage of the power increase required for each of these conditions is not known, an analysis that evaluates a worst case in which all of the power increase is assumed to go into the temperature rise of the blade is made.

To perform the analysis of temperature affects on the ID blade the KshelHC program is used. This program uses the same Kshel blade model described previously except a heat conduction algorithm performs the temperature analysis. KshelHC uses a two dimensional model of the blade (see Chapter III.5). The heat conduction boundary condition specified for the inner diameter of the blade is the resultant flux. The resultant flux is defined as the flow of heat per unit length across the reference surface. Using the total power increase of 300 Watts or .284 Btu/sec determined from the current draw of the spindle motor and dividing by the circumferencial length of the inner diameter, 25.13 inches, the resultant flux was found to be .011 Btu/sec/inch. The boundary condition on the outer diameter edge of the heat conduction model is temperature which is specified at ambient or 0 degrees Fahrenheit. The other properties which need to be defined are (from reference [16].):

- -Specific heat of stainless steel is .12 Btu/lb/F.
- -Film coefficient of the coolant on the face of the ID blade is assumed to be .0204 Btu/sec*in*in*F, which is a typical heat transfer coefficient for forced convection of liquids.
- -Thermal conductivity of the stainless steel core at a reference temperature of 212 degrees fahrenheit is .2176E-03 Btu/s/in/F.
- -Ambient temperature is 0 degrees fahrenheit.

A second part to this temperature analysis is to determine if the stiffness of the blade is affected by the

temperature rise of the blade. After the temperature profile of the blade has been modelled, the maximum transverse force of 0.22 pounds as described in Chapter IV.3 will be applied to the KshelHC blade model and the resulting deflections determined.

6. VIBRATION

In order to better understand the interaction of the blade with the ingot, it is useful to determine the vibration characteristics of the blade. This allows the determination of the excitation frequencies needed to cause resonance of the blade and hence large transverse displacements which could severely damage one or more of the elements on the ingot-blade system.

The Kshel blade model is used to determine the vibration characteristics of the ID blade. In order to accountant for the stiffness of the blade in the transverse direction, the analysis requires the blade model to be placed in a prestressed condition before the vibration analysis is performed.

The prestressed condition is obtained by first modelling the blade tensioning as described in Chapter IV.1. The membrane normal stress resultants (force per unit length), NPHI and NTHT resulting from that analysis are applied as the prestress.

The prestress is then used in the Kshel model of the blade. Since the free vibration algorithm can only determine the vibration of an unloaded blade, the inner diameter boundary conditions, NPHI, QPHI, MPHI, and NFTH are constrained to be zero. The outer diameter boundary conditions, W, UPHI, BPHI, and UTHETA are also constrained to be zero. The algorithm in KshelFV program is then used to determine the natural frequency for various Fourier wave numbers.

The natural frequencies of the blade are then compared to the operating rotational frequency of the blade which is specified by the blade manufacturer at 1600 rpm or 26.67 rev/sec for the blade in this analysis.

The second part of this free vibration analysis uses a prestress multiplier to simulate a loss in prestress or tension of the blade. The natural frequencies of the blade at these specified tensioning values are compared to the operating rotational frequency of the blade to determine if a loss of tension will provide resonance.

V. RESULTS

1. TENSIONING

Using the Kshel boundary condition analysis model for the tensioning of the ID blade, Table 1 was created. Listed are the inner diameter radial displacements of the blade and the stress components in the theta direction for given values of outer diameter stretch. In order to achieve the maximum blade stiffness, the blade should achieve the greatest stress value without exceeding the yield point. Given that the yield strength for the stainless steel core is between 245,000 psi and 262,000 psi, it can be concluded from Table 1 that an inner diameter displacement of .065 to .069 inches will provide this maximum blade stiffness. Figures 10 and 11 show the radial displacement and radial stresses respectively for an inner diameter displacement of .069 inches.

For this ID blade, the manufacturer suggests a inner diameter expansion from .064 to .068 inches which demonstrates the tensioning boundary condition analysis is in good correlation.

2. ROTATION

The Kshel boundary condition model was used to determine the radial displacement and radial stresses developed from the inertial forces of the rotating blade. The results indicated that the radial displacement and the radial stresses were negligible, providing little or no addition loadings to the blade.

An analytical solution for a thin circular disk with a central hole was performed in Appendix 4. This analysis was performed to verify the results obtained from the Kshel program. The problem definition and values were equivalent to the Kshel model. The trends and stress magnitudes obtained from this analytical solution compare very well with the trends and stress magnitudes in the Kshel boundary condition model, as can be seen in Figures 12 and 13. Figure 12 plots the results from the Kshel model. It shows the plot of the radial phi and theta stresses resulting from the inertial forces of the rotating blade. Figure 13 plots the radial phi and theta stresses of the blade under the same conditions, using the analytical calculation shown in Appendix 4.

3. GRINDING FORCES

The Kshel analysis for both the normal and tangential force components indicated that at the maximum values of these force components, the radial and theta stresses and the deflections were negligible.

The Kshel analysis for the transverse force component resulted in a transverse or axial blade deflection of 6 microns at the location of maximum transverse force or longest grinding interface. This result compares in magnitude with the actual deflection recorded by the deflection monitor during the slicing process. Figure 14 is a printout of the blade deflection for several slices through a 125 mm ingot. Each loop on this printout is a blade deflection path for a single slice, starting at zero deflection, reaching a maximum deflection of approximately 10 microns at the center of the ingot diameter, and returning to zero deflection when completely through the ingot diameter.

4. BLADE STIFFNESS

The Kshel analysis of the ID blade stiffness with a point load acting was performed at several tensioning values. The results of the blade stiffness is plotted in Figure 15 as a function of inner diameter radial displacement along with the measured results obtained from a blade deflectometer test on the specified blade. The data points on the plot represent the tensioning values analyzed. As can be seen for both methods, the deflection is large for small radial displacements or tensioning. As the radial displacement is increased, the deflection decreases rapidly, until it reaches the earlier specified tensioning range where the deflection levels off as the tensioning values increase. Tensioning the blade to values beyond those for this plot, would enter the stainless steel core material into the plastic deformation range and would decrease the blade's stiffness.

5. TEMPERATURE

Using the KshelHC model described in the modeling section, the worst case temperature rise was analyzed by assuming that all measured power increase during the grinding process went into the temperature rise of the blade. This worst case condition resulted in a average temperature rise across the two dimensional inner edge of the blade to be 9.3 degrees fahrenheit. Also, it was determined that due to the forced convection of the coolant on the inside and outside of the blade, this 9.3 degree rise in temperature was dissipated very quickly, within the length of the diamond plating. This result agrees with the general theory of grinding which predicts minimal rise in temperature when grinding with diamonds.

The second part of this temperature analysis assumed that the maximum transverse force component of .22 lb (reference [12]) was applied as a boundary condition to the blade's inner edge together with the 9.3 degree temperature rise. This analysis showed there was no significant increase in axial deflection or blade stress over the same Kshel model analyzed in Chapter V.3 with no temperature rise.

This temperature analysis demonstrates that the temperatures resulting from the grinding operation for the conditions given in the KshelHC model has no significant effect on the blade.

6. VIBRATION

The vibration characteristics were determined by using the KshelFV model. The free vibration results listed in Table 3, indicate that the lowest Fourier wave number, 0, has the lowest natural frequency or fundamental mode at 508 cycles per second and the natural frequencies increase as the Fourier wave numbers increase. Comparing the lowest natural frequency of the blade to the blade's operating rotational frequency of 26.67 revolutions per second, it can be seen that the rotational frequency would have to increase its magnitude at least 20 times in order to reach resonance.

For the free vibration analysis of the Kshel model, the prestress of the blade was varied to examine if a loss in tension would result in resonance. From the KshelFV results listed in Table 3 it can be seen that the prestress would have to be reduced to near zero in order to reach resonance.

From this free vibration analysis of the ID blade it can be concluded that the rotational frequency of the blade is unlikely to be a source of excitation near the fundamental mode.

VI. GENERAL CONCLUSIONS AND REMARKS

Using Kshel, an accurate boundary condition model of an ID slicing blade was developed and analyzed for the various slicing operating parameters. It was determined from this analysis that the tensioning value and the transverse grinding force component were the operating parameters which significantly affected the control parameter or the deflection of the blade as it sliced through the ingot.

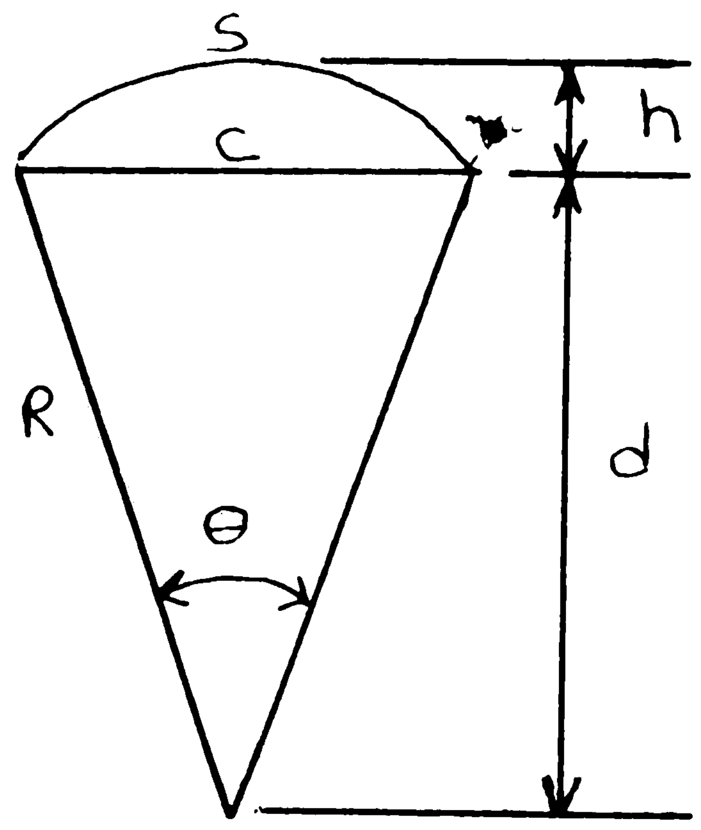
Given the ID blade's geometry and material characteristics, the Kshel model indicated that a tensioning range from .064 to .068 inches would achieve maximum stiffness of the blade.

The result of the transverse grinding force component analysis indicated that a maximum axial blade deflection of 6 microns occurs at the maximum grinding interface. This axial deflection is the slicing output parameter which needs to be controlled in order to obtain the wafer quality needed for leading edge semiconductor manufacturing.

Further work is required to determine the causes of this transverse force component and the means to control and reduce it.

APPENDIX 1

Calculation to determine the grinding interface length as the ID blade travels through a five (5) inch diameter silicon ingot. An assumption is made that the blade plunge path through the ingot is a straight line. The following analysis is from reference [17].



