COMPUTER AIDED BRILLIANT CUTTING OF FLAT GLASS

ROGER J.W. BEST

A thesis submitted in partial fulfilment of the requirements of De Montfort University for the degree of Doctor of Philosophy

May 1995

De Montfort University

ABSTRACT

Brilliant Cutting is a nineteenth century development of the ancient art of wheel engraving glass. This thesis investigates and evaluates how this traditional craft can be modernised through the use of CAD/CAM technology.

The techniques of the craft were analysed and a methodology for defining the characteristic three dimensional topographical features using two dimensional CAD was developed. Parametric CAD was used to aid draughting for this feature based system.

A suite of programme modules are used to generate five axis CNC instruction code from the two dimensional CAD data. The description of the methods used constitutes an original analysis of the generic techniques of wheel engraving crafts.

The unique five axis CNC brilliant cutting machine designed and developed for this project is capable of cutting and polishing the full range of traditional designs. A number of sample designs are illustrated including marketable products.

Dedication

To Mum, good luck with *your* degree

Acknowledgments

Many thanks to my friends and colleagues at De Montfort University for their support and professionalism in helping me with this project, and to Cal English for his company for several years.

Also thanks are due to a large number of individuals from the glass industry whose generosity with their time and wisdom was given so freely and gave the project purpose.

A special thank you to my supervisor Dr David Stockton and my wife, Hilary Best, without whose combined support, faith and cajolement these grateful words would not be written.

CONTENTS

ILLUSTRATIONS

Photographs by the author unless otherwise attributed.

Chapter 1

Chapter 2.

Chapter 3.

Chapter 4.

Chapter 5.

Chapter 7.

Appendix B.

There follows a key to figures 87 and 88.

Figure 89. The method of wheel mounting, using a split cone, used on the brilliant cutting machine.

GLOSSARY

This thesis contains a number of technical terms used within the glass and automation industries which have specific meaning. A number of these terms are explained below:

ASCII: A method of encripting data as text whereby all characters are represented by a byte or binary code.

Axis/Axes: a descrete function or unit of automation. For example if a device moves up and down independantly of its motion back and forth then it is described as having two axes.

Baked: describing something that has been heated in an oven for a period of time.

Bevelling: grinding a taper onto the edge of a sheet of glass.

Brilliant cutting: a form of wheel engraving of glass described in detain in chapter one.

CAD: Computer Aided Design

CAD/CAM: The integration of CAD with Computer aided Manufacture

Daisy chain; a form of connecting descrete electronic devices in a chain so that data can be distributed.

Depth profile: a term coined for automated brilliant cutting to describe the variation of depth of cut along the length of the cut.

Dressing: treating the surface of a grinding wheel so as clean and rejuvenate it.

DXF: Data eXchange Format, a recognised standard for data interchange.

Embossing/ Acid etching: applying chemicals to whiten the surface of the glass.

Enamelling: painting glass with enamel paints to colour it.

Field: a unit of data containing a single parameter belonging to the subject.

Float glass: sheet glass produced by floating moulten glass on mercury until it cools.

Frost: a description of the surface of glass that has been treated in some way so as to resemble frost.

Gilding: applying gold leaf to glass.

Good eye: a coloquialism describing a craftsman ability to produce accurate work without the aid of geometric measuring equipment.

Matting: producing a frost of matt (non sparkling) appearance.

Mastic: adhesive sealant

Plate glass: sheet glass produced by rolling and polishing.

Prismatic; term refering to robotic axes that extend and retract, or move back and forth without rotation.

Record: a collection of data refering to a single subject

Silvering: applying silver to glass by chemical deposition.

SMCC: Smart Motion Control Card, a proprietary computer capable of controlling two axes of a machine, or in combination with a number of other cards a machine of many axes.

Spark out: a term used in engineering to denote the condition when grinding a metal object when the grinding wheel no longer touches the workpiece and the sparks produced cease.

Waviness: a surface finish parameter that describes undulations in the surface of a distinct wavelength greater than that of the dominant roughness.

Chapter 1

Introduction

1.0 Introduction

Brilliant cutting is the trade name given to the process of engraving decorative patterns into flat sheets of glass using grinding and polishing wheels. The process of brilliant cutting was introduced into the U.K. from the U.S.A. by M. Bowden of Bristol in 1850 [1]. Historically this introduction coincided with James Chance's invention of "patent plate" glass in 1838, the removal of excise duties on glass in 1845 and the repeal of window tax in 1851 [2, 3]. Glass, hitherto an exclusive material, became generally available and in keeping with Victorian fashions was ornately decorated. A number of decorative processes were developed to complement brilliant cutting, such as bevelling, enamelling, gilding, silvering, staining, acid embossing and acid etching, [4]. The combination of brilliant cutting and embossing, in particular, became the standard form of decoration for glass panelling by 1871. A typical example of combining these processes is shown in Figure 1.

Between 1879 and 1880 many of the public houses in London and other cities were refurbished with brilliant cutting panels resulting in a large increase in the demand for such glass. Beginning in 1890 there occurred a further period of public house refurbishment in which much of the existing brilliant cut glasswork was replaced. This was followed by a dramatic crash in the brewery industry which stopped all development except for a few public houses in Liverpool and other major northern cities. These buildings were decorated in the Art Nouveau style of post 1900 [1] to which brilliant cutting is ideally suited as illustrated in Figure 2 .

The majority of those public houses decorated using brilliant cut glass have since been destroyed. However, examples still exist of which the Star Inn within the Beamish Open Air Museum is one example, [5]. A typical window panel from this building is illustrated in Figure 3. Other examples of window panels exhibited in the museum which illustrate the diversity in brilliant cut design features are shown in Figures 4 and 5. The demand for brilliant cut glass never regained the level of popularity that it enjoyed during the last century. However, renewed interest arose in the late 1980's due to a revival in the fashion for Victoriana in public houses and the increased demand from the general public for decorative mirrors and window panels.

The current areas for brilliant cut products are:

* decorative mirrors in both public and domestic buildings,

* decorative windows, and

* decorative glass panels in items of furniture, eg wardrobe doors.

Although market demand for such products continues, the ability of manufacturers to satisfy that demand has remained inadequate. Currently supply is limited because of the lack of skilled craftsman who can brilliant cut glass to both the required quality and cost. The primary reasons for this are:

a. problems recruiting apprentices due to the poor image involved in working within a factory environment, and

b. the long training periods required before skill levels can be raised to a level were the economic production of brilliant cut articles can take place.

The introduction of high speed 4-axis CNC glass grinding equipment to specific market segments has met with limited success. Although these machines are capable of achieving the cutting rates required to maintain low costs, they do not possess the ability to reproduce the full range of patterns and cut types that are typical of the manually brilliant cut products currently in demand.

The manual brilliant cutting industry is expected to decline in the future due to the lack of sufficient numbers of apprentice craftsmen entering the industry. There is, therefore, a need for a more sophisticated form of glass grinding automation that will produce the full range of manual and automated techniques required to satisfy market demand for traditional decorative styles at affordable prices.

The research reported here, arises from the development of a prototype CAD/CAM system for brilliant cutting, into flat glass, the full range of decorative techniques that can currently be manually produced. A dedicated CNC machine has been developed, [6,7,8] that can be programmed off-line, ie a CAD system is used to produce the brilliant cut designs and part programmes are then generated using the CAD drawing files. A technical solution is, therefore, presented to the problem of supplying complex designs of styles that are currently popular to a cost sensitive industry.

The basic constraints surrounding the research project are:

a. the cost of such equipment must be low in order that potential buyers can afford the initial outlays and capital investment payback periods, and

b. the system must be efficient in order to provide a suitable return on investment.

The aims of the research project have been to investigate and experimentally evaluate the technical viability of the CAD/CAM route to automated brilliant cutting by:

a. developing and demonstrating a methodology of defining cuts using CAD,

b. developing and demonstrating a methodology of generating CNC instruction code from CAD data,

c. developing and demonstrating a CNC machine capable of performing the traditional brilliant cutting engraving techniques that require cutting wheels to be tilted, and

d. identifying and demonstrating a suitable tooling technology for an automated brilliant cutting system.

The work reported here, therefore, attempts to resolve the major problems involved in developing a suitable CAD/CAM glass grinding system for flat glass that can replace existing manual brilliant cutting techniques.

Chapter 2 presents a detailed argument for the development work carried out by examining the brilliant cutting process, the industry and the products produced. In order to gain an understanding of the current state of the brilliant cutting industry a survey was carried out that involved visiting a range of companies including those who performed brilliant cutting and those who specialised in selling brilliant cut products. From these visits the techniques involved in manual brilliant cutting have been identified. The chapter describes the types of cuts that a CAD/CAM machine must be capable of reproducing and provides examples of each cut type. The ability of a CAD/CAM machine is, therefore, defined in terms of the cutting processes that need to be performed. The basic market segments involved in the brilliant cutting industry have been identified along with the current state of automated brilliant cutting technology and the limitations of this technology. It is concluded that a five axis CNC brilliant cutting machine capable of producing decorative glass in the traditional style would overcome the fundamental limitations to the manual process that dissuade potential manufacturers from entering the brilliant cutting market despite increased demand for hand produced brilliant cut products. In addition, it would enable the advances in productivity, quality and throughput rates, realised in other machining processes, to be achieved for the brilliant cutting process.

Chapter 3 provides a detailed examination of the grinding and polishing processes involved in decorative glass manufacture. The potential constraints that need to be taken into consideration when developing a CAD/CAM machine are identified. The relative benefits and limitations of alternative grinding wheel materials are initially discussed and metal bonded diamond wheels identified as the most suitable. A detailed review of the relevant literature on research into diamond grinding was carried out in order to determine the effects of individual grinding variables such as cutting speed and wheel speed. From this information it was possible to establish a unified system model for the grinding of glass using metal bonded diamond wheels. Problems that may arise during the diamond grinding of glass were also identified and solutions proposed for their resolution. The basic information contained in Chapter 3 provided essential information used to develop the specification for the CNC brilliant cutting machine.

Chapter 3 also contains comparisons of alternative polishing processes. From published material it was unclear which polishing process would be most suitable for the automated brilliant cutting process since the type of process chosen affects many aspects of machine design.

Computer Aided Design and its application to automated brilliant cutting is described in Chapter 4. Although CAD encompasses a variety of methods of aiding the design process, it was found that for the purpose of brilliant cutting the primary functions required were:

a. to provide data for the generation of CNC instruction code, and

b. to facilitate the design of brilliant cut products.

Procedures for draughting brilliant cut features in two dimensions have been derived and described in Chapter 4. A commercial two dimensional CAD system, DesignCAD 2D, was selected as a suitable platform to perform CAD for brilliant cutting. The ergonomic capabilities of this system have been exploited by the use of bespoke icon menus and parametric design techniques. Determining the nature of the CAD output defines the input to the software for generating CNC part programming code.

Chapter 5 describes the design and development of the geometric structure of the unique CNC grinding machine. The geometric structure of this machine had to be considered in parallel with the specification for the CAD/CAM software since both needed to be integrated into a single system. The brilliant cutting machine is of a cartesian format which employs components from a commercial modular automation system. The workpiece is held stationary whilst the grinding head is moved in five axes. A specially designed and developed grinding head assembly, consisting of a rotary axis and remotely powered spindle, provides the necessary tilting motion of the wheel relative to the workpiece. This motion enables the objects that characterise manual brilliant cutting to be generated and, therefore, distinguishes this system from other automated engraving machines. The grinding head assembly was manufactured to close dimensional tolerances and is of light weight in relation to the power transmitted and the grinding forces involved.

Chapter 6 initially describes the programming language and method of operation of the CNC controller. The development of the part programming software is then described in which programming modules for each type of brilliant cut have been included. For each of these modules their operation, constraints, theory and cutting techniques are explained. Part programming software for each of the cutting techniques normally used in brilliant cutting are represented and illustrations of cuts and designs produced using the system are provided. Included in this work are the techniques that require continuous five axis motion which formally have only been possible manually.

Chapter 2

Brilliant Cutting

2.0 Introduction

2.1 Manual Brilliant Cutting

2.1.1 Design and Planning

2.1.2 Marking Out

2.1.3 Rough Cutting

2.1.4 Intermediate Polishing

2.1.5 Final Polishing

2.2 Types of Cuts

2.2.1 Round Cuts

2.2.2 Mitred Cuts

2.2.3 Edge Cuts

2.2.4 Panel Cuts

2.3 Brilliant Cutting Equipment

2.3.1 Traditional Machines

2.3.2 Modern Equipment

2.3.2.1 Multi-Purpose Machines

2.0 Introduction

This chapter examines the stages involved in manual brilliant cutting and describes the basic types of cut that can be produced. Traditional manual and automated brilliant cutting equipment is then critically examined and the limitations of such equipment explained. It is found that existing automated equipment is technically unable to perform the range of techniques used during manual brilliant cutting.

The equipment and techniques used within the glass decorating industry to perform associated glass decorating techniques, such as acid etching, are examined and are shown to reflect the varied nature of those companies who produce engraved products.