From geometry, we have the following relationships for a sector and segment of a circle.

$$S = R\theta$$

$$C = 2R\sin\frac{\theta}{2}$$

$$\theta = 2\sin^{-1} C/2R$$

Looking at the equations for the blade.

$$S_B = R_B\,\theta_B$$

$$S_B = 2R_B\sin^{-1} C_B/2R_B$$

Looking at the equations for the ingot.

$$C_I = 2R_I\sin\frac{\theta_I}{2} = \sqrt{4h_I(2R_I - h_I)}$$

From the geometry at the grinding interface, we have.

$$C_I = C_B$$

Substitute into equation.

$$S_B = 2R_B \sin^{-1}\left[\frac{\sqrt{4h_I(2R_I - h_I)}}{2R_B}\right]$$

Using the values for the ID blade model grinding through a five inch diameter ingot.

$R_B = 4.0$ inch

$R_I = 2.5$ inch

Table 4 shows the results of grinding interface length and degree per depth of cut.

APPENDIX 2

Following is a calculation to determine the Fourier wave number coefficient for nonsymmetric load of the normal force component. This calculation is also used to determine the wave number coefficients for the non symmetric tangential and transverse force components.

The maximum normal force of 5 pounds is obtained from references [12, 13, 14, and 15]. This maximum force is assumed to be present for the longest grinding interface while plunging through a 125 mm ingot. From Table 4, this maximum length is 5.401 inches or 84.93 degrees of the inner diameter of the blade. From this assumption, the normal force per degree can be found.

FPD = maximum force / maximum degree

For the normal force component.

FPD = 5 pounds / 84.93 degrees = .0589 pounds/degree

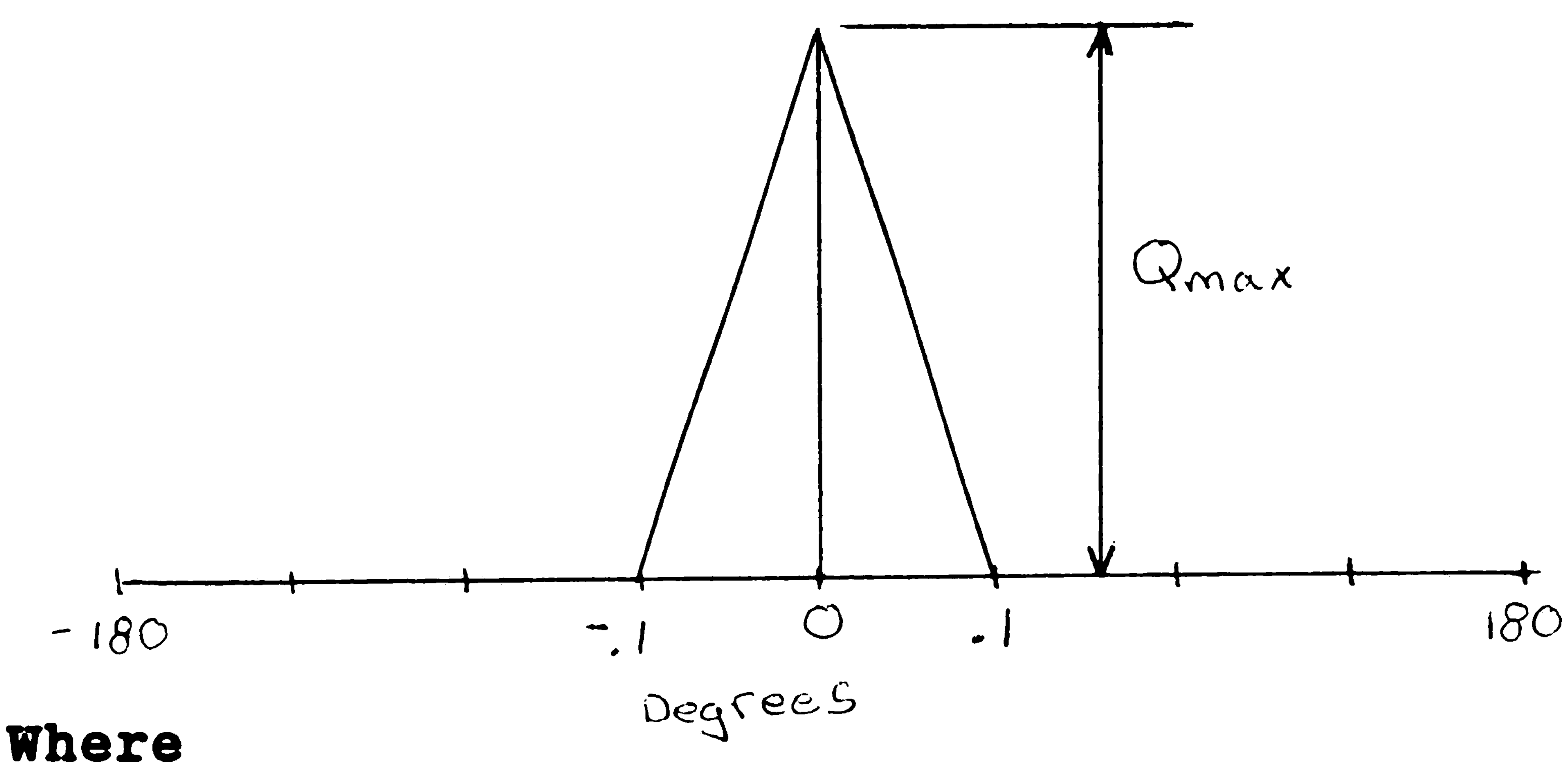
This FPD load is input into the FKshel program for the specified depth of plunge or degrees. The FKshel program then calculates the Fourier wave number coefficients for the specified wave numbers of 1 through 12.

A seperate Kshel analysis is performed for each wave number, using the fourier wave coefficient calculated. These seperate cases are then superpositioned upon each other in the post processor of the Kshel program.

APPENDIX 3

Fourier Series Expansion to determine coefficients for transverse point load.

Calculation to determine load input.



Where

$$S = r\theta$$

$$dS = r\,d\theta$$

Substituting into force equation.

$$F = \int_{-\alpha}^{\alpha} Q_{max}\, r\, d\theta$$

Integrating from $-\alpha$ **to** α **.**

$$F = Q_{max} r \alpha$$

Rearranging

$$Q_{max} = \frac{F}{r\alpha}$$

Therefore,

$$Q_{max} = 113.67 \text{ lbs}$$

Where,

r = 4.0 inches

α = .001745 rad

F = .7934 lbs

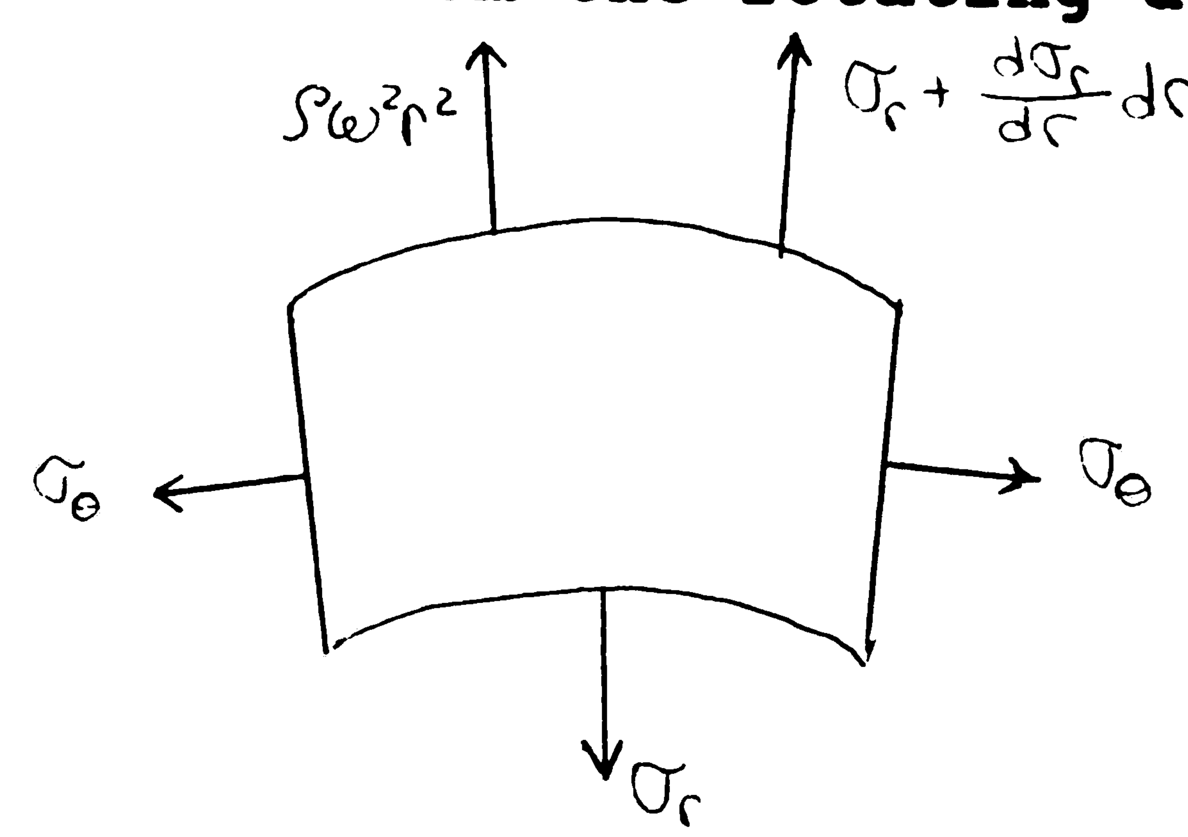
The results from the fourier series expansion gives the following expression for the point load.

$$F = .07116 + .14232 \cos\theta + .14232 \cos 2\theta + \cdots$$

APPENDIX 4

Analytical determination of rotational stress and radial displacement to verify results from Kshel. The thickness of disk is assumed sufficiently small so that it is affectivity in a state of plane stress (theta z=0). From reference [18].