A survey of the glass industry was carried out and the results identified a number of problems within the manual brilliant cutting process that restrict its economic viability, despite promising market demand. The survey concluded that an automated CNC machine of appropriate design would overcome these problems and, in addition, offer advances in productivity and production rate.

2.1 Manual Brilliant Cutting

The steps involved in manually grinding and polishing decorative patterns into flat glass are described in Sections 2.1.1 to 2.1.5.

2.1.1 Design and Planning

Generating the design to be cut into the glass is often an interactive process between the brilliant cutter and the customer. A level of compromise may be required between cutter and customer in order to make a design concept into a practical and cost effective design. For example a design will be easier and less costly to produce if standard wheel profiles can be used and the number of cut types can be minimised.

Depending on the skill of the craftsman and requirements of the customer, the design may be in the form of either:

a. a detailed and scaled sketch of the design,

b. a rough sketch of the important elements of the design, or

c. a verbal description of the type of design required, eg of "Victorian" style.

2.1.2 Marking Out

This step involves placing the plate of glass on top of a drawing of the design to be cut into the glass and tracing, normally using a wax crayon or chinagraph pencil, the features of the design onto the glass. In order to avoid parallax errors during the grinding process the side of the glass cut is that on which the design is drawn. A skilled craftsman would not need to draw all the features of the required design onto the glass to ensure that the reproduction of the design is acceptable to the customer [1]. In many cases the design is drawn onto the glass without the assistance of a drawing.

When repetitions of a design are needed a skilled craftsman often requires only a few marks sketched onto the glass to ensure accurate reproduction of the design [1]. In these circumstances the time taken to sketch the design on to the workpiece is normally less than 1% of the total production time. For new designs and one-off commissions, the craftsman will be required to mark-out in detail. The proportion of total production time for such designs is then approximately 3%.

2.1.3 Rough Cutting

This is the process of grinding the pattern of required cuts into the glass using an assortment of shaped abrasive wheels. Rough cutting requires a high degree of skill on the part of the craftsman since the cut geometry is determined entirely by eye. In this situation, quality is described by the geometric smoothness of curves, accuracy of form and position and consistency of surface finish. In order to ensure accuracy of form and position, the majority of brilliant cuts are produced using multiple passes of the grinding wheel, ie initial passes remove the majority of the material and subsequent passes finish the cut geometry.

If material is removed in error, either the defects produced must be blended into the cut design or the workpiece must be scrapped. If the cut shape itself is poorly formed it may be possible to improve its smoothness and form by removing more material using either a grinding or smoothing wheel. Experienced craftsman rarely need to scrap workpieces. However, to achieve this level of performance may take many years of training.

The consistency of surface finish may be controlled by dressing the rough cutting wheel. Dressing roughens the grinding surface, consequently wheels that have recently been dressed are capable of removing material at a faster rate then wheels that have been in service for some time. However, recently dressed wheels produce rougher surfaces that consequently require greater amounts of polishing. A part worn grinding wheel cuts smoothly but more slowly, hence improving surface finish and accuracy of cut geometry but increasing production time. An experienced craftsman can maintain a specific level of wheel roughness and, therefore, can control the surface finish produced according to a subjective optimum [1].

The proportion of total production time for the rough cutting stage will vary with mean depth of cut, surface finish required for the smoothing operation and quality of the final polished surface. In general, rough cutting represents approximately 20% to 30% of the total production time. As the rough cutting, smoothing and polishing processes use identical equipment and small quantities of consumables, their processing times can be used as an indication of their relative costs.

2.1.4 Intermediate Polishing

Intermediate polishing or smoothing is the process of fine grinding the cuts to reduce their surface roughness in preparation for the final polishing process.

This is normally accomplished using a wooden wheel with pumice powder as the grinding medium, (Section 3.4.3). The wheel, traditionally made of willow, [1] is turned to the same cross-sectional shape as the wheel used at the rough cutting stage. Although the geometry of the cut has been defined at the rough cutting stage, intermediate polishing may be used to improve this cut geometry and to produce a consistent and smooth surface finish.

Although it is a subjective decision by the craftsman that determines what finish is appropriate it is essential that all surface finish blemishes are removed. The material removal rates of final polishing techniques are low. Hence, deep scratches, waviness, undulations and other surface defects must be smoothed to a finish that will minimise the time required to perform the final polishing operations. The smoothing process, takes approximately 30% of the total production time. After the intermediate polishing process the cut surfaces must contain only a slight whiteness or dullness caused by the small scratches that arise from the smoothing process itself.

2.1.5 Final Polishing

This is the final process of removing the last trace of frost from the cut surface and is traditionally carried out using a brush or felt wheel and a fine abrasive such as rouge or cerium oxide powder. The final surfaces of the cuts, although completely transparent are not necessarily smooth as an element of "wavyness" across the direction of cutting is normally present. At each grinding and polishing stage the brilliant cutter subjectively determines what finish is appropriate.

The time taken to final polish a design to the brilliant sparkle characteristic of the process is usually equal to the time spent smoothing, but a limited number of microscopic scratches may be present on the cut surfaces. This can be acceptable for applications in which the cut panel is frosted. In these circumstances the minor blemishes resulting from the microscopic scratches are not readily observable by eye. However, if the panel is to be silvered, in order to produce a mirror, then such scratches are clearly visible as a frost or greyness on the silvering. In order to produce a surface suitable for high quality silvered products, final polishing times may be doubled. In general the proportion of total production time required to final polish is of the order of 40%.

The low material removal rates of fine polishing processes enables inexperienced operatives to be employed without the danger of workpieces needing to be scrapped. The abrasive slurry obscures the cut so that it is almost impossible to gauge progress without removing the workpiece from the wheel and cleaning the cut. The craftsman needs to be aware of the polishing performance of the slurry and, hence, the resultant feed rate and pressure that must be applied. During polishing the motion of the wheel relative to the workpiece must be smooth and consistent to ensure an even polished surface. When inspecting polished surfaces the craftsman must be capable of identifying any blemishes remaining on the cut surfaces along with an understanding of the surface quality required for the job.

2.2 Types of Cuts

There are four categories of cut used in manual brilliant cutting [9] and each require a grinding wheel of a specific cross-sectional shape or edge profile. These cut types are round, edge, mitre and panel cuts and within each of these categories variations in the cross-sectional profile of the cut can be produced by altering the diameter and edge profile of the wheel.

2.2.1 Round Cuts

A rounded wheel profile, as illustrated in Figure 6, is used to produce round punts, oval punts and to produce a matting effect. Matting is the technical name used in engraving for the process of producing a fine frost which is often the type of surface finish required by round punts. Matting is produced by moving the round edged wheel over the glass and lightly brushing the surface. This technique is used in modern brilliant cut designs to "frost" an area whilst retaining the surface relief that is a fundamental design characteristic of brilliant cutting. The matting technique contrasts with the traditional method of frosting which involves lapping with emery powder, (which is an impure form of aluminium oxide [10]), to produce an even, flat frost [1]. On brilliant cut products such as mirrors, which are silvered on the cut surface, rough frosted surfaces appear grey since the silver enters the fine cracks that penetrate the surface to produce a surface that dissipates light. In order to control the degree of matt the area may be semi-polished to a partially reflective state.

Oval punts, also known as ovals or olives [11], are generated by feeding the glass, onto the wheel, along a direction perpendicular to the surface of the glass. Round punts, which are common in traditional designs, are produced by rotating the workpiece around the point of contact with the surface of the glass, whilst simultaneously feeding the workpiece onto the grinding wheel along a direction perpendicular to the surface. A high level of skill is required to produce a visually circular indentation which has the optical effect of a polished lens. Rotation of the glass about the point of contact has been found to improve the surface finish and, therefore, assists in reducing polishing times. If the wheel is not rotated in this manner then it must be accurately profiled to the shape of a sphere in order to produce the circular cut required. Frequent redressing is then needed to maintain the required wheel profile.

2.2.2 Mitred Cuts

Traditionally only straight lines were cut using a mitred or "V" shaped wheel, in which the wheel was positioned normal to the workpiece. This enables leaf motifs, star motifs and border lines to be produced [1]. However, a practice was subsequently developed that involved using the mitred wheel to produce additional cut types such as curves and lines of varying shapes. In these cases the "V" cross-section of the cut may be made asymmetric, as illustrated in Figure 7, by tilting the wheel such that one of its flanks moves further to the horizontal and hence becomes broader than the other flank. Matcham [11] emphasises how this technique increases the brilliant cutters scope for artistic flair particularly when producing lettering.

2.2.3 Edge Cuts

Edge cutting requires a square edged wheel of the type illustrated in Figure 8 which is normally from 15mm to 25mm in width. In order to produce edge cuts the wheel is tilted such that the plane of the surface of the glass intersects with one side face of the wheel and its edge. The imprint of the wheel in the workpiece is "D" shaped, the size and proportions of which may be controlled by the depth of cut and angle of tilt of the wheel. In general, cuts are made such that the straight side of the profile forms the tangent to the inside edge of the cut, as shown in Figure 8. It is, however, possible to move the wheel in any direction away from the straight edge. This technique is known as "slipping" and is frequently used in other forms of glass engraving, such as copper wheel engraving, (Section 2.4.1), since it is easier to perform on a small scale where greater control is possible.

Edge cutting is the most frequently used technique in traditional designs since the shape of the cut may be easily controlled, even when the cutting wheel becomes worn. Edge cuts require shorter polishing times than other cut types because the polishing wheel needs only to have a square edge in order to fit the cut profile. Mitred and round edged wheels require the polishing wheels to have an accurate edge profile in order to maximise surface contact. Tilting the wheel to produce edge cuts requires five degrees of freedom and allows a wide variety of decorative effects to be produced.

2.2.4 Panel Cuts

Panel cutting, which is used to produce borders, is performed using a square edged wheel of the type shown in Figure 9. The cutting wheel is held perpendicular to the surface of the glass. It can be seen from Figure 9 that the edge of the wheel is not perfectly square since its corners are radiused. The sides of the wheel may taper slightly towards the edge. The cut produced is rectangular in cross-section and conventionally is a maximum of 9mm wide and 0.5mm deep. In order for panel cuts to be visually acceptable it is essential that both the depth and surface finish of a cut are not allowed to vary along the length of the cut. This level of control is difficult to achieve during the manual brilliant cutting process.

2.3 Brilliant Cutting Equipment

2.3.1 Traditional Machines

The traditional equipment used to manually brilliant cut glass has altered little since its original development [11]. As illustrated in Figure 10 the grinding or polishing wheel (A) is permanently mounted on the horizontal spindle (B). When mounted, the wheel will be carefully balanced such that it rotates without vibration. The ends of the spindle are tapered and these tapers rotate in holes in blocks of seasoned hardwood (C) which are themselves wedged tightly into the supporting frame (D). Supporting frames are normally constructed in-house using wood or perforated steel angle.

Mounting the spindle in rigid plain bearings prevents "play" in the wheel. Attempts have been made to replace wooden plain bearings with rolling element bearings (Interview with J. Macdonnel of Gray and Macdonnel). However, these attempts failed due to the abrasive dust produced during the brilliant cutting process entering the bearing housing and causing premature wear of the bearing. It was found that wear of the order of 0.025mm allowed irregular motion of the wheel to occur which was detrimental to the control of the cutting process. The rigidity of the bearings allows grinding wheels to be trued whilst still on the machine [1].

The spindle (B) also carries a belt pulley driven from a powered shaft (E) which is normally located at the rear of the frame. Both the alignment and tension of the belt are adjusted manually by repositioning the frame. The speed at which the spindle rotates is controlled by using pulleys of varying diameters mounted on the shaft. Traditionally several frames may be driven from a single shaft as illustrated in Figure 11.

The surface speed generated is determined by the diameter of the wheel which will itself be chosen according to the radius of the curve to be ground into the glass. A large wheel diameter has a tendency to cut straighter and faster since grinding occurs over a greater and more elongated surface area. Wheel diameters up to one metre in diameter have been used in order to benefit from this effect [1]. A simple rule used when engraving states that "the diameter of the wheel used should be approximately equal to the diameter of the arc to be ground into the glass" [11]. The smallest wheel diameter practicable on a brilliant cutting frame is approximately 120mm. When attempting to use wheel diameters less then this minimum value, the workpiece interferes with the bearing blocks. Cuts with radii smaller than this value are, therefore, difficult to achieve using the brilliant cutting process. As described in Section 2.2, different types of cut are produced with different edge profiles. In order to produce the range of decorative effects displayed in traditional brilliant cutting a craftsman would require approximately 30 wheels, each of which would differ in both edge profile and diameter [1, 11].

The surface speed of the wheel during the cutting process is approximately four metres per second. This is a relatively slow speed when compared to the speeds used in grinding metallic materials. However, these slow speeds allow material to be removed at controlled rates and prevent excessive heat being generated due to frictional effects. The heat that is generated does not rise above the levels that may be easily cooled by the thin layer of water that is applied to the wheel from a wet sponge which is located in a trough (F) underneath the wheel, or fed along a coarse twine from a reservoir (G) which is suspended from the ceiling. If the coolant flow rate is too great, the surplus is flung from the wheel by centrifugal force, hence only small amounts are available for cooling purposes. The water performs the additional function of preventing airborne dust being produced.