Consider the element from the rotating disk



The radial equilibrium of the element is

$$r \frac{\partial \sigma_r}{\partial r} = \sigma_\theta - \sigma_r - \rho\omega^2 r^2$$

The stress - strain equations may be written as

$$\varepsilon_r = \frac{\partial u}{\partial r} = \frac{1}{E}(\sigma_r - \nu\sigma_\theta)$$

$$\varepsilon_\theta = \frac{u}{r} = \frac{1}{E}(\sigma_\theta - \nu\sigma_r)$$

Eliminating u from these two equations and combining this with the radial equilibrium equation gives

$$\frac{\partial}{\partial r}(\sigma_r + \sigma_\theta) = -(1+\nu)\rho\omega^2 r$$

This equation is integrated to obtain (   ), which can be substituted into the equilibrium equation to give

$$\sigma_r = A + B\frac{b^2}{r^2} - \frac{3+\nu}{8}\rho\omega^2 r^2$$

$$\sigma_\theta = A - B\frac{b^2}{r^2} - \frac{1+3\nu}{8}\rho\omega^2 r^2$$

where A and B are to found from the boundary conditions.

at r = a $\sigma_r = 0$

at r = b $\sigma_r = 0$

These conditions give

$$A = \frac{3+\nu}{8} \rho \omega^2 (a^2 + b^2)$$

$$B = -\frac{3+\nu}{8} \rho \omega^2 a^2$$

Substituting these into the stress equations results in

$$\sigma_r = \frac{3+\nu}{8} \rho \omega^2 \left(a^2 + b^2 - \frac{a^2 b^2}{r^2} - r^2 \right)$$

$$\sigma_\theta = \frac{3+\nu}{8} \rho \omega^2 \left(a^2 + b^2 + \frac{a^2 b^2}{r^2} - \frac{1+3\nu}{3+\nu} r^2 \right)$$

and the radial displacement, u, can then be found from stress-strain equations to be.

$$u = \frac{(3+\nu)(1-\nu)}{8E} \rho \omega^2 r \left\{ a^2 + b^2 - \left(\frac{1+\nu}{3+\nu} \right) r^2 - \left(\frac{1+\nu}{1-\nu} \right) \frac{a^2 b^2}{r^2} \right\}$$

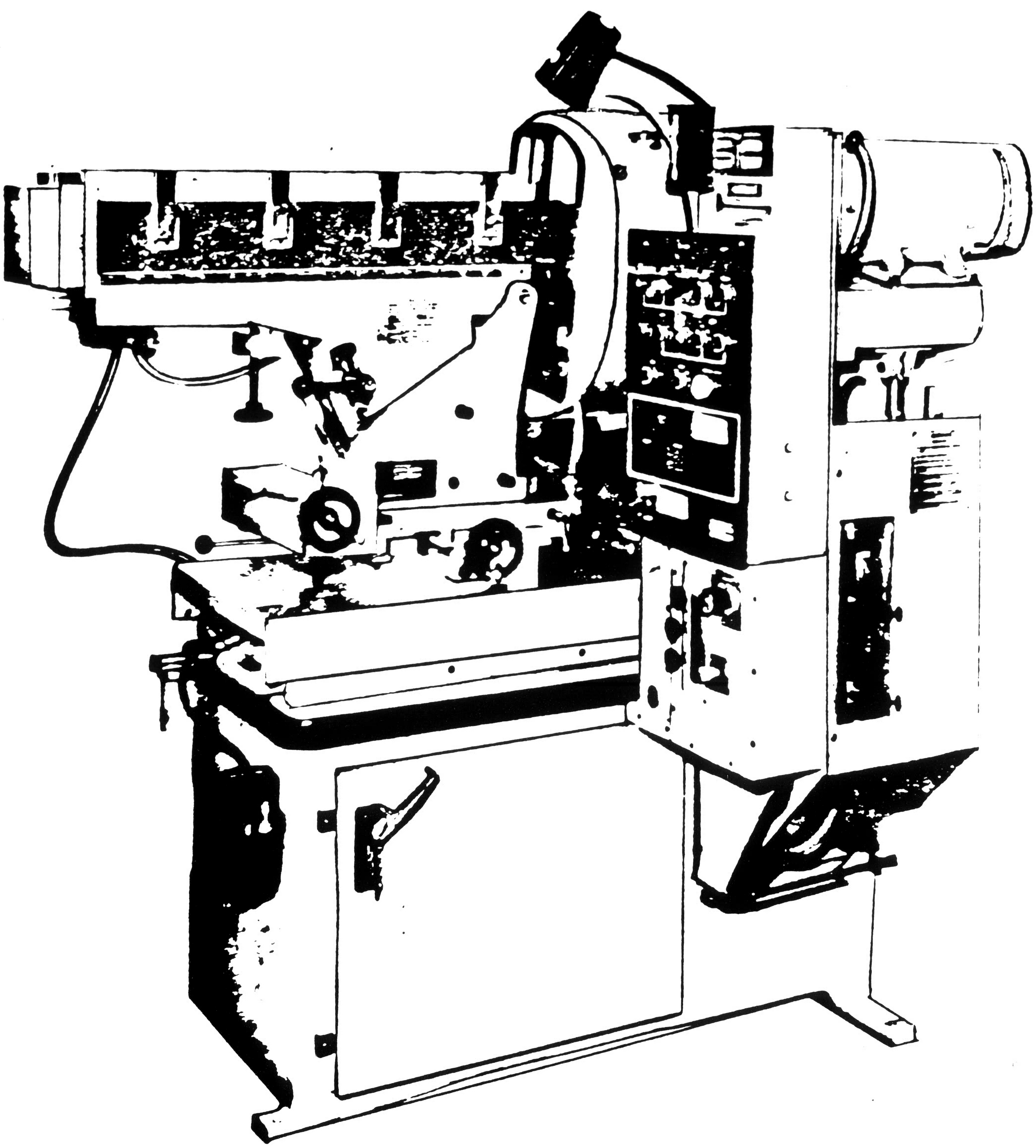


Figure 1. STC Model 2200 Wafering System

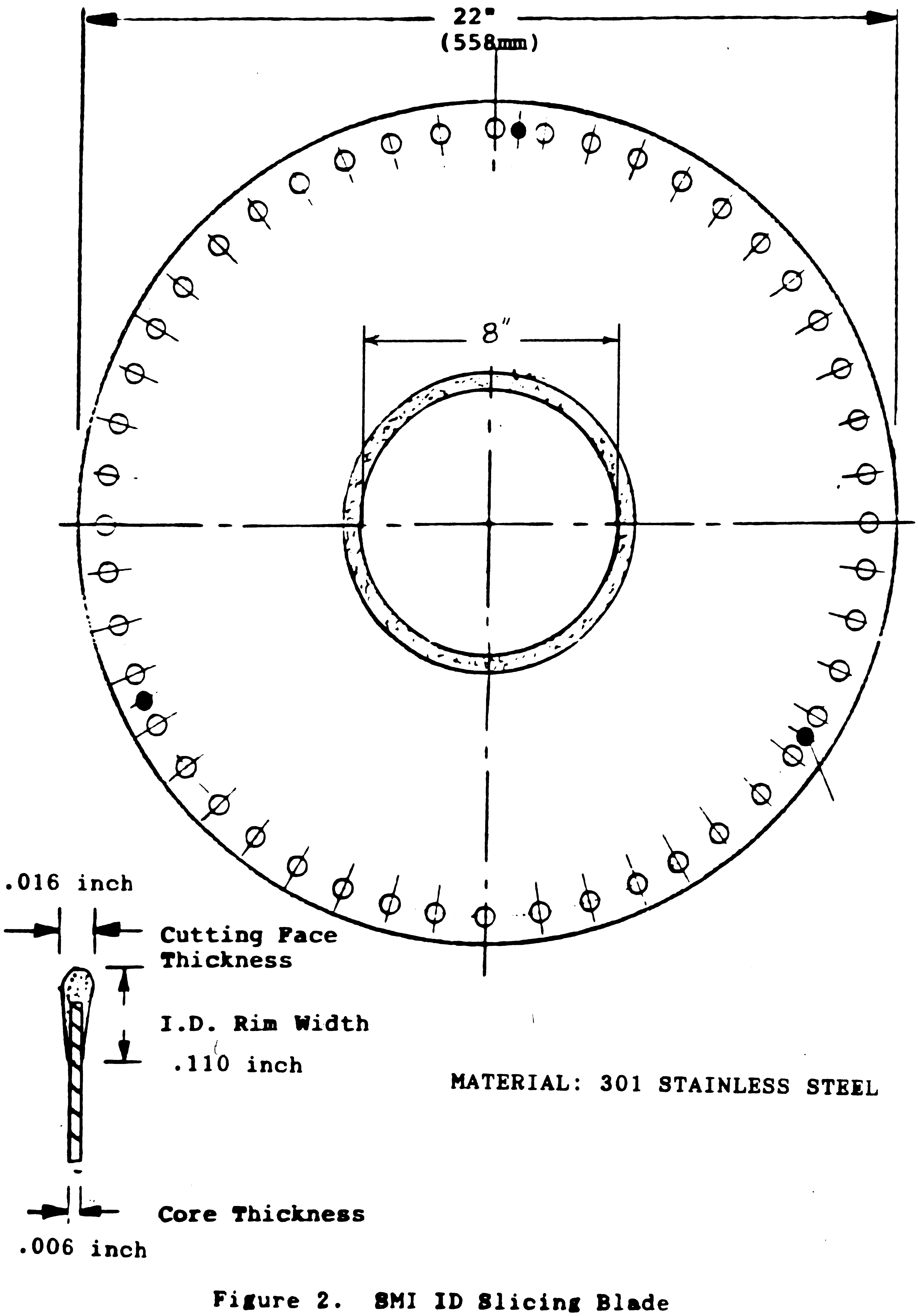


Figure 2. SMI ID Slicing Blade

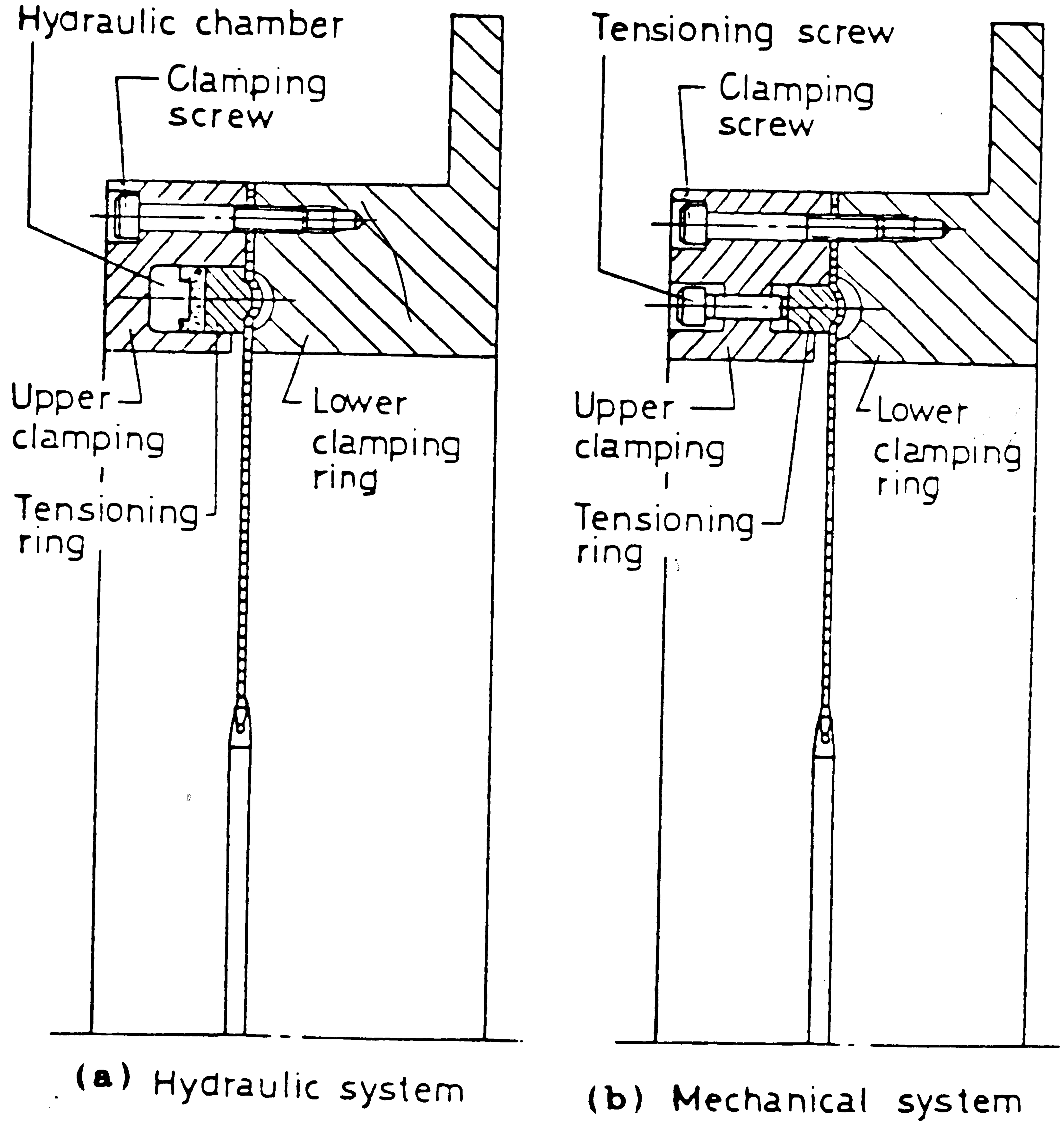


Figure 3. Tensioning a)Hydraulic b)Mechanical

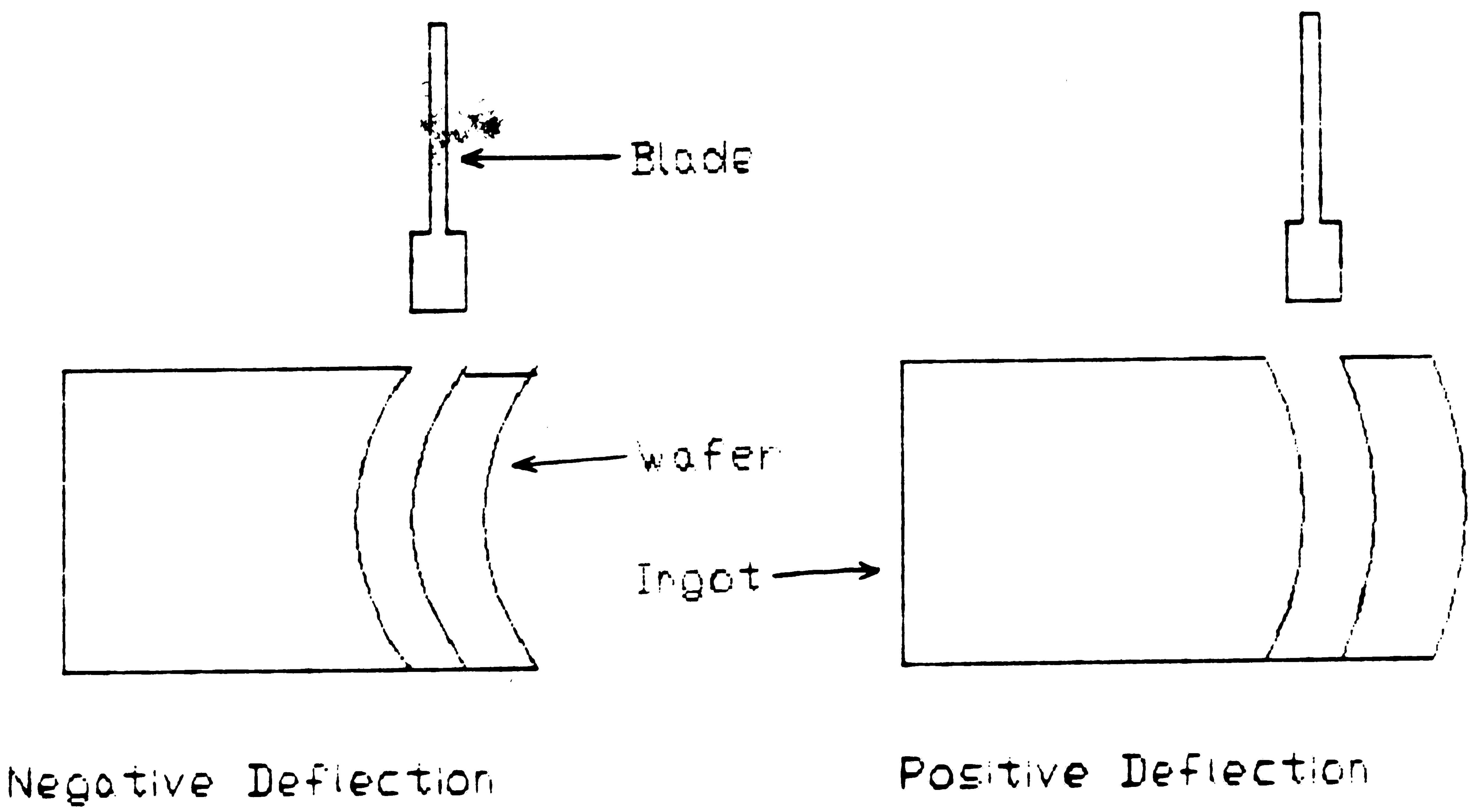
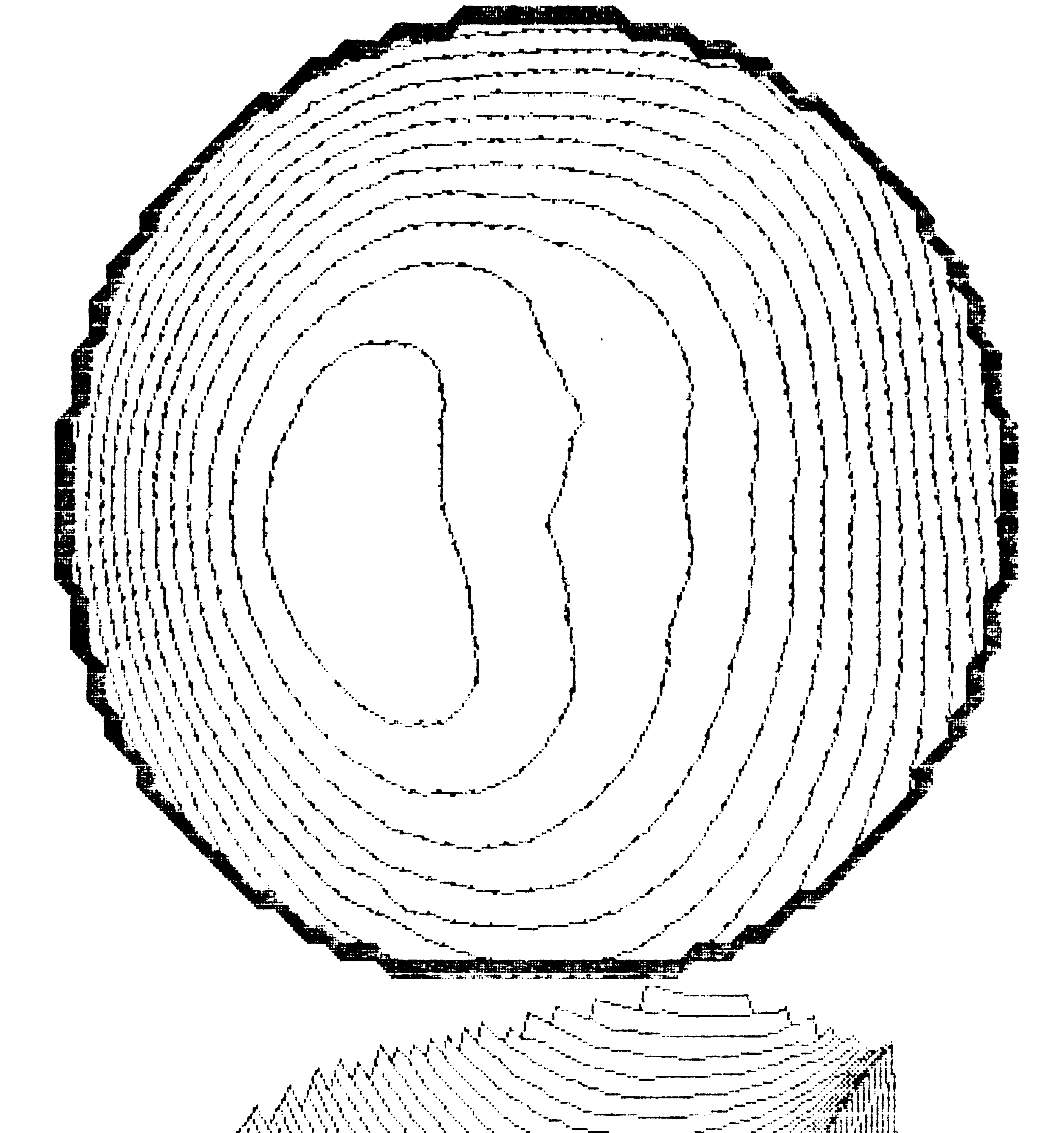