The size of glass that may be held without the aid of mechanical supports is limited by the physical strength of the craftsman. Large panes of glass, ie to a maximum length of 2.5m, can be suspended using a counterbalance beam (H) of Figure 10 that runs along a track (I) above the cutting equipment. When using such a device additional operators may be required to guide the workpiece. The team-work then needed to brilliant cut the glass requires total co-ordination from each team member since the forces required to grind glass are relatively low. In addition a large area must be cleared to allow freedom of movement, hence compounding the difficulty of producing large brilliant cut glass panels.

2.3.2 Modern Equipment

The equipment currently used for automated brilliant cutting of float glass may be classified into the groups described in Sections 2.3.2.1 to 2.3.2.3. A sample of the equipment available is compared in Figure 12.

2.3.2.1 Multi-Purpose Machines

These machines are capable of producing only straight or circular mitred brilliant cuts, [12]. They employ positionable grinding heads which require careful setting for each individual cut as illustrated in Figure 13. In addition to performing brilliant cutting, these types of machines are also used to edge cut and bevel glass. Machines currently on the market generally have either one or two cutting heads and can perform only one function at any one time.

2.3.2.2 Dedicated Straight Line Cutting Machines

Dedicated straight line cutting machines of the type illustrated in Figure 14 possess multiple spindles each of which is independently driven and adjusted. Each wheel takes a portion of the total cut, ie. the first wheels in the cutting sequence take roughing cuts and the latter wheels polish the surface of these cuts. Machines are commercially available with up to eight spindles and five grades of wheel [13]. Machines vary according to whether they feed the glass under the wheels or move the head of the cutting wheel over the table on which the glass is positioned. Dedicated straight line cutting machines have long set-up times, usually of the order of days, since each wheel must be positioned to take exactly the right cut to provide suitable conditions for the following wheel. Once set-up, however, multi-spindle machines have high material removal rates, eg 4.0m/min for both rough grinding and polishing [13].

2.3.2.3 Four Axis CNC Machines

Four axis CNC machines are capable of generating both straight and curved cuts. The movement of the four axes is controlled using part programmes generated from a CAD/CAM system. The decorative glass items produced using these machines, however, do not have the full range of features possible through manual brilliant cutting. The primary reason for this is that the machines cannot tilt the grinding wheel and hence do not possess the five degrees of freedom required for edge cutting and tilted mitred cutting.

The Intermac Masterglass machine, [14], shown in Figure 15, possesses the three wheel carousel illustrated in Figure 16, which indexes the wheels into the cutting position. Although the machine is expensive, (approximately £100,000), it is considered a commercial success since several hundred have been sold throughout the world. Due to the limitation of the carousel design, however, the machine is only capable of producing mitred cuts.

The Bavelloni Aton/90-CNC machine [15], has the same sized bed as the Intermac but is physically much larger, as shown in Figure 17. This machine has the advantage of an automatic tool changing device of the type used on CNC machining centres [16,17]. Although this facility theoretically allows wheels of different shapes to be used, in practice only variations on mitred and round edged wheels are marketed. This machine has been commercially available for a shorter period than the Intermac and up to the present has had little impact in the market place. The Aton/90 costs approximately £200,000 but has a claimed feed rate of 8.0 m/min [15]. Bavelloni have recently introduced new machines using the overhead gantry concept employed by Intermac and Technometal [18]. For example the Alpa 91 CNC machine has manual tool changing facilities and the KAM 91 CNC machine possesses an eight station automatic tool changer. The KAM 91 CNC machine has a presetting system which automatically measures and records the dimensions of the grinding wheel before each work cycle begins. This machine costs approximately £100,000.

Technometal manufacture the ET.04 CW CNC machine [19] which can perform a variety of processes other than brilliant cutting, ie cutting of laminated glass, cutting of toughened glass, edging and bevel edging. The machine also has a multi-station tool changer.

2.4 Associated Glass Decorating Techniques

There are several other processing technologies for decorating flat glass through material removal and each can be considered an alternative to the brilliant cutting technique of grinding. These may be categorised as either wheel engraving methods or erosive methods.

2.4.1 Wheel Engraving Methods

In addition to brilliant cutting there are three other variations of wheel engraving, ie copper wheel engraving, cut glass engraving and flexible drive engraving.

Copper wheel engraving employs small copper disks, usually less than 50mm diameter, interchangeably mounted on a cantilevered spindle [4, 11]. The spindle is permanently mounted in a lathe, as shown in Figure 18, which is itself mounted on a workbench. The workpiece, which may be any type of glass object, is normally held below the wheel such that the operator can observe the cuts being made. In keeping with the scale of the process, copper wheel engraving is normally used for fine, intricate work on relatively small glass objects such as wine glasses.

Cut glass engraving is a process in which regular, deep, geometric patterns are cut and polished into tableware [4, 11, 20, 21, 22, 23]. Wheel diameters normally range between 75 and 900mm and are mounted centrally on a spindle supported at both ends [4]. Cut glass products are produced in large volumes, hence in order to minimise set-up times engraving wheels are generally not disturbed until worn out [24].

Flexible drive engraving is an attempt to free the wheel from a fixed position allowing the workpiece to remain stationary [11]. The size of the equipment required varies with the scale of the decoration required, for example dentists drills are used for fine work. Equipment using wheels up to 100mm may be air driven but electrically driven systems [25] offer a slower, controlled speed which is more suitable for grinding glass. A small unit built as part of this project is shown in Figure 19. This technique has been successfully used on large murals [11] with perhaps the most significant example being the Great West Window of Coventry Cathedral. This window illustrated in Figure 20 was engraved by John Hutton and has over sixty panels with each panel being 2.4m x 1m in size [26, 27].

In contrast to these accredited works of art, Matcham & Dreiser [11], stated that the "inherent difficulties of brilliant cutting tend to restrict lyrical freedom". Duthie [1], recognised the lack of artistic innovation in brilliant cutting and identified the need for a remotely powered system. He stated that "if any satisfactory method can be devised by which the wheel may be moved instead of the plate the scope of the process will be considerably enlarged, while the waste of time involved in handling the plates as at present will be considerably reduced".

The advantages of the brilliant cutting lathe, when compared with the flexible drive, are improved precision of cut and finer surface finish. These arise from the use of larger grinding wheels and the lack of vibration encountered in brilliant cutting since the wheel is firmly supported and readily trued (Section 2.3.1). When using a lathe, the weight of the glass also contributes to the total forces exerted during cutting. However the flexible drive engraver must support the grinder and cable and push the wheel against the glass which has a detrimental effect on precision as the engraver tires [11].

2.4.2 Erosive methods

Erosive glass decorating techniques include grit or sand blasting and acid etching. Acid is used primarily to whiten flat glass to create decorative effects in a process called French Embossing [1, 4, 11]. To selectively erode the surface of glass is known as acid etching. Acid is also used to polish the surface of glass, in particular tableware. Hydrofluoric acid forms the basis of the chemicals used to perform acid etching. The use of such chemicals to decorate flat glass is restricted due to their hazardous nature. They are also costly when used for decorative effects that involve large amounts of materials being removed as in the case of brilliant cutting [11]. The fumes from such chemicals can quickly discolour the surface of glass, (termed "bluing"), if not efficiently contained.

Grit blasting has been found to be a more economical technique of material removal than either acid etching or flexible drive engraving [11]. The material removed by grit blasting is not controlled by the geometry of a wheel or resist, ie the acid resistant used in French Embossing and acid etching. The product, therefore, is completely defined by the imagination of the operator. Grit blasting applied artisticaliy has a freedom unmatched by wheel engraving [11]. In order to achieve consistent surface finishes it is necessary to control both grit size and velocity. The advantage of using grit blasting is its sculptural lyricism, ie any free form surface can be created. The advantages of wheel engraving are precise geometry and readiness to produce polished surfaces.

2.5 The Brilliant Cutting Industry

In order to gain an understanding of the current state of the brilliant cutting industry a survey was carried out. This involved visiting a range of companies which included both those who performed brilliant cutting and those who specialised in selling brilliant cut products. The results of this survey indicated that the present market for brilliant cut glass may be categorised into sectors as follows:

Market Sector 1

Products manufactured using mechanical brilliant cutting equipment containing only straight brilliant cut features as illustrated in Figure 21. This sector consists predominantly of panels for doors and items of furniture such as wardrobes and bookcases that possess glass doors.

Market Sector 2

Products manufactured using 4-axis CNC machines, containing both straight and curved brilliant cut features, eg Figure 22, [28].

Market Sector 3

Hand-cut, mass produced mirrors and panels having a small skilled labour content and requiring a minimum number of wheels. Figure 23 contrasts the difference in styles between market sectors 2 and 3.

Market Sector 4

Hand-cut, low volume products, containing large numbers of brilliant cut details and additional features such as bevelled edges, embossing or quality frames. For example traditional door and pub panels as shown in Figure 24 and "Venetian" mirrors as shown in Figure 25. These products are frequently produced to specific customer requirements.

The market leader, Gray and McDonnell [29], operate in market sectors 1, 2 and 3 and employ flow line production techniques to maximise productivity and throughput rate.

Sekon Glass Ltd and Architectural Antiques, [30] are small companies that specialize in manufacturing mirrors to customers specific designs. Such designs can often be complex in terms of the brilliant cut features required and may be cut to traditional styles that must match the existing interiors of customers premises. Both of these companies can operate in market sector 4 only because brilliant cutting is a small part of their overall turnover and sales fluctuations can, therefore, be absorbed.

Many companies surveyed began as brilliant cutting concerns and have since diversified into manufacturing such products as double glazing and conservatories. The increased profitability provided by such products has enabled companies such as Solaglass [31] to purchase a four axis CNC brilliant cutting machine in order to compete in market sector 2.

The survey revealed that manufacturers regarded automation as a method of expanding present output and moving into higher value market sectors.

2.6 Limitations of Current Brilliant Cutting Technology

Since its introduction into the UK there has been no radical improvement to the process of manual brilliant cutting. There have been minor improvements such as developments in abrasive types and polishing mediums. The main limitations of the brilliant cutting process are:

a. high level of skill is required to brilliant cut at an acceptable quality and workrate and brilliant cutting is traditionally only part of a glass processing apprenticeship, the typical length of which is five years,

b. processing times are long, ie a mirror of relatively simple design, as illustrated in Figure 23, can take up to twenty minutes to cut and polish,

c. much time is lost in handling the work-piece and dressing wheels, this can account for 10% of the total production time, and

d. there is little scope for improving the efficiency of the process when manufacturing in small batch sizes, ie large batch manufacturing can be achieved using flow processing lines in which separate work areas are set-up to perform individual sections of a brilliant cut design hence reducing or eliminating the need for wheel changes.

Due to the increasing disposable income of the UK population, and changes in fashion, the market for decorated glass expanded considerably throughout the 1980s, with particular growth in 1987. This has caused major problems for brilliant cutting producers, ie:

a. sales demand has tended to fluctuate in a "boom and bust" manner in line with the changes in the disposable income of customers, and

b. there has been an inability to match production with the growth in market demand, ie a lack of skilled craftsmen have prevented increases in production volumes from being achieved to take advantage of the market opportunities when they do occur.

The lack of skilled craftsmen has been a particular problem in recent years since potential apprentices are dissuaded by:

a. low pay whilst training due to low productivity and wastage,

b. long training periods,

c. dirty, wet and dangerous work,

d. working in a factory environment, and

e. lack of interest in traditional skills.

As described in Section 2.3.2 there are automated machines available to perform a limited range of brilliant cutting techniques. However, none of the machines currently on the market can compete technically with a craftsman performing the manual brilliant cutting process and, therefore, cannot meet the requirements of market sectors 3 and 4.

The industry survey revealed that an automated brilliant cutting system, capable of reproducing the traditional manual brilliant cutting techniques, would assist in overcoming the shortage of skilled personnel that currently prevents the future development of the higher value end of the market.

It may be concluded from the above that it is not practical to satisfy the demand for high value brilliant cut products using current technology. To overcome the problems of labour shortages in the short term, and low productivity in the long term, the limits of current brilliant cutting technology need to be overcome.

A five axis CNC brilliant cutting machine capable of producing decorative glass in the traditional style would:

a. overcome the fundamental limitations to the manual process that dissuade potential manufacturers from entering the brilliant cutting market despite increased demand for hand produced brilliant cut products, and

b. enable the advances in productivity, quality and throughput rates, realised in other glass machining processes, to be achieved for the brilliant cutting process.

Chapter 3

Grinding and Polishing Technology

Contents

3.3.5 Grit Friability

3.3.6 Wheel Condition

3.3.7 Cutting Speed

3.3.8 Feed Rate and Grinding Pressure

3.3.9 Balancing Wheel Design and Application Parameters

3.4 Achieving Polished Surfaces

3.4.1 Chemical Erosion

3.4.2 Impregnated Polishing Wheels

3.4.3 Polishing Slurries

3.4.4 Advanced technologies

3.0 Introduction

This chapter examines the grinding mediums used to grind and polish glass. Metal bonded diamond wheels are identified as the preferred grinding medium for automated glass processing. Existing research is used to establish a unified system model for the grinding of glass using metal bonded diamond wheels. This model can then be used as a tool to identify how variations in individual grinding parameters may effect the overall process.

3.1 Grinding Materials

A survey of the abrasive materials used for the grinding of glass was carried out, and their suitability evaluated for automated brilliant cutting. These materials are described below.

3.1.1 Carboniferous Sandstone

Traditionally this material was used throughout the brilliant cutting industry. It was considered a suitable material for manual cutting since it allowed a consistent material removal rate to be achieved and could produce a fine finish that was readily polished [1]. However, such wheels are difficult to manufacture in the large quantities required by the industry and have, therefore, been superseded by the grinding materials described subsequently.

3.1.2. Aluminium Oxide

This material succeeded sandstone and is currently the most commonly used material for manual brilliant cutting. Aluminium oxide is available in a variety of grades and bonds [31, 32]. However, frequent wheel dressing is required to retain the quality of cutting since the spaces between the particles tend to fill with glass fragments and the grits themselves become dull. Aluminium Oxide has been found to be a suitable material for "smoothing" rough cuts produced using grinding mediums such as silicon carbide. Aluminium oxide is also used in mechanised applications such as finger grip machines [34], because of its ability to produce a fine "frosted" finish.

3.1.3 Silicon Carbide

Silicon carbide wheels are used in the glass industry for heavy stock removal. Although silicon carbide is harder than aluminium oxide [35] it is more brittle [36, 37]. It has been hypothesised that small silicon carbide grains can exhibit excessive brittle fracture when used to grind glass. Research [38] has shown that this material grinds glass less efficiently than diamond, ie more power is required to remove the material and wheel wear rates are higher. However, an advantage that silicon carbide wheels possess when compared to diamond grinding wheels are their relatively low purchase price.

3.1.4 Diamond

Diamond is currently the most common grinding abrasive in glass industries due to its ability to remove glass more efficiently and economically than other abrasive materials [39, 40]. Diamond wheels are manufactured in a wide variety of shapes and sizes to suit various applications [41]. In addition the diamond abrasive material of these wheels is available in a variety of grit sizes and concentrations to serve a wide variety of rough, medium and smooth grinding applications.

The ability to produce controlled removal rates is considered to be important in manual brilliant cutting since this characteristic reduces the sensitivity of the grinding process to applied pressure. Within an automated system this characteristic is less important since feed rate can be accurately controlled. Hence an abrasive possessing "free cutting" characteristics may be selected. A grinding wheel is said to possess "free cutting" characteristics if it requires only low cutting forces to remove large amounts of material from the workpiece surface.

The most important criteria for automated grinding were found to be:

a. that the surface finish be suitable for polishing, and

b. wheel wear must be limited in order that the geometry of the wheel be maintained.

From previous research [31 to 41], it is apparent that diamond grinding wheels are the most suitable for automated brilliant cutting applications.

3.2 Manufacturing Diamond Grinding Wheels

Diamond grinding wheels consist of a metal wheel base onto which the abrasive grains are bonded to the grinding surfaces. The various methods of applying the diamond grains are as follows.

3.2.1 Electroplating

This method involves using a thin layer of nickel alloy to form a mechanical bond between the diamond and the base metal of the grinding wheel. The depth of the abrasive layer formed by the diamond grit is approximately equal to the diameter of the diamond grains. The advantage of this method is that an open bond is produced that results in large gaps existing between grains, hence reducing the cutting forces required. Ishida [42], compared nickel plated with bronze bonded wheels of the same grain type and concentration. Nickel plated wheels were found to possess a grinding ratio approximately 20% greater than the highest grinding ratio obtained from a bronze bonded diamond wheel. However, the results also revealed that the surface roughness height was approximately 30% greater and is dependent on the mean protrusion of the grains, (see Section 3.3).

Diamonds have also been successfully electroplated onto mesh disks as opposed to solid wheels previously described. Although this arrangement was initially developed for stone grinding applications, this type of wheel is considered suitable for use as a low cost cutting wheel [43, 44].

3.2.2 Resin Bonding

Resin bonded wheels, as their name suggests, hold the diamond grinding medium within a matrix of polymer resin. In glass processing this type of bond is normally found on wheels used in multi-spindle glass grinding machines and is used for intermediary coarse polishing, [34], although resin bonds are the preferred type at all times when grinding carbide [45]. These wheels normally contain small diameter diamonds and are, therefore, commonly referred to as "microdiamonds". Black [46] states that where friable diamonds are used with a resinoid bond the performance of the wheel can be enhanced by coating the diamonds with an equal mass of nickel. The nickel chemically bonds to the resin matrix and allows the diamond to fracture, thereby exposing fresh cutting edges, without the diamond being torn from the bond matrix. The grinding efficiency of such wheels is improved by 50%, when compared with non-coated diamonds, whilst wheel wear and the temperatures generated during the cutting process are reduced.

Burman [47] mixed an epoxy binder with rubber to form a two phase solid which consisted of a rigid polymer matrix that contained diamond grains and rubber globules of diameters between 1 and 5 microns. The rubber has the effect of dissipating crack energy, therefore, producing a wheel with high tensile strength that is resistant to thermal shock.

3.2.3 Vitreous Bonding

Vitreous bonding is achieved by mixing diamond grinding materials with ceramic powders. The usual ceramic materials employed are feldspars [48] which are naturally occurring minerals that consist mainly of aluminium silicates, [10]. These minerals, in clay form, are mixed with the diamond abrasive and baked until solid [36]. Wills [35] states that although vitreous bonded diamond wheels are used in some industries they are sensitive to machine vibration and, therefore, susceptible to accidental damage.

3.2.4 Metal Bonding

The normal type of diamond wheel found in the glass industry is of the metal bonded type. The diamond grits are held within a sintered metal layer which is located around the periphery of the wheel. A range of standard wheel geometries is specified in BS2064 [41]. These wheel types are readily available commercially with abrasive layers normally six millimetres thick. Consequently a metal bonded wheel possesses a much longer service life than an equivalent electroplated wheel. This increased service life offsets the greater purchase price of such wheels. Because they are produced from solid, metal bonded wheels are normally tolerant of considerable hard use provided they are not abused, [49].

3.3 Grinding Glass Using Metal Bonded Diamond Wheels

From the literature a unified system model, (Figure 26), has been constructed to indicate both the variables involved in glass grinding and the relationships between these variables. These parameters can be categorised as:

a. parameters that are designed and define the application, eg grain size, and

b. parameters that are resultant, eg surface finish.

3.3.1 Degree of Viscous Work

Huerta [50] describes how, when grinding glass using diamonds, material is removed in two stages. Initially viscous deformation occurs as the diamond grain enters the glass. This process is then followed by brittle fracture of the glass. The term "viscous" is used to denote that during deformation the glass behaves in a similar way to that of a fluid rather than a plastic solid. The force required to cause viscous deformation increases as the speed with which deformation takes place increases, ie. in the manner of a liquid. Shinker [51], when experimenting with a single grit, found that the depth to which glass exhibited plastic behaviour was between 0.3 and 2 micrometer. The actual depth to which plastic behaviour occurred was found to depend on the type of glass being cut and the cutting speed. Below this depth brittle fracture was found to occur. Shinker [51] states that in these circumstances a layer of glass, of the order of one micron in depth, immediately below the diamond, experiences viscous flow and chips of glass are produced. At high cutting speeds the heat energy produced may soften the glass until it becomes fluid.

Globules of solidified glass were observed adhering to the surface adjacent to the path of the grain.

Below this layer of softened glass is a distinct layer, the density of which has been increased, by being permanently crushed into a reduced volume. After cutting has taken place the pressure that has caused the increase in density is released and large internal stresses are formed between the denser layer and its surrounding glass. These stresses cause the glass within this denser layer to produce conchoidal fractures. These fractures can then propagate throughout a zone which is in front of and to the sides of the diamond tip and which may penetrate beyond the denser layer. This zone is also subject to shear with Shinker [51] observing slip faces at an oblique angle to the direction of cut.

Huerta [38, 50] demonstrated that the grinding energy utilised in brittle fracture is negligible when compared with the energy required to promote viscous flow. Therefore, the effect of grinding parameters on grinding energy may be explained purely by the extent and intensity of viscous flow experienced during cutting.

Khait [52] concluded that in order to optimise the time taken to produce a polished surface both the roughness of the rough cut surface must be considered and the depth of cracking below the ground surface.

3.3.2 Type of Coolant

Kobayasi [37] states that some form of coolant is essential to prevent thermally induced cracking. Coolants currently used in glass grinding applications include water, water with oil based additives, paraffin and cutting oils. The desired properties of coolants according to Ishida [42] are good permeation and lubrication. The optics industry favours oil based coolants [53, 37] whilst the flat glass industry prefers coolants based on water with oil and antiseptic additives [47, 54, 55, 56, 57].

Salter [58] investigated the thermal characteristics of coolants whilst examining the problem of "workpiece burn". He observed that the proportion of grinding energy conducted into the workpiece when using water based fluid is approximately 1-2%. However, this rises to 15% when employing oil based coolants. Konig [53] noted that glass softens when heated, causing an improvement in cutting efficiency. This improvement will be greater for optical grinding applications in which the fine grades of grits used result in there being many more cutting edges and proportionally higher levels of viscous work deformation. Salter [58] found that because water boils at a lower temperature than oil there is an increased probability of burning occurring to both the workpiece and wheel, as the steam generated prevents the ingress of further coolant fluid reaching the cutting area. In addition, vapours are themselves poor heat conductors, hence the heat generated cannot be removed quickly enough to prevent burning taking place.

Within the flat glass industry the main criterion for grinding, as described by Burman [54], is the material removal rate, particularly when edging [59], and bevelling glass. Therefore, diamond wheels with larger grit sizes are normally used. These wheels generate localised heat at the diamond tip which must be efficiently cooled. Satisfactory cooling is possible using water since with larger grit sizes there is greater space between the tips of the grains for the passage of coolant. A further reason for not using oil based coolants is the need to clean the workpiece economically, in this respect water based coolants readily wash off.

The effective delivery of coolant is important to ensure best results. the use of radial distribution grooves and holes [55, 61], has been demonstrated to offer improved performance. This technique is used by Intermech on their brilliant cutting machine, [14].

Sanatulin [60] has demonstrated that the inclusion of additives, (eg. 2% mineral oil and 2% polishing compound), to water based coolants can yield reductions in polishing time of 10-15%.

3.3.3 Bond Hardness

Ishida [42] stated that bond hardness must be carefully selected in order to match bond wear with diamond wear. In this respect it is important that the average grain sharpness corresponds with the desired combination of surface finish and grinding rate. Wills [35] describes the available bonds in order of hardness and length of life as bronze, iron, steel and carbide respectively. Bronze bonds are normally used in glass grinding applications since they provide the necessary free cutting characteristics required by the industry.

Matusek [62] states that, once dressed, softer bonds yield a high initial grinding rate since the bond is more easily eroded. Diamond sharpness is maintained as the diamonds in the cutting zone are torn out by the cutting forces before they can become worn, ie grit retention is reduced. However, when this process occurs, wheel wear is found to be correspondingly high. Matusek studied a comprehensive range of bronze wheels which possessed Brinell hardnesses of between 600 and 2200 MPa. Konig [53] noted that when a prominent diamond grain cuts deep into an exposed edge a visible chip is produced. Softer bonds can cause the grain to be torn out, therefore, reducing or preventing the damage to the exposed edge.

3.3.4 Diamond Concentration and Size of Grains

The concentration of diamond cutting wheels is defined by the mass of diamond per unit volume, [41]. The standard 4.4 carats (22g) per cm^3 is given the concentration 100 and wheel concentrations are specified as percentages of this figure, eg. a concentration of 50 equals 2.2 carats per cubic centimetre. Ishida [42] stated that smaller grains and/or higher concentrations result in a finer finish because there are more cutting edges. From experiments Matusek [62] found that the surface roughness of the workpiece increases with grit size and decreases with concentration according to the relationship:

$$Ra = k.\ z^{1.5}\ .\ c^{-0.5} \qquad (1)$$

Where:

Ra = the surface finish parameter, ie the arithmetic mean of the departures of the profile from the mean line, (micrometer),

k = an empirical constant,

z = the average grit size, (micrometer), and

c = the concentration of diamond.

Matusek [62] also stated that Ra is independent of wheel speed, applied pressure or type of glass. Burman [47] investigated the depth of damage below the surface roughness. The size of the damaged layer was found to increase with grain size, but the rate of increase of the damaged layer decreases with grain size according to the quadratic relationship:

$$T = ad^2 + bd + c \qquad (2)$$

Where:

T = thickness of the damaged layer,, (micrometer)

d = size of the diamond grain,, (micrometer)

a = empirical constant (value equals -1.4)

b = empirical constant (value equals 441), and

c = 481

Huerta [38, 50] recorded an increase in specific grinding energy with higher diamond concentration and finer grain size. In both instances the number of cutting edges increased. Each cutting edge must penetrate the viscous layer before a chip is removed and the fewer penetrations required to remove a specific volume of glass the more energy efficient the process will be.