Figure 4. Negative and Positive Blade Deflection



Scale 1.00 µm / contour
Warp 14.9 µm
Bow -8.6 µm

Figure 5. Autosort Free State Wafer Plot

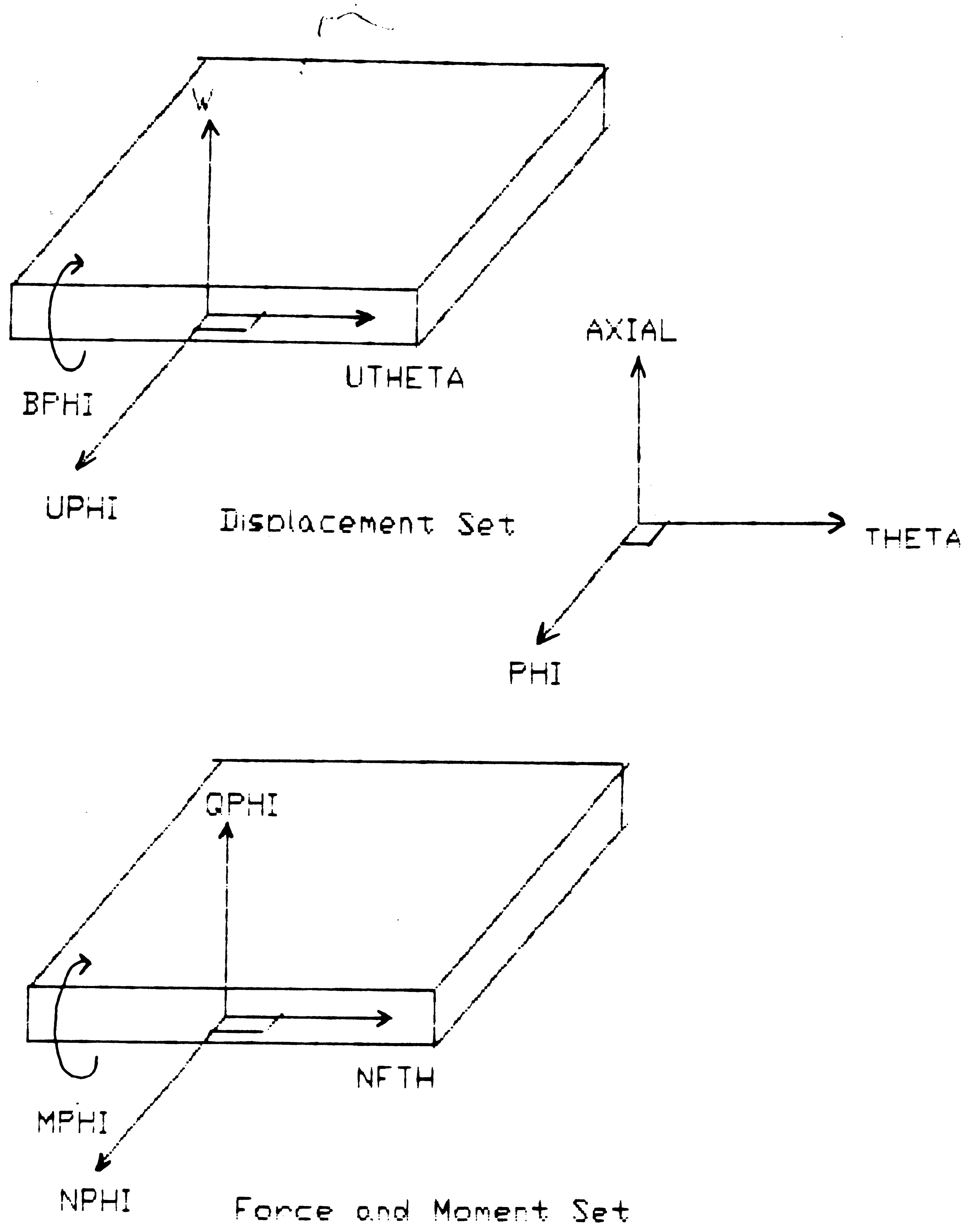


Figure 6. Boundary Condition Coordinate Directions.

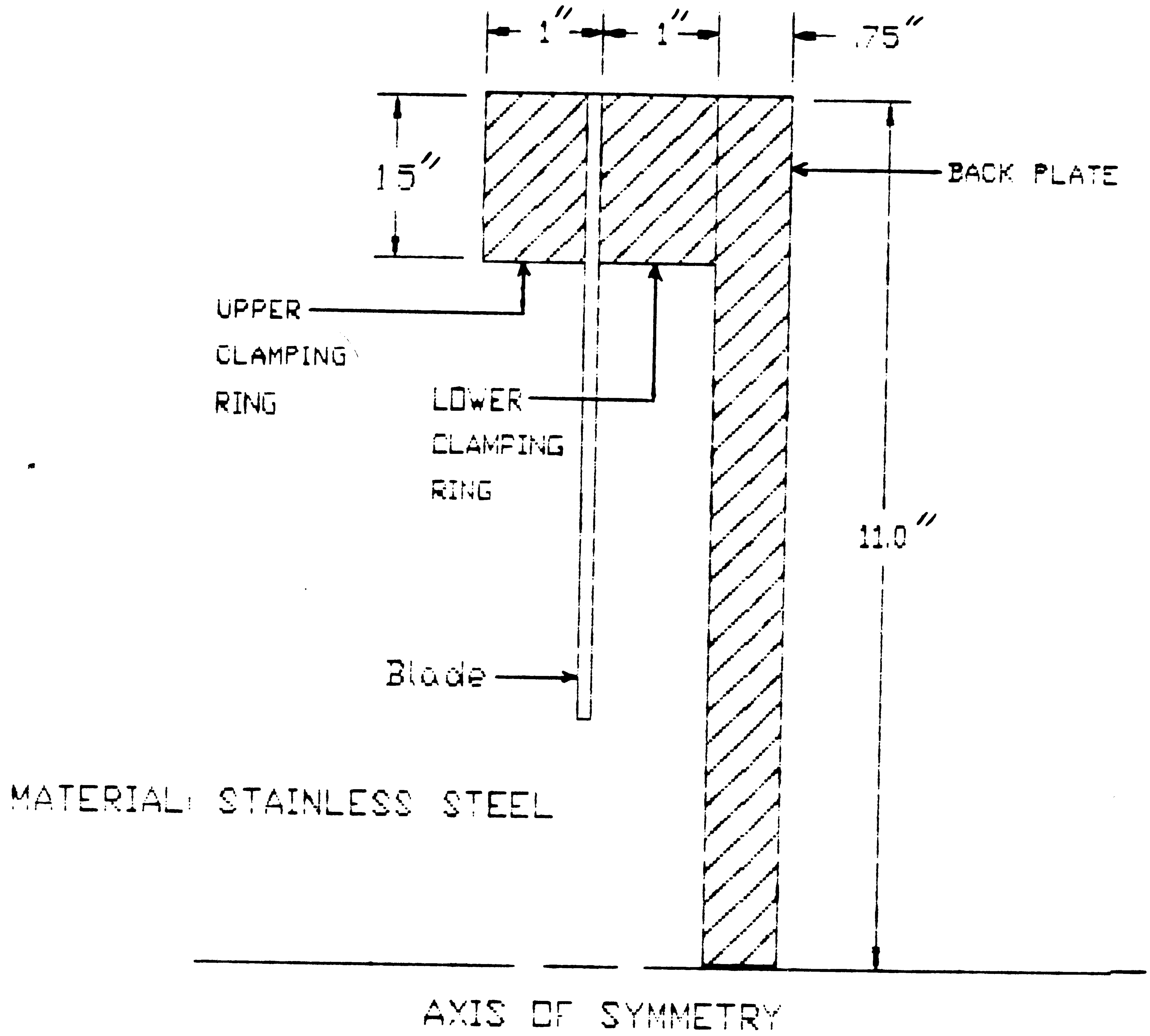


Figure 7. Cross Section of Blade Mount and Back Plate.