Khait [52] observed an increase in specific diamond consumption with smaller grains and higher concentrations. Taeyaerts [63] stated that for high numbers of cutting edges it may be impossible to penetrate the viscous surface zone when the wheel is rotating at high speeds. In addition, there are also practical problems with the homogeneous dispersal of small grains throughout the bond, hence for small grains a low concentration is recommended. Konig [53] stated that as wheel wear is due to the free abrasion of the glass chips on the wheel, a reduced space will increase wear. This effect places greater importance on the chip shape, size and hardness characteristics of the glass.

The problems associated with small diameter diamonds and higher diamond concentrations can be partially overcome by using segmented wheels of the type normally employed on glass engraving machines, (Section 2.3.2). These wheels have the bonded diamond mounted in teeth around the periphery. Gaps between the teeth allow coolant to reach the glass and allow glass chips to escape from the cutting zone. The teeth are effective in increasing the specific pressure of the abrasive wheel on the glass. This is essential when using hard, concentrated grades of wheel which are more resistant to wheel wear [63].

The main types of tooth pattern used on wheels for glass engraving machines are illustrated in Figure 27. Here type A [34] is available for straight line machines and the tread pattern is machined from solid.

With type B; ie the type used on the Intemac CNC machine [14, 34]; only one third of the circumference of the wheel is bonded with a diamond grinding medium. Holes are also drilled into the teeth to allow centrifugal action to force coolant between the teeth. Users contacted in the industrial survey, (Section 2.5), reported that this type of wheel is, however, prone to tooth breakage.

Type C, used on the Aton/90 [64] possesses a distinctive wave pattern which provides greater wheel strength. The pattern maintains almost constant contact area which has a beneficial effect on the amount of torsional vibration produced.

3.3.5 Grit Friability

Both naturally occurring and synthetically manufactured diamonds are used in grinding wheels, [54, 65]. Industrial diamonds are characterised by the diamond trade as irregular or blocky according to their shape [65]. The characteristics of these diamond types have been summarized below, ie:

a. Irregular shaped grains have many surface facets and contain internal flaws. Their large surface area increases the strength of the bond between grain and matrix material. Wills [35] states that the most important property of irregular diamonds is their friability. This characteristic of a diamond grain is defined as "the ability to fracture to form new, sharp edges". The ability of diamond grains to fracture arises from the internal flaws and cracks that irregular diamonds contain.

b. Blocky grains are manufactured synthetically and can be grown in a near perfect cubo-octrahedral shape [65] that normally contain few or no flaws. This shape produces a high compressive strength. Kobayashi [37] has indicated that the sharp edges of grains may be removed and their surfaces polished. This type of treatment is said to increase grain strength and improve grinding ratios, ie the ratio between material removed and grinding medium consumed. Ishida [42] observed that blocky shaped grains tend to wear rather than fracture as in the case of irregular shaped grains. With blocky shaped diamond grains consumption occurs when the load on the grain becomes so great that the grain is torn from the matrix.

Diamonds are graded according to their compressive strength and mesh size [66], with the strongest grains normally being reserved for heavy grinding applications such as stone grinding [65]. Diamond grades used for glass grinding vary according to the application. For example, stronger grades are recommended by De Beers [65] for pencil edging or lens grinding. More friable grades of diamond are recommended for engineering applications in which edge breakout and chipping must be avoided.

Yu [66] determined that diamond strength has only a minimal effect on surface roughness, ie less than 12% of the Ra value. Although softer diamond grains produce smoother surfaces when polishing, stronger grains can reduce diamond consumption by up to 30%.

Ishida [42] found that as the protruding tips of the diamond wear a slight improvement in the smoothness of the surface finish is obtained. Although grain wear is not solely determined by grain strength, Shulman [67] noted that harder diamonds are less liable to grain wear resulting in a greater average height of grains above the surface of the bond material.

Tanaka [68] has shown that the strength of diamonds diminish in direct proportion to the number of thermal shocks received. Kobayashi [37] noted, however, that the experiments carried out by Tanaka did not simulate the large number of shocks that occur in the actual grinding process. Therefore, it is difficult to separate the effects of this phenomena from other loads imposed on the grains. It has been shown [69] that diamond life can be enhanced by reducing the thermal gradient across the grains.

3.3.6 Wheel Condition

The condition of the wheel may be described in terms of:

a. the average degree of wear on the diamond grains,

b. the mean prominence of grains,

c. the degree of damage to (friable) grains,

d. the proportion of grains completely torn out, ie since blocky grains leave a hole when removed the proportion of holes to grains visible is used as a measure of grain retention,

e. the presence of shoulders, ie a build-up of bond behind the grains which both supports grains and indicates the level of grit retention and results in a high mean protrusion for the size of grain, and

f. the degree of clogging, ie the amount of glass adhering to the wheel thereby impairing grinding.

Microscopic examination is necessary to measure the above parameters. Hence when deciding whether to dress a grinding wheel, operators will normally use one of two parameters, ie:

a) loss of performance from the wheel and

b) reduction in accuracy of the wheel profile.

Several researchers [39, 62, 63], investigating constant pressure applications, defined performance in terms of rate of volume removed per unit of pressure applied. For fixed feed rate applications cutting performance is defined as pressure required or spindle load for a given removal rate, ie a loss of cutting performance increases the required spindle load.

Ebor [34] recommend aluminium oxide sticks as a suitable medium for dressing bronze bonded diamond wheels manually, as normally occurs when cutting tableware [24]. Khimach [70] developed an electro-contact dressing method using rotating wire brushes as electrodes. This process, when compared with other dressing methods such as manual dressing, was found to be more economical in terms of the amount of diamond that needed to be removed to complete the dressing process. In addition when applied during grinding the performance of the wheel, in terms of both cutting capacity and specific diamond consumption, was significantly improved.

Wills [35] stated that both prior to the cutting process beginning and periodically throughout a wheels cutting life, a diamond wheel must be trued. Before truing can take place the wheel must be mounted as accurately as possible to minimise material wastage [71]. Hoecker [24] recommended, as a suitable truing method, turning the grinding wheel against an aluminium oxide wheel. This procedure as been adopted for use on the Interdima machine [15, 64]. Barret [72] argued that when using this method that erosion of the aluminium oxide wheel is excessive and that electro-discharge machining is a superior method of producing precise profiles. Electro-discharge machining has been adopted by the leading grinding wheel manufacturers Van Moppes IDP Ltd. and Shaw Bros. Ltd.

The surface condition of the grinding wheel may also be maintained by applying either ultrasonic or low frequency vibration, [73]. The erosive capacity of ultrasonic vibration is a powerful aid to the grinding action, resulting in increased grinding rate, [74, 75].

Matushek [76] found that, after dressing, the performance of a wheel, in terms of its grinding rate for a given pressure, would decline with time. Two phases of tool wear were observed, ie:

a. the first phase, lasting approximately ten seconds, was found in softer bonded wheels and corresponded to a 70% drop in performance, and

b. all wheels where found to demonstrate a second phase lasting up to ten minutes during which performance fell by 23% to a new steady state value. This lower level of performance could then be retained if the wheel was operated within its defined limits. The rate of decline was found to be greater the smaller the product of grain size and concentration.

3.3.7 Cutting Speed

Matushek [76] determined, for a given grinding pressure and for surface speeds below 15 m/s, that grinding rate is linearly proportional to surface speed. Above 15m/s the grinding rate/surface speed curve, (Figure 28), diverges to a local maximum which occurs between 20-25 m/s. Above this latter speed range there is a progressive and substantial increase in surface roughness. The maximum grinding rate can be 20-45% greater than the linear extrapolation of the initial part of the curve. The speed at which maximum grinding rate occurs is independent of grit size and concentration.

Questions have been raised about the onset of unacceptable surface roughness observed by Matusek. Ammel [39] for example quoted roughing speeds of 28-38 m/s, using similar wheels to those of Matusek, for use when grinding tableware where quality is a critical criterion. Ishida [42] recorded decreasing roughness when using cutting speeds up to 48 m/s. However, these results were obtained using a more effective, oil based coolant.

Research by Kobayashi [37] identified that grinding ratio decreases as the speed of the wheel increases when using metal bonded wheels. Ishida's results [42] support this general relationship. Kobayashi [37] observed that diamond wear rate increases exponentially as the speed of the grain rubbing against the glass increases.

Ammel [39] recommended that when using slower speeds, that wheels containing higher diamond concentrations should be employed. Taeyaerts [63] explained that slower speeds allow deeper penetration of the glass which causes larger sized chips to be removed. A higher diamond concentration offsets the increased bond erosive effect of the larger chips.

Huerta [50] noted that, for a fixed "feed rate/revolution", the specific energy, (ie energy per unit volume of material removed), involved in removing material increased with increases in wheel speed. These last two observations may be explained in terms of the viscous flow dependant phenomena described in Section 3.3.1.

3.3.8 Feed Rate and Grinding Pressure

For speeds below 15 m/s, Matushek [60] determined that:

$$b = F \cdot P^{1.5} \qquad (3)$$

Where :

b = grinding rate (volume per time),

F = an empirical constant and

P = pressure (force per unit area)

Black [46] found that each wheel has an optimum grinding pressure at which the grinding rate is a maximum. If the pressure is below this optimum then the grains are allowed to become worn. If the pressure is above this optimum then wheel wear increases due to increased bond wear and diamonds are torn out of the bonding matrix prematurely. The resulting reduction in the mean protrusion height of grains prevents the grinding rate being maintained.

3.3.9 Balancing Wheel Design and Application Parameters

During an automated glass grinding process the only parameters that can be varied by the operator are the "feed rate" and the "frequency with which wheels are dressed". Wheel dressing, however, has been shown, to consume large proportions of the diamond grinding medium, [24, 72]. Therefore, the main source of control the operator can exert over the cutting quality is feed rate. If the feed rate is set too low then the diamond grains will become worn faster than the bond. Grinding efficiency will, therefore, decline and wheel clogging may occur. In this type of situation the power required will increase and the wheel will require dressing. If the feed rate is set too high then bond wear will increase causing the grains to become more prominent and sharper. Pits may also be visible where diamond grains have been torn from the wheel and excessive wheel wear will result. Surface roughness will increase, and hence polishing time increases, as a result of the sharper nature of the grinding wheel. Hence, increasing feed rates beyond the optimum for the wheel is a false economy.

If feed rate is high then large numbers of the most prominent grains will be torn out of the matrix, hence placing greater loads on the remaining grains. A situation could then occur in which the wheel cannot cope with the feed rate used. When constant feed rates are employed it is possible that the volumetric removal rate can exceed the removal rate sustainable by the wheel in those conditions, therefore a collision will occur.

3.4 Achieving Polished Surfaces

The primary methods of producing polished surfaces are chemical erosion, the use of impregnated polishing wheels and polishing slurries and these methods are now examined.

3.4.1 Chemical Erosion

As described in Section 2.4.2 chemical erosion is mainly used when polishing glass tableware since such objects may be totally immersed in relatively small volumes of hydrofluoric acid which polish the entire surface [11]. The high ratio of ground to total surface area of tableware objects improves the economics of the chemical polishing process. For large sheets of brilliant cut glass, however, the proportion of ground to total surface area is considerably smaller, hence the majority of the polishing acid would be wasted. Immersion is also more difficult since masking may be required to protect those areas that must remain frosted. The polishing process releases high volumes of toxic fluoride gas which necessitates the use of ventilation equipment. For these reasons acid polishing is not normally used to polish large brilliant cut objects.

3.4.2 Impregnated Polishing Wheels

Impregnated polishing wheels, commonly referred to as "composition" wheels, are used on the majority of automated polishing machines. They are normally cooled using water and consist of an abrasive medium which is held in a rigid polymer matrix. Multi-spindle bevelling machines use cup shaped wheels mounted as shown in Figure 29, [78]. By using more than one polishing wheel, suitably orientated a high quality finish can be produced, [79]. In contrast with bevelling machines, where the grains cut across the direction of feed, brilliant cutting and edging machines, [80] always cut and polish with the grains following the direction of feed. The need to minimise the number of passes in order to maintain economic throughput rates also limits the finish achieved by such machines.

3.4.3 Polishing Slurries

This method of polishing glass uses a suspension of abrasive material in water which is fed on to a carrier wheel. The material used to manufacture carrier wheels may be brush, felt, pitch or synthetic polymers. The traditional polishing materials employed are iron oxide, (ie rouge), or finely ground pumice, as described in Section 2.1. These traditional polishing materials have largely been replaced by cerium oxides that are now commonly used in the optical, flat glass and television [78,81,82,83] industries. Cerium oxide has been found to possess a polishing rate that is 58% faster then rouge. The use of these polishing mediums requires that the surface is initially pre-polished using a composition wheel in order to remove the majority of the roughness. Cerium oxide powders have particle sizes of a few microns and are suspended using agitated water. When felt or pitch wheels are used the cerium oxide slurry is recirculated. A disadvantage of using cerium oxide powders is the presence of toxic impurities such as radioactive thorium. In addition, if dust is created then the atmosphere must be sampled and tested in accordance with health and safety legislation. Despite these disadvantages much of the glass industry uses cerium oxide.

The polishing process is a combination of mechanisms, ie mechanical wear, plastic flow, chemical erosion and mechano-chemical erosion. Since the action of diamond wheels are limited to mechanical wear they are not suited to fine applications such as optics. Cook [84,85] reports that the mechano-chemical mechanism is probably the most significant for the reactive polishing agents such as cerium oxide. Cook suggested that the polishing material chemically bonds with the glass. The mechanical passage of the polishing grain then pulls a number of silica molecules from the glass. Further chemical reactions displace the silica into solution and restore the balance of ions in solution.

3.4.4 Advanced technologies

Precision optical surfaces can also be polished by ion bombardment, [86,87,88,89,90,91], however this technology has not yet been applied on a mass production scale.

Measurement of ground surfaces is possible by measuring the degree of scatter of light shone at or through the surface, [92,93,94,95,96,97,98]. Again development of these technologies is as yet only experimental, however the potential for an easy, non contact method of quality control is there.

Chapter Four

CAD for Brilliant Cutting

Contents

4.1 Introduction

This chapter describes Computer Aided Design and how it has been applied to the automated brilliant cutting process.

CAD is a broad term that encompasses several methods of aiding the design process. Of these the purpose of CAD for brilliant cutting is to provide data for the generation of CNC code and to facilitate the design of brilliant cutting products. This chapter describes how brilliant cutting features may be defined graphically. A commercial CAD package has been employed and the ergonomic capabilities of the selected system have been exploited by the use of icon menus and parametric design techniques.

4.2 The Purpose of CAD

Groover and Zimmers [99] have defined CAD has being any computer application which aids in the analysis, development, costing and ergonomic problems associated with design work, ie CAD, therefore, provides assistance in the following areas:

a. draughting,

b. design review and evaluation,

c. engineering analysis, and

d. geometric modelling.

Draughting involves generating a drawing that contains a complete specification for the product and is the CAD function most relevant to the current work. The ability to easily generate new designs, re-use and modify existing designs is essential as is the facility to make use of the dimensional data generated from these designs. The facility to produce full scale hard copy drawings is also a valuable CAD feature that would enable customers to visualise and evaluate the proposed product.

Reviewing and evaluating the design for possible errors and potential problems is also essential to ensure that the proposed design does not contain features that cannot be brilliant cut. In this respect, it is important to determine the type of grinding wheel that should be used to generate each feature of the design. In this respect it is possible to automate specific design review and evaluation tasks. For example the radius of curvature of curved lines could be calculated and compared with a minimum radius that can be effectively brilliant cut.

During the design process engineering analysis can be used to test the properties of the design, eg stress, strain or heat transfer. Since no mechanical functions need to be considered when producing brilliant cut designs, engineering analysis functions are not necessary.

Geometric modeling involves using a mathematical description of an object to represent that object on the screen [99]. The methods used to describe an object's geometrical structure are:

a. wire-frame modeling, which describes objects in terms of lines connected to points with objects appearing on the screen as if made of wire,

b. surface modeling, which in order to describe 3D surfaces defines an object in terms of points, lines and faces, and

c. solid modeling which describes objects in terms of the volumetric shape which they occupy.

These methods are frequently used to provide basic positional data for such applications as complex 3D toolpath simulation and simulating the movements of robots [100]. The use of such modeling techniques can greatly simplify the generation of complex 3D objects. For example, solid modeling involves creating objects using the following predefined primitives, ie boxes, cubes, wedges, cylinders, spheres, tori and cones. These primitives are combined to form the desired shape, hence, draughting time for complex shapes, such as found in brilliant cutting designs, would be considerably reduced.

Brilliant cut features are essentially two dimensional in aspect, ie the third dimension, depth of cut, is a function of the wheel geometry and the cut depth selected by the operator. The depth of cut will vary only in the following circumstances:

a. when a grinding wheel is progressively fed into the workpiece surface such as to produce a tapered start and end to a cut, and

b. when curved surfaces are being created the cut depth is determined from the wheel geometry and the required shape of the cut.

It is, therefore, possible to define a three dimensional object using a two dimensional design by implying the third dimension as a result of the brilliant cutting process itself.

4.3 Drawing Procedures for Brilliant Cut Objects

4.3.1 Mitred Punts

Both the length and orientation of a mitred punt can be defined as illustrated in Figure 30:Cut Type *a* using a straight line between two points. In order to visualise the shape of the mitred punt, two arcs are drawn either side of the straight line. These arcs are only approximations of the correct shape but are beneficial since they enable mitred punts to be clearly distinguished from oval punts (Section 4.3.3).

4.3.2 Round Punts

Round punts can be defined using a circle as shown in Figure 30:Cut Type *b* and for a specific punt diameter, the depth of the cut will be a function of the radius of the wheel.

4.3.3 Oval Punts

As with mitred punts, oval punts, Figure 30:Cut Type *c*, can be defined using a centreline which provides an accurate indication of orientation and length and positional data for the machine control system. Oval punts derive their precise proportions from the wheel geometry in the same manner as mitred punts. The width of an oval punt varies with its length in a non-linear fashion. In order to visualise an oval punt the use of an ellipse is a suitable approximation.

4.3.4 Panel Cuts

Panel cuts, Figure 30:Cut Type *d*, can be represented using filled lines of the same width as the required panel cut itself. However, although this is a visually accurate representation of a panel cut, problems can arise when such cuts either need to join or intersect each other. On these occasions the exact positional detail of the panel cut is obscured leading to difficulties in draughting. In these circumstances, in order to achieve an accurate definition of a panel cut, a designer must use a centreline that is drawn using the CAD systems normal line width.

4.3.5 Mitred and Round Cuts Type 1

- wheel not tilted : constant cut depth: constant cut width

The constant cut depth of these types of cut, illustrated in Figure 30:Cut Types *e*, *f*, *k*, *l*, and *m*, and the vertical position of the grinding wheel result in a constant cut width. They can, therefore, be defined using only a centreline along the length of the cut. This centreline can be represented, using a CAD system, by a single drawing entity, ie a curve, arc or straight line.

4.3.6 Mitred Cuts Type 2

- variable wheel tilt: variable cut depth: variable cut width

These cut types are shown in Figure 30:Cut Type *j* and require a complex tool path as described in Section 6.5.8. They may be defined using three curves which represent the two edges of the cut and the path of the point of the wheel.

4.3.7 Edge Cuts

Although edge cuts, Figure 30:Cut Types *g* and *h*, possess a uniform depth profile, (see section 2.2.3), both their cut width and curvature can vary. There are several categories of edge cut, ie:

a. symmetrical segments, which can be represented by a straight line and an arc,

b. asymmetrical segments, which require a straight line and a curve,

c. symmetrical crescents, which can be represented by two arcs, and

d. asymmetrical crescents, which can be represented either by two curves or a combination of a curve and an arc.

4.4 CAD Features for Brilliant Cutting

From the above description of how brilliant cut features may be presented, the minimum features required of a CAD system may be derived. These features may be categorised as:

a. those features that are required to enable brilliant cut objects to be constructed, ie:

* point set, freehand, snap to grid, gravity to nearest point,
* freeform curve, through a number of points,
* straight line between two points,
* arc - drawn thought any three points, or specified by centre beginning and end,
* circle - specified by centre and radius,
* ellipse - specified by centre, major and minor axes, and
* visible grid of variable size.

b. those features required to aid the design generation process, ie:

* erase and unerase,
* duplication of groups of entities or individual entities,
* mirroring of groups of entities,
* rotation of groups of entities,
* file handling utilities,
* multiple colours, and
* multiple layers.

c. a method of performing feature based CAD/CAM ie differentiating between identities that refer to different types of cut, eg:

* the use of a specific drawing layer to represent a particular type of cut, and
* assigning a particular colour to the entities stored on a specific layer in order to aid visualization of individual brilliant cut features.

The minimum specification for a CAD system for brilliant cutting is brief compared with the list of functions provided by the majority of commercial CAD packages. When selecting a CAD package, therefore, additional criteria had to be applied, ie:

a. ease of use, efficiency and minimisation of training requirements especially for operators who possess few technical skills,

b. availability of a recognised standard format for drawing storage, in order to allow the substitution of preferred or more advanced CAD systems at a future date, without prejudice to existing CAD/CAM software,

c. availability of comprehensive file and block manipulation facilities in order that a library of brilliant cut designs can be developed, and

d. overall cost of the CAD/CAM system, in terms of computer hardware, software and development time, has to be relatively low.

4.4 DXF Data Files

A key criteria for selection of a suitable CAD system is that the drawings can be stored in a manner that would allow dimensional data to be extracted. A number of formats are available for storing drawings in a suitable manner the primary ones being IGES, DXF, STEP and miscellaneous plotter formats such as HPGL [101]. The Data eXchange File standard is the most frequently used format for micro-computer based CAD applications [102]. Actual DXF formats can vary between CAD packages and have often been modified when updated versions of CAD software are released to the market. However, this format is reasonably standard that any changes made would have minimal effect on the part programming software that uses such formats. DXF formats are also both easy to understand and to access.

In addition DXF files are of consistent and predictable structure and are drawing entity orientated. That is, within a DXF data file each entity in the drawing is labelled in terms of its type, layer, point positions and parameters. DXF files are stored in ASCII format, hence, minimal programming code is required to retrieve and interpret dimensional data. Ease of use, therefore, is an important benefit when using DXF files and was the primary contributing factor to the choice of this format for the development of the brilliant cutting CAD/CAM system.

4.5 DesignCAD 2D

DesignCAD 2D is a low cost, "easy to use" CAD package which provides all the essential features required to support CAD/CAM for brilliant cutting. The "ease of use" of a package was assessed by subjectively examining the logical nature of the menu system and the speed and ease at which a required CAD function could be found and used. DesignCAD 2D compared favourably with other CAD systems, ie DOGS, CADKEY, GenericCAD and AutoCad. In addition, since the system is intended for use by non-technical personnel the ease of use of DesignCAD was considered most important in its eventual selection.

DesignCad 2D also contains an icon menu system [103] which allows commonly used functions to be placed permanently on the screen, hence, allowing users immediate access to these functions. Trials were carried out to determine the frequency with which CAD functions were used during the construction of brilliant cut designs. Design 2D menu icons were then constructed for those used most frequently. In addition, those functions that were difficult and time consuming to access were also identified and assigned menu icons. Using these icons a purpose built menu system, (Figure 31), was developed for brilliant cutting. This system was found to give significant advantages in terms of reducing the time spent in finding and activating the drawing functions.

4.6.1 Parametric Design Aids

DesignCAD also possesses methods for linking drawing functions, ie macro's and BasicCad. A "macro" is a set of commands that can be combined into a sequence and this sequence initiated by a single command [103].

BasicCAD is a programming language within DesignCAD 2D and programmes generated using this facility can be run as would any DesignCAD 2D command, by typing the command or using a menu icon. BasicCAD programmes can be developed to perform all DesignCAD 2D functions. This facility allows parametric design to be carried out in which a design is generated automatically using a limited number of specified parameters.

Although the majority of brilliant cut features can be defined by a single entity, (see Section 4.3), additional drawing entities are required to allow customers to visualise the cut. Constructing this additional detail greatly increases the time taken to produce the design. In order to reduce this time, parametric, [104] design programmes were written for mitred and oval punts. These programmes, activated by the commands "MPUNT" and "OPUNT", initially require the two points that define the punt to be input. The length of the punt is then calculated and displayed. This facility allows accurate representation of the proportions of the punt, makes the system easier to use and reduces the time taken to construct arcs. It is, therefore, more appropriate for use by non-technical personnel who need only to input the appropriate width for a particular punt length. The non-linear relationships between punt lengths and their widths is shown in Figure 32. Using information obtained from this curve a BasicCAD programme, is able to construct appropriate arcs or ellipses to represent the punt.

Chapter 5

Development of the Brilliant Cutting Machine

Contents

5.7 Grinding Head Assembly

5.7.1 Design Concepts

5.7.2 Spindle/Gearbox Assembly

5.8 Ancillary Systems

5.8.1 Machine Base and Structural Alignment

5.8.2 Coolant System

5.8.3 Workpiece Mounting

5.8.4 Safety System

5.8.5 Flexible Drive Transmission

5.0 Introduction

This chapter decribes the design and development of the Brilliant Cutting machine. The design was produced from first principles, analysing functions and criteria and selecting suitable methods of performing functions according to the criteria. Information was drawn from current BC practice, as described previously, and from research in the field of automated cut glass engraving, described within this chapter. The manufactured design combines standard and purpose built component to produce a five axis CNC machine.