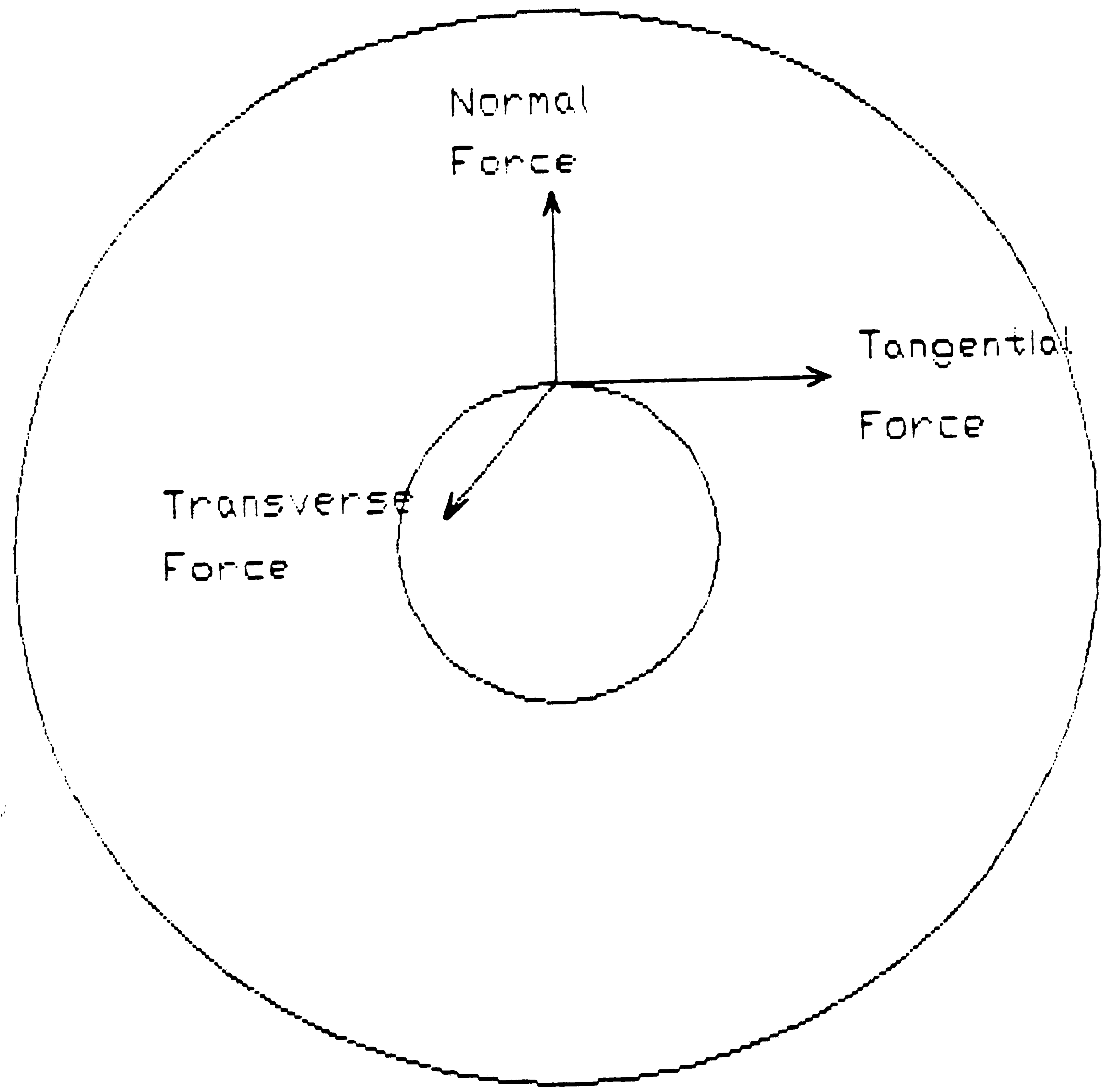


Figure 8. Direction of Grinding Force Components

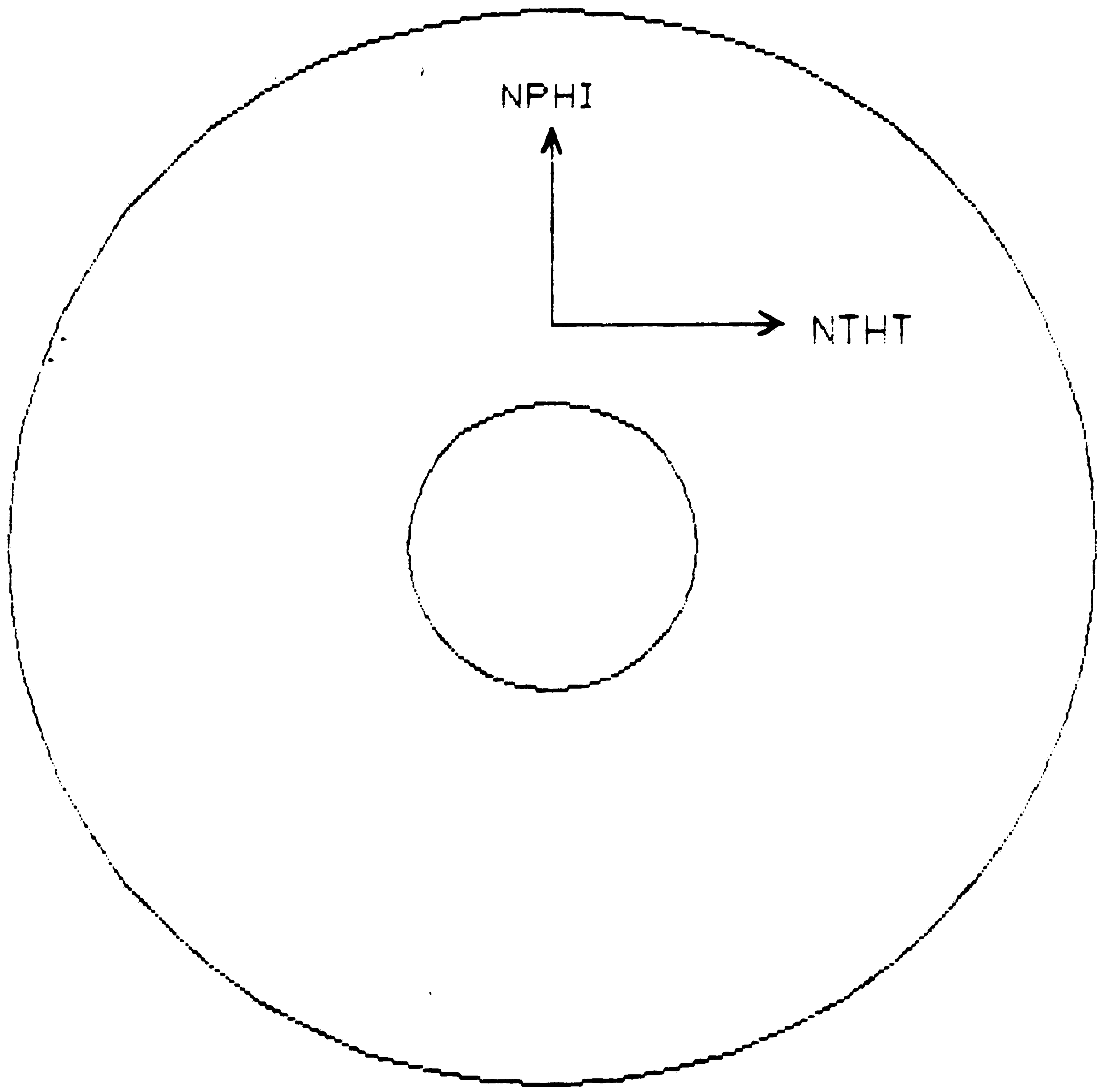
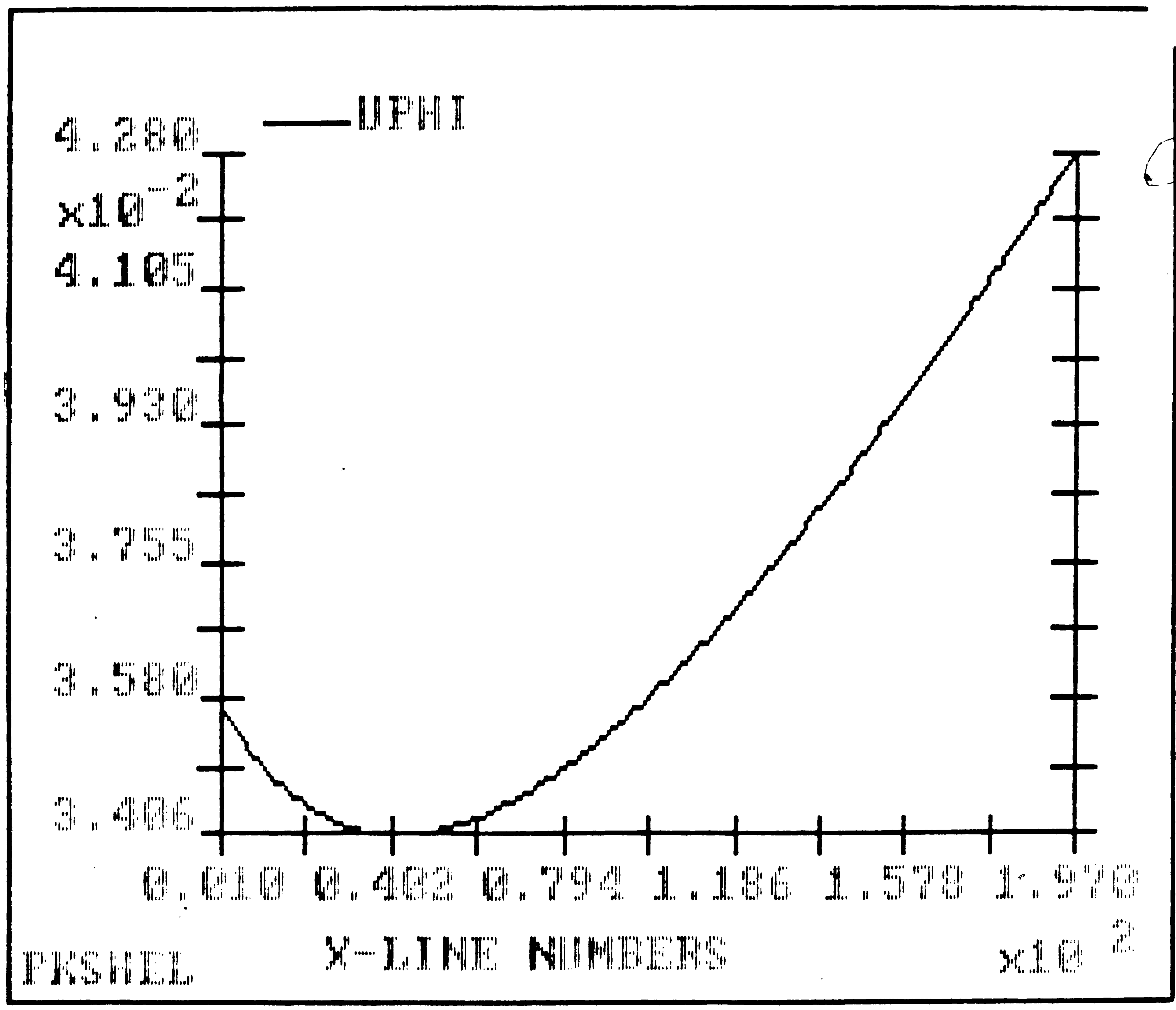
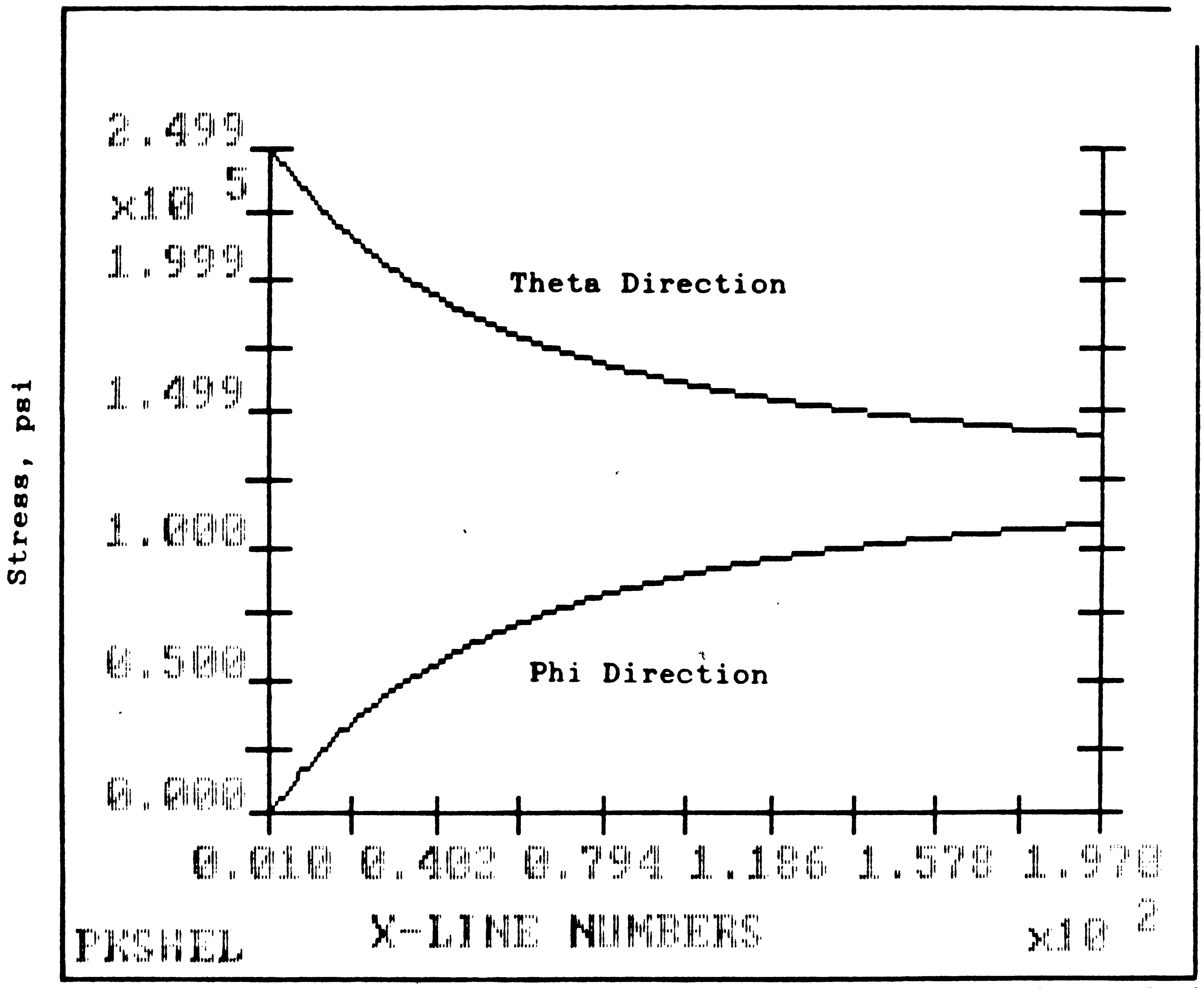