5.1 Kinematics of Brilliant Cutting

Brilliant cutting requires a machine with a minimum of five degrees of freedom. To justify this statement consider a grinding wheel in three dimensional space.

If the wheel is to have complete freedom of motion it must be able to translate in the three orthoganal axes that define that space and also rotate about those axes. The wheel would, therefore, require six degrees of freedom. If the frame of reference is relative to the wheel, such that one of the orthoganal axes passes through the centre of the wheel whilst the other two axes form a plane in which the disk of the wheel lies, then complete freedom of rotation must be possible around each of these axes. However, since a grinding wheel is being considered which normally rotates about its rotational axis and is, therefore, partially constrained, positional control of its rotational axis is not required.

Therefore, only five degrees of freedom are required for brilliant cutting, ie translation in three orthoganal axes and rotation about two axes.

A critical aspect of brilliant cutting machine design is the machine structure itself since this determines both the capability of the machine and the mathematics of the CAD/CAM part programming system. In addition, it is considered necessary to ensure that the machine geometry adopted enables the prototype machine developed to be "productionised" without the need for radical alterations to the software.

5.2 Concept Design Criteria

Design criteria for a brilliant cutting machine were identified from:

a. analysis of the range of brilliant cut types, (Section 2.2),

b. experimentation to identify the cutting forces involved in grinding glass,

c. the previous experience of other researchers (described in Section 5.3), and

d. results of the industry survey, (Section 2.5).

These criteria are now described in the following sections.

5.2.1 Functional Criteria

1. The machine must enable the cutting wheel to possess five degrees of freedom as previously explained in Section 5.1.

2. Cutting tests on a horizontal grinding wheel, using a dynamometer to measure cutting forces, indicated that a load of 50N should be sustained simultaneously in each axis.

3. Although positioning accuracy is not an engineering requirement it is necessary to ensure that brilliant cut objects are visually acceptable. In this respect, discussions with manual brilliant cutters indicated that positioning accuracy must be less then or equal to +/- 0.01 mm.

4. Positioning repeatability must be such that polishing wheels can perform their function without altering the outline shape of the cuts that have been produced by rough grinding.

5. No absolute values for cutting speeds and feeds were set since it was necessary to enable these to be varied in order to identify suitable operating conditions.

5.2.2 Operational and Safety Criteria

1. The machine should be capable of operating on an intermittent basis for at least 3000 hours without major breakdowns, ie approximately two working years.

2. The reliability of high cost components, such as motors, should be high.

3. Rating should be continuous, ie the machine needs to be able to operate without stopping during the normal working period of the user.

4. Maintenance required should be minimal.

5. In order to avoid accidents the operator must be isolated from the machine during its cutting operations.

6. Emergency stop buttons must be fitted at appropriate locations.

7. The machine should satisfy any legal requirements, for example with respect to noise levels.

5.2.3 Environmental Criteria

1. In order to protect both computer equipment and the machine operator the atmosphere in the immediate vicinity of the machine should be protected from both glass dust and water spray that contains glass particles.

2. Waste coolant must be contained for appropriate disposal.

5.3 Alternative Design Strategies

The problem of how to satisfy the concept design criteria was examined using an algorithmic design process [105, 106]. This process was used to generate over fifty alternative design concepts each of which were evaluated systematically. Initially it was necessary to decide which method to adopt to move the grinding wheel and workpiece relative to each other whilst still connecting the wheel to the motor. Essentially a number of methods are commercially available for achieving this movement with the required five degrees of freedom and these are now considered.

5.3.1 Robotic Devices

Commercial robotic handling devices are normally provided with six degrees of freedom in order to maximise the range of industrial applications for which they are suitable [100]. For this reason they also possess well developed CNC programming capabilities. The cost of commercial robots is a direct function of their payload and positioning accuracy, ie powerful, accurate robots are expensive.

Commercial robots have been used to brilliant cut a variety of decorative patterns into crystal glassware. For example, Nagarajah [107] developed a robotic system that used a vacuum gripper to move a glass tumbler against a grinding wheel. The CAD/CAM system developed was capable of cutting linear "V" profiled cuts into conical tumblers. The CAD element of the package employed a local co-ordinate system to represent the surface of the glass with the CAM element converting this data to that of the co-ordinate system of the robot. Such a programming arrangement was essential to ensure that if subsequent design modifications took place then only minor modifications would be required to the post processor.

Edwards et al. [20, 21, 108, 109] continued the work of Nagarajah and developed the CAD/CAM system such that it had the ability to cut curved "V" profile cuts. Edwards demonstrated the advantages of using CAD/CAM technology to introduce a "radial correction factor" that allowed wheels to cut curves for which they are normally too large. Although this was achieved by reducing cutting speeds it was observed that a feathering effect could be produced on sharp curves. This effect was attributed to a combination of such factors as the smoothness of the toolpath, the vibration generated by the wheel and the response of the robot to such vibration. Edwards concluded that off-line programming was a suitable approach for such a complex application. However, the effectiveness of this approach was limited by the accuracy of the robot. For example, allowance had to be made for robot compliance in order to successfully control the positioning of the glass relative to the cutting wheel and hence achieve the required cut depth.

Edwards [20],also identified the need to:

a. improve the effectiveness of off-line programming and avoid the need for tool position compensation by ensuring the positioning accuracy of the equipment used,

b. avoid cutting movements which go out of reach or approach a manipulators singularity points by performing checks to ensure that such impossible positions are not sent to the robot,

c. control cutting depth by maintaining the position of the glass relative to the cutting wheel, and

d. perform frequent redressing of grinding wheels in order to achieve consistent results.

Further research [109] has highlighted the importance of:

a. providing methods of compensating for variation in workpiece dimensions,

b. the need for improved robotic and computer technology, and

c. enabling allowances for robot compliance.

When evaluating the use of a robot to aid the brilliant cutting process the following problems were identified, ie:

1. Although a commercial robot could readily provide the basis for a brilliant cutting machine, acquiring the necessary positional accuracy within the capital investment budget of most brilliant cutting companies could not be achieved.

2. Most brilliant cutting companies would wish to produce brilliant cut panels of lengths up to two metres. To obtain a sufficiently large working area would require a large robot, which assuming it were to be built in the same manner as large welding robots of similar payload, would again be inordinately expensive.

5.3.2 Bespoke CNC Machinery

The varied demands of manufacturing industry for CNC equipment has resulted in a large number of companies who specialise in the supply of modular CNC components for building "purpose designed" automated machinery. For example Unimatic Engineers [110] market ranges of guide systems, ball screws, gearboxes, drives and control systems. As indicated a 5-axis brilliant cutting machine would require two rotary axes. However, since CNC axes providing rotary motion are not commonly used in industry, "bolt-on", off-the-shelf revolute axes are not commercially available.

Mayers [111, 112, 113] developed and commercially manufactured machines for engraving wine glasses and for grinding prisms. These machines are constructed in the manner of traditional metalworking machines, ie. with heavy castings and slideways. These machines are capable of producing a wine glass containing traditional mitred cuts in approximately eighty seconds. The mathematics of transposing engraved designs onto the curved rotational surface of glassware has been thoroughly developed by Bruckner and Gaal [114] and Renner [115].

The use of CNC machines in the opthalmic industry dates back to the 1970's [116], but is gaining renewed interest in the field of ultraprecision grinding of aspheric component, [117, 118, 119, 120]. There are a number of other instances of CNC and CAD/CAM technology being successfully applied to engraving or glass processing, [121, 122, 123, 124]

5.3.3 Gantry Type Robots

A number of companies design and manufacture gantry type robots which possess load bearing linear actuators and which were originally used as simple pick and place units. However, when driven by CNC servo motors such units can form powerful and flexible cartesian robots. Because these types of robots are of highly modular construction, Figure 33 and 34, they provide an ideal basis for bespoke automation systems.

The use of such systems for automating the brilliant cutting process offer the following important advantages, ie:

a. positional errors are not compounded by the geometry of the machine,

b. the load on the horizontal cartesian axes can be supported by a prismatic joint,

c. the actuators for these horizontal axes primarily experience an inertial load, hence geometric accuracy and rigidity are enhanced,

d. it is normally possible to use relatively smaller gearbox and motor assemblies to drive each of the axes, hence reducing their costs and the costs of associated electrical power equipment,

e. the working volume of such systems may be large, for example with axes several metres in length, and

f. the supplier of such systems contributes to the development work by designing and testing equipment, hence lead times for development may be reduced.

Although it is possible for the positioning device to move the glass workpiece relative to a stationary grinding wheel difficulties can arise, ie:

a. the positioning device may need to be strengthened in order to maintain its required positioning accuracy [20],

b. the weight and inertial load of a pane of glass is much greater than that of a wheel even when the gyroscopic effect is taken into consideration,

c. the effect of the cutting forces on the workpiece must be considered, ie if the throughput rate of a craftsman is to be improved upon, then the cutting forces may need to be increased beyond that possible with an unsupported workpiece, and

d. moving the workpiece requires a larger space around the cutting wheel then moving the grinding wheel relative to the workpiece.

In conclusion, to move the workpiece would significantly limit the size of the workpiece that it is possible to brilliant cut. This is not considered acceptable by the brilliant cutting industry. It was, therefore, decided to hold the workpiece stationary and to move the cutting wheel.

5.4 Effect of Grinding Wheel Diameter

The diameter of the grinding and polishing wheels in use was found to be fundamental to the design of the machine. In this respect increasing the wheel diameter results in a larger contact area between the grinding wheel and the workpiece surface and hence increases:

a. the payload, (ie as defined by the mass, size and moment of inertia), for the machine,

b. the cutting load, ie the reaction force to the cutting process and the load torque,

c. the size of the motor and transmission required to power the wheel,

d. stock removal rates,

e. the minimum cut radius [11], and

f. the potential for cooling problems to arise [58].

British Standards exist for grinding wheels [41] but these do not contain the edge profiles used in traditional brilliant cutting. In addition such edge profiles are not available as standards from commercial grinding wheel manufacturers [125]. Since cutting wheels had to be purpose made, therefore, it was possible to select a grinding wheel diameter of 75mm and a width of 12mm. Grinding wheel dimensions of this size would:

a. require comparatively small cutting loads since the area in which grinding occurs decreases with reductions in wheel diameter,

b. be suitable for fine work such as short lines and curved lines which contain small radii, and

c. enable brilliant cut objects to be produced of a similar size to those that can be obtained manually.

A 75mm diameter wheel when rotated at the speed of the motor, ie 2800rpm, produces a peripheral surface speed of 15m/s. This surface speed is within the wheel speeds recommended for use with diamond wheels [63] and under the design load requires a motor with a rating of half a horsepower.

5.5 Selection of Main Elements

Once a decision had been made concerning the diameter of the wheel to be used it was necessary to select the guide system, power source and the control system.

5.5.1 Guide System

Guide systems available "off the shelf" are either shaft or rail based. Shaft based guide systems are cylindrical in shape and are, therefore, not intended to resist moments about their axis. Rail based guides, however, are capable of resisting loads in these directions and for this reason a rail based guidance system needs to be employed and was, therefore, chosen.

The most accurate method of obtaining linear motion along guides is to use a ballscrew. These systems are expensive but can achieve tight positional tolerances if required. For applications that require less accurate positioning requirements lower cost methods are available that make use of either rack and pinions, screw threads or toothed belts. However, the latter system, although inexpensive does not possess the rigidity found in the other systems and it was decided, therefore to select a rack and pinion system.

5.5.2 Power Source and Control System

Many early robots used fluid power actuators since these provided a high force to weight ratio and this is a key factor in determining the payload to cost ratio of the system [100]. However current technology uses electrical motors, in combination with reduction gearboxes, of which the types considered for the current application where AC servo-motors, DC servo-motors, brushless servo-motors and stepper motors.

Both AC and DC servo-motors require position feedback encoders and an application orientated control algorithm. The values of the parameters used in the control algorithm must be set to conform to the application and offer the best performance compromise throughout the operating range.

Stepper motors do not require position feedback [126] since the power input is of digital format and control is, therefore, simple and economical [127]. Positional errors can occur if the motor misses a step for example through overloading. In these circumstances, if control is open loop then accuracy is lost and positional problems could arise [127]. The use of positional feedback not only eliminates this problem can improve system performance [128].

The positioning accuracy of a stepper motor can be enhanced by microstepping, [129, 130] which involves precise control of phase currents. Generally, stepper motors give high torque at low speed and are stable when stationary, although their maximum speed is limited. There may be a lower operating speed limit to avoid resonance occurring at the natural frequency of the motor/load system. The magnetic fields controlling the position of the motor act as a torsional spring. The problem of resonance is frequently exaggerated and there are several methods by which this problem can be eliminated [126,131]. As stepper motors have no brushes or commutators they are relatively maintenance free. Stepper motors may also be stalled at full current without damage.

Stepper motors have already been successfully used in the cutting of tableware [111, 112]. In this work resolutions of 0.1mm on linear axes and 0.01 degrees on rotational axes were achieved. Since this work demonstrated the suitability of stepper motors for glass processing applications and because such systems offer clear financial advantages when compared with servo-motors, an open loop micro-stepper motor actuation system was chosen for the brilliant cutting machine.