Figure 9. Direction of Prestress Forces



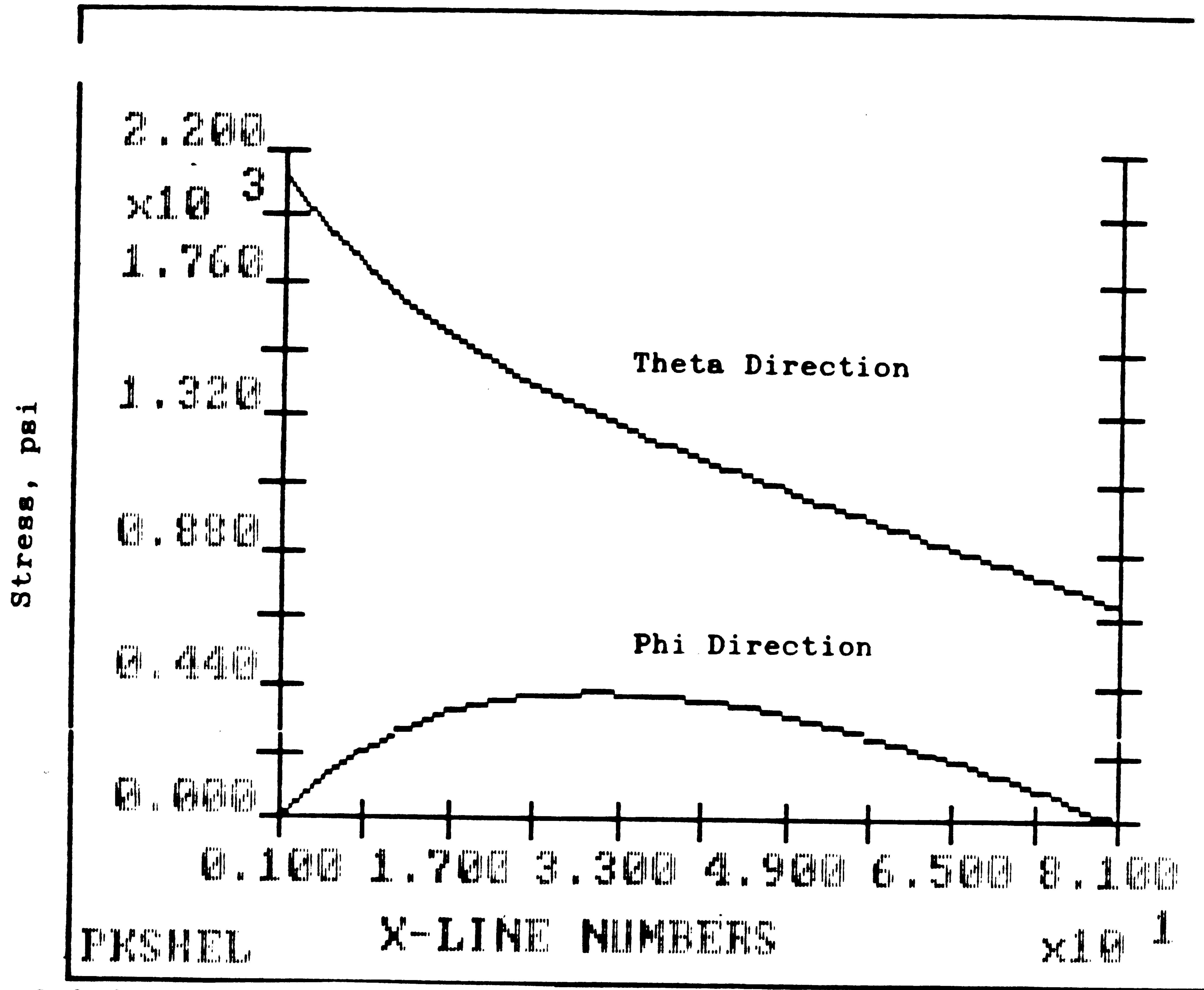
Kshel assigns X-Line Numbers to segments along the radius of the blade.
The X-Line Numbers correlate to the 4" to 11" radius of the blade.

Figure 10. Kshel Plot of Radial Displacement Due to a Tensioning Value of .069 inches vs. Radius of Blade.



Kshel assigns X-Line Numbers to segments along the radius of the blade.
The X-Line Numbers correlate to the 4" to 11" radius of the blade.

Figure 11. Kshel Plot of Stresses Due to a Tensioning Value of .069 inches vs. Radius of Blade.



Kshel assigns X-Line Numbers to segments along the radius of the blade.
The X-Line Numbers correlate to the 4" to 11" radius of the blade.

Figure 12. Kshel Plot of Rotational Stresses vs. Radius of Blade.

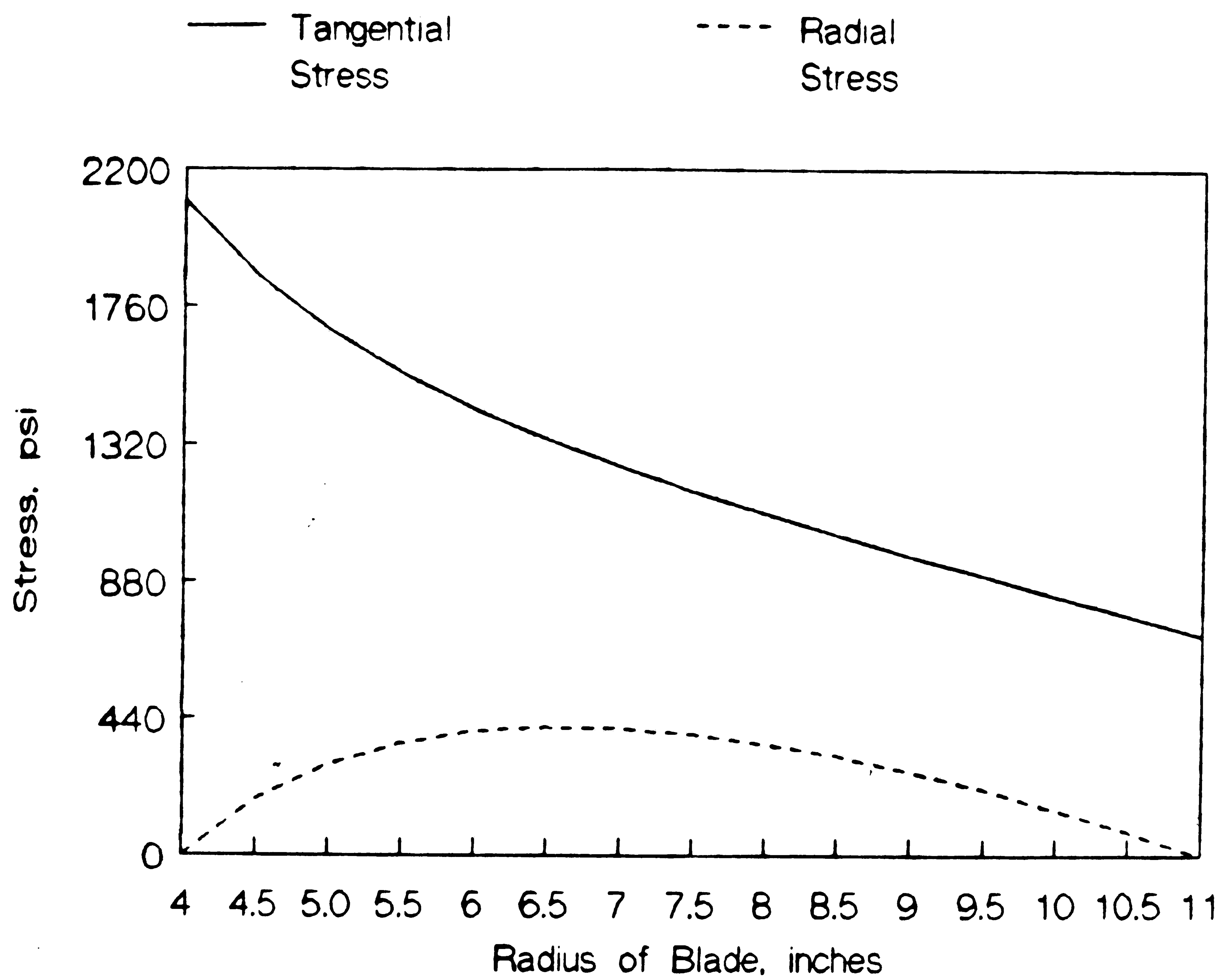


Figure 13. Analytical Plot of Rotational Stresses vs. Radius of Blade.

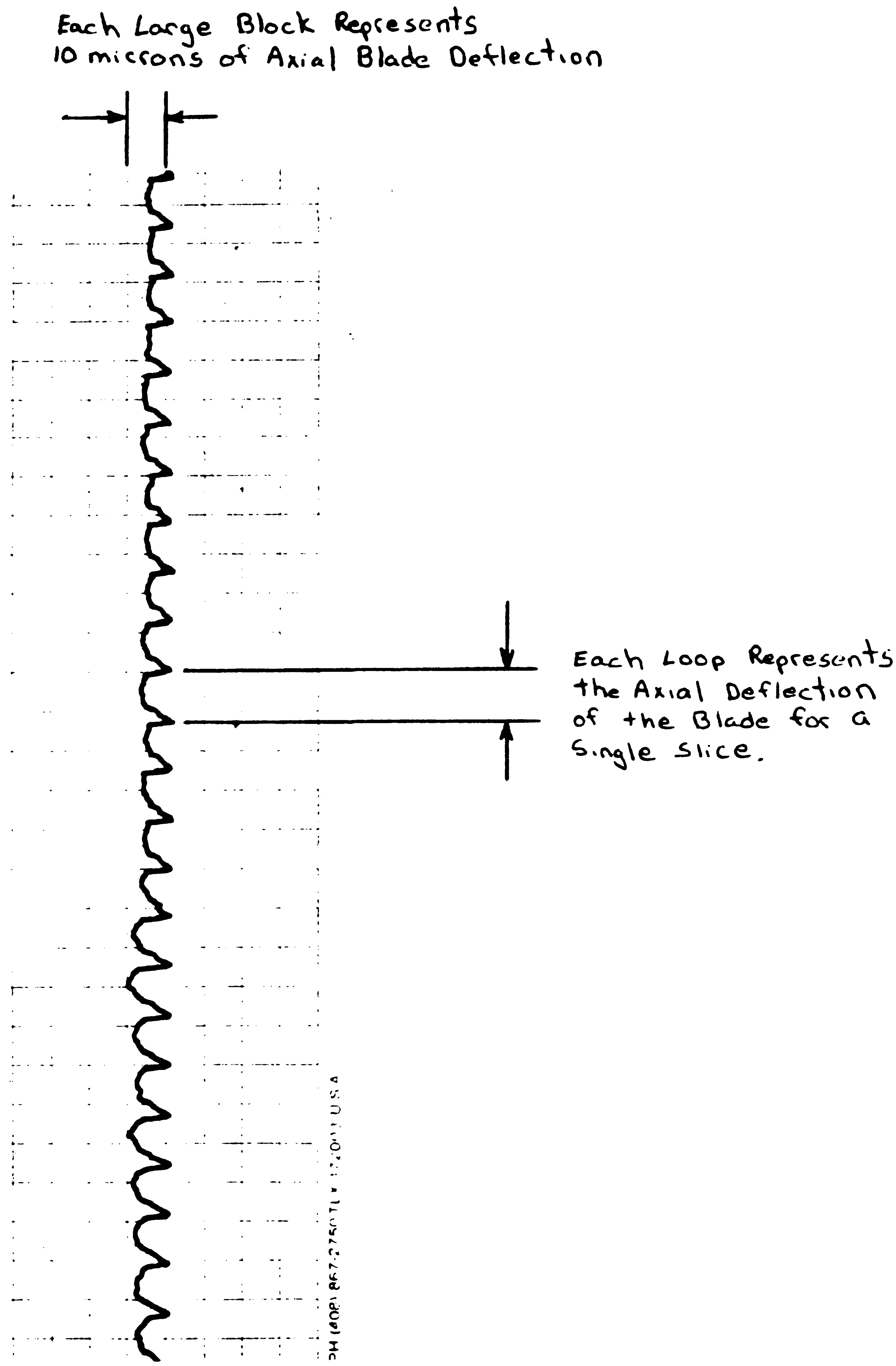


Figure 14. Blade Deflection Monitor Printout.

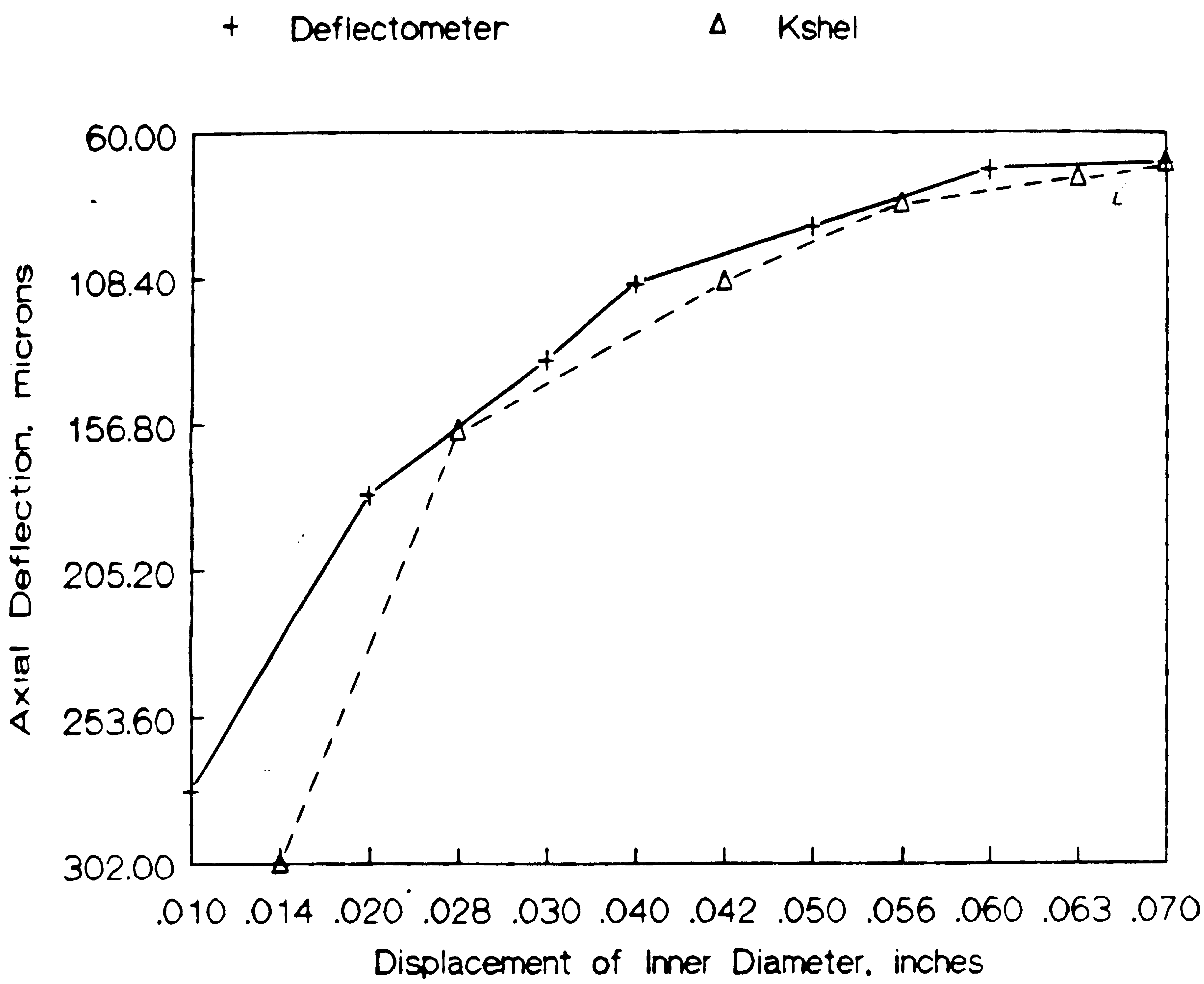


Figure 15. Plot of Axial Blade Deflection vs. Displacement of Inner Diameter Due to a .7934 lb. Point Load at the Inner Edge of the Blade.

TABLE 1.

Values of inner diameter radial displacement and stress for various radial displacements of outer diameter.

OD	ID	Theta Stress
.072 in.	.055 in.	207,000 psi
.076 in.	.058 in.	219,000 psi
.080 in.	.061 in.	230,000 psi
.084 in.	.064 in.	242,000 psi
.090 in.	.069 in.	259,000 psi
.092 in.	.071 in.	265,000 psi
.096 in.	.074 in.	276,000 psi
.098 in.	.075 in.	282,000 psi
.100 in.	.077 in.	288,000 psi

TABLE 2.

Natural Frequency for various wave numbers.

Wave Number	Natural Frequency
0	508 cps
1	701 cps
2	1001 cps
3	1299 cps
10	2980 cps
11	3228 cps

TABLE 3.

Natural Frequency of Wave Number 0 vs. Prestress of blade.

Inner Diameter Theta Stress	Natural Frequency
259,000 psi	508 cps
194,250 psi	441 cps
129,500 psi	361 cps
64,750 psi	257 cps
38,850 psi	200 cps
0 psi	17 cps

TABLE 4.

Grind Interface vs. Plunge Depth.

Plunge Depth	Length of Grind Interface	Angle of Grind Interface
0.0 in	0.0 in	0.0 degrees
0.5 in	3.075 in	45.21 degrees
1.0 in	4.189 in	63.15 degrees
1.5 in	4.880 in	75.17 degrees
2.0 in	5.272 in	82.46 degrees
2.5 in	5.401 in	84.93 degrees
3.0 in	5.272 in	82.46 degrees
3.5 in	4.880 in	75.17 degrees
4.0 in	4.189 in	63.15 degrees
4.5 in	3.075 in	45.21 degrees
5.0 in	0.0 in	0.0 degrees

BIBLIOGRAPHY

1. Silicon Technology Corporation. Operating Manual for the STC Model 2200 Wafering System. 1980, Oakland N.J.

2. Kalnins, A., "Analysis of Shells of Revolution Subjected to Symmetrical and Non-symmetrical Loads", Journal of Applied Mechanics, vol. 31, 1964, pages 467-476.

3. Kalnins, A., and Lestingi, J.F., "On Nonlinear Analysis of Elastic Shells of Revolution", Journal of Applied Mechanics, vol. 34, 1967, pages 59-64.

4. Kalnins, A., "Free Vibration of Rotationally Symmetric Shells", Journal of the Acoustical Society of America, vol. 36, 1964, pages 1355-1365.

5. Kalnins, A., and Biricikoglu, V., "Deformation of Prestressed Thin Shells", Journal of Nuclear Engineering and Design, vol. 16, 1971, pages 343-357.

6. Kraus, H., and Kalnins, A., "Transient Vibration of Thin Elastic Shells", Journal of the Acoustical Society of America, vol. 38, 1965, pages 994-1002.

7. Kalnins, A., and Godfrey, D., "Seismic Analysis of Thin Shell Structures", Nuclear Engineering and Design, vol. 27, 1974, pages 68-76.

8. Updike, D.P., and Kalnins, A., "Cyclic Elastic-Plastic Analysis of Pressure Vessel Components", Proceedings of the 8th International Conference on Structural Mechanics in Reactor Technology, North-Holland Pub. Co., Paper L-7/1*, Aug. 19-23, 1985, Brussels.

9. Updike, D.P., Kalnins, A., and Yang, S.J., "Creep Analysis of Shells", Proceedings of the 6th International Conference on Structural Mechanics in Reactor Technology, North-Holland Publishing Co.,Paper L11/4, August 1981, Paris.

10. Semiconductor Material Inc. "ID Diamond Slicing Blades and Edge Grinding Wheels", Catalog Number 195X25KV45, 1988.

11. Kistler Piezo-Instrumentation. "Optimize Metal Cutting by Measuring the Cutting Forces", Catalog Number 62.201 e, 1986.

12. Tonshoff, H.K., Professor, and Von Schmieden, W., "Improving the ID Cut-off Grinding of Silicon", CIRP Annals, (1988), pp.181-188.

13. Brinksmeier, W. and Von Schmieden, W., "ID-Cut-off Grinding of Brittle Materials" CIRP Annals, Manufacturing Technology Vol. 36 (1987), pp. 219-222.

14. Kobayashi, A., Komine, N., and Kuniyoshi, S., "Improving Cutoff Characteristics of Semiconductor Materials Using New Diamond Wheel" Toshiba Review No. 73, (1972), pp. 1-6.

15. Asahi Diamond Industrial Co. LTD., "Production and Application of ID Saw Blade" A Report Prepared by the Asahi Diamond Industrial Co., 1988.

16. Incropera,F.P., DeWitt,D.P. Fundamentals of Heat Transfer New York: John Wiley & Sons, 1981.

17. Beyer, W.H., Ph.D. CRC Standard Mathematical Tables. 27th ed. Florida: CRC Press, Inc., 1984.

18. Chakrabarty, J. Theory of Plasticity. New York: McGraw-Hill Book Co., 1987.

VITA

George S. Mazur, son of Mr. & Mrs. George Mazur, was born on March 5, 1962 in Allentown Pa. He attended the Pennsylvania State University and graduated in June, 1984 with the degree of Bachelor of Science in Mechanical Engineering.

Mr. Mazur has worked for five years with AT&T Microelectronics as an manufacturing engineer. He began his graduate study at Lehigh University in January, 1985.