5.5.3 Wheel Power Source

To ensure consistent material removal rates it was necessary to select a motor that would rotate at a constant or near constant speed. This facility would enable feed rates, (ie distance moved per revolution of the wheel), to be controlled. In order to obtain this facility a "capacitor start induction run 240V single phase AC motor" was selected. Although lacking the horological accuracy of a true synchronous motor this type of motor is more readily available and of greater reliability. The motor selected weighed six kilograms and was 250mm long and 130mm in diameter. Both the size and the weight of the motor prevented it being positioned on the axis containing the actual grinding wheel, ie the axis that tilts the grinding wheel.

5.6 Concept Design

From examining the alternative concept designs it was found that the machine geometry which minimised the overall working area required was that of a

Cartesian machine which had three orthoganal linear axes and two rotational axes. This type of geometry also means that developing the required CAD/CAM control software is made conceptually easier since the workpiece is placed in the plane of two orthoganal linear axes.

The design concept adopted was, therefore, based on a commercial gantry style robot. This enabled a machine with a bed of approximately 2m x 1m, a size considered more appropriate for a commercial machine, to be developed. This concept uses the cartesian arrangement illustrated in Figure 35 and the arrangement of axes shown in Figure 36. A gantry moves along the major axis, ie the X-axis. A carriage then moves along the gantry, ie the Y-axis. A rotary axis, (R-axis), is mounted on the Y-axis carriage and a linear axis, (Z-axis), is mounted in the centre of the rotary axis such that a box section moves vertically with respect to the workpiece. Attached to the end of the box section is an additional rotary axis which tilts the wheel. The development of this tilt axis is described in detail in Section 5.7. Mechanical power is transmitted to the tilt axis via a flexible drive from the AC motor which is mounted on the Y-axis carriage. The weight of the motor is, therefore, supported by the major axes, ie the X and Y-axes. Hence, both the weight and cost of the machine can be considerably reduced.

In order to prevent coolant contaminating the electrical equipment, the X and Y-axes of the machine were mounted at a distance above the bed of the machine. Access to the bed of the machine, in order to load and unload work, was through the side of the machine, as illustrated by Figure 37. The machine was to be driven by an open loop stepper motor system for those advantages outlined in Section 5.5.2. The main advantages of this design concept are:

a. workpieces of realistic size are possible,

b. a significant portion of the detailed design was commercially available,

c. the compatibility of the electrical components was proven,

d. the structure is strong and rigid,

e. the resources required to produce the major components were reduced, and

f. a modular design allows for future modifications such as larger working axes.

A requirements specification was established, included as Appendix A, and three manufacturers requested to provide quotations. The system selected from the replies was the CAM Systems Ltd "V" plan system [132] which uses a rack and pinion drive system. Although this form of drive results in additional wiring and load, (ie the motor often has to move along the axis), the repeatability and rigidity of the system is acceptable. CAM Systems Ltd supplied the four axes, shown in Figure 38, a motor for the fifth axis, the SMCC controller and the stepper drives.

5.7 Grinding Head Assembly

The grinding head assembly is attached to the lower end of the vertical axis and its primary functions are to hold, tilt and transmit power to the grinding wheel.

5.7.1 Design Concepts

When designing the grinding head assembly it was necessary to minimise its weight and second moment of inertia. In this way the loads carried by all other axes would also be minimised. Using a flexible drive was considered essential since this would allow the weight of the motor to be removed from the tilt axis. Since the flexible drive restricts the rotation of the main rotary axis to approximately 220 degrees, the tilt axis must rotate in both directions about the vertical in order that any direction of cut may be possible.

The design characteristics of the grinding head assembly were identified as:

a. attachment to the vertical axis,

b. it must facilitate rotation about a horizontal axis which is perpendicular to the plane of the wheel axis and the vertical axis of rotation,

c. it must enable the wheel to be tilted +/- 15 degrees to the vertical as this range is approximately the maximum used in manual brilliant cutting,

d. rotary motion must be actuated by a means compatible with that used for the other four axes,

e. it must provide a mount for the grinding and polishing wheels,

f. it must enable a flexible drive to power the wheel,

g. it must provide a support for the ducting required to bring coolant to the wheel, and

h. it must safely enclose the wheel.

The design and position of the tilt axis in terms of its geometric relationship with other axes has a major influence on the CNC part programming software. Alternative concept designs were generated of which two were examined in closer detail, ie a wrist arrangement and an edge-pivotal arrangement as shown in Figure 39. These are now discussed below.

1. Wrist arrangement - here the tilt axis pivots about a point nominally further away from the glass than the diameter of the wheel. Tilting the wheel requires simultaneous motion of the tilt axis, the Z-axis and either or both of the X and Y-axes

2. Edge-pivotal arrangement - this design enables the wheel to be tilted about a point on its edge using only the tilt axis. The point at which the wheel pivots

is termed the Tool Centre Point (TCP) and is the mid-point of the width of the wheel at its lowest point. The wheel is mounted such that the centre line of the rotary axis also passes through the TCP and, therefore, actuation of either the Tilt or Rotary axes results in a true circular motion about the TCP. From a control point of view the machine dynamics are simplified both conceptually and practically as a typical cut requires only modest X and Y allowances for a given motion in the Tilt axis. In the case of tilted mitred cuts, no allowance is required.

A design, Figure 40, was developed that employed a curved rail to enable rotation to take place about a TCP that is below the surface of the workpiece. Because of the need to tilt the wheel +/- 15 degrees, the flexible drive could not be connected in line with the wheel. In order to prevent fouling of either the workpiece or robot, the flexible drive had to be aligned in a direction away from the vertical axis by a combined spindle and gearbox assembly. This allowed the flexible drive to enter at an angle of 45 degrees to the horizontal when the wheel was in the position illustrated in Figure 40.

The tilt axis stepper motor was mounted on a plate to counterbalance the weight of the spindle and gearbox assembly (SGA) and in addition to reduce the moment of inertia of the assembly. The function of the stepper motor is to drive a quadrant gear which is mounted on the rail. This arrangement provides mechanical advantage to the motor and hence, the size and weight of the motor can be reduced. Because of the advantages of simple geometry and low load this concept was chosen over the wrist concept.

The spindle and gearbox assembly unit is attached to the vertical axis of the robot by means of a two part bracket which is itself fixed to the curved rail. In order to ensure accurate alignment, the majority of components in this assembly are fixed by means of dowels and screws.

Around the rail are Hepco journals [133] which are arranged in pairs with a concentric journal opposing an eccentric journal as shown in Figure 41. The eccentric journals are adjusted to preload the assembly, therefore, rigidly constraining the mounting plate to rotate about the TCP.

Actuation is achieved using a stepper motor which drives the quadrant gear illustrated in Figure 42. Alignment of the quadrant PCD centre with the TCP axis is facilitated using an adjustable eccentric sleeve at one end and an adjustable thrust pad at the other. The stepper motor is mounted on a second mounting plate which is adjustable in a radial direction using radial feed screws and position locking screws. This arrangement ensures a controlled preload of the pinion with the quadrant, preventing backlash and excessive side load to the motor shaft. An alternative to this arrangement would have been an anti-backlash gear, however these are only available in sizes [134] that would have reduced resolution and increased load torque.

The gear ratio selected is 450 degrees of motor rotation to 30 degrees of axis rotation which results in only a few millimetres of motion at the actual cutting surface. A three stack motor was selected in order to match the characteristics of the motor with the inertia of the load.

The tilt axis motor, which is sited next to the grinding wheel, is fully enclosed within the sealed perspex box shown in Figure 43. An additional shaft seal secured in the motor mounting plate further protects it from coolant. A proximity sensor is also mounted in the box, aligned to a target attached to the motor shaft which protrudes from the back of the motor. The sensor is used by the robot controller to determine the home position. No adjustment of the target relative to the sensor is necessary since the controller possesses software offsets. A heat sink surrounds the motor and protects the temperature sensitive proximity sensor from heat build-up. This arrangement also allows the motor to be run permanently at full current, thereby increasing holding torque and rigidity.

5.7.2 Spindle and Gearbox Assembly

The functions of the spindle and gearbox assembly (SGA) are to:

a. provide a means of coupling the flexible drive to the grinding wheel, such that the flexible drive is not fouled or twisted,

b. provide a support for mounting the wheel, with minimal axial and radial play, onto the tilt axis mounting plate, and

c. allow adjustment of the grinding wheel when wear takes place.

The design concept required the stub shaft of the flexible drive, to mate with an input driveshaft which is itself aligned both perpendicular to the axis of the wheel and 45 degrees to the horizontal. In order to achieve this arrangement it was necessary to use gears to transmit the torque from the input shaft to the output shaft, ie the spindle on which the wheel is mounted. Bearings are required for both input and output shafts and need to sustain the reaction forces of both the cutting process and the gears. The gearbox is continuously rated at 375W and must be less then 75mm x 75mm x 65mm in size.

The wheel may be adjusted radially to the TCP so that the mid-point of the edge passes through this point as illustrated in Figure 41 panel C. By adjusting the wheel to the TCP, mechanical compensation for variation in wheel diameter is introduced. This is achieved by fixing the gearbox to a plate which is itself fitted to the mounting plate such that the SGA can travel up to three millimetres across the mounting plate.

A description of the development of the SGA is included as Appendix B.

5.8 Ancillary Systems

5.8.1 Machine Base and Structural Alignment

The supporting structure of the machine consists of two basic assemblies, ie:

a. a flat bed on which the workpiece is fixed, and

b. a frame which supports the five axes above the bed.

Several concept designs were generated and analysed and the concept design finally selected is shown in Figure 44. The design is essentially a box frame, the four sides of which are 50mm square box section. This section has also been welded together to form the beams that support the robot. The constraints of floor space and flexible drive resulted in the robot being mounted asymetrically as illustrated in Figure 45. However, the modular structure can be easily modified if desired. The bed is 12mm thick aluminium plate which is supported by box section cross beams, which are themselves supported by double section beams running the length of the bed. The bed is situated in a sheet metal tray that collects the coolant running from the bed. The coolant is pumped from the tray to a filtering system and then the filtered coolant is returned to the cutting wheel. All elements of the structure that are subject to corrosion attack have been protected.

When the machine was assembled the rectangular X-axis frame was levelled using the adjustable feet, shown in Figure 45, ie Panel A and Part 7 of Panel B. The angle between the X and Y-axes was adjusted using the mounting screws that secure the gantry to the X-axis carriages.

By using a dial gauge mounted at the end of the vertical Z-axis member and moving this axis back and forth in the X and Y directions, the variance in the position of the bed relative to the machine was measured. Adjusting screws, labelled as Part 5 in Panel B of Figure 45 and shown in detail in Panel C, then allowed accurate alignment of the ends of the bed support beams. The flatness of the bed is achieved by adjusting the screws securing the aluminium plate to the support beams and compressing the mastic on which the plate is bedded. After adjustment, the position of the bed was found to be parallel to the X-Y plane to within +/- 0.01mm.

Alignment of the Z-axis direction, which is also the axis of rotation of the R-axis, is determined by the construction of the rotary axis bearing and cannot be altered. The alignment was checked by mounting the dial gauge on a rod approximately 200mm from the Z-axis. When the vertical assembly was rotated a variance in dial gauge reading of within +/-0.01mm was observed.

Similarly the position and alignment of the axis of rotation of the tilt axis is determined by the mechanical construction of the grinding head assembly. The alignment of the axis of rotation must be within a horizontal plane parallel to the X-Y plane. Alignment was performed by tightening the bolts securing the Z-axis vertical member to the support bracket whilst holding the bracket square to the bed. However, this adjustment method can only be as accurate as the alignment of the bed itself.

The rotary axes, R and Tilt, are the only axes whose zero position is important as these zero directions must be aligned with cartesian axes. The zero or home positions are finely adjustable using the zero offset parameter within the SMCC controller software. This allows a resolution of less than 42 seconds of arc on the tilt axis and 0.01 degrees on the R-axis. The accuracy of alignment relies on the quality of the datum. The zero position of the tilt axis was set by offering a set square to the spindle face of the gearbox, which is approximately 70mm high. The rotary axis may be checked by setting the axis to zero, placing a dial gauge in contact with the face of the grinding head support bracket and moving the gantry in the X-axis only.

5.8.2 Coolant System

The coolant system, illustrated in Figure 46, uses a powered pump and may use either recycled or fresh water from the mains. Used coolant drains from the bed and is filtered into a small holding tank from which it is pumped to the drain U-bend, or to the grinding head. A flexible pipe conveys the coolant to a nozzle mounted on the wheel guard. The nozzle is formed to produce a flat, high speed jet which hits the wheel at the point of grinding such that coolant is readily carried beneath the wheel. The excess coolant has the effect of sweeping glass chippings away from the work area.

5.8.3 Workpiece Mounting

The workpiece is restrained by means of strips of metal bolted to tapped holes in the bed of the machine as shown in Figure 43. The strips are slotted and a selection made in various lengths such that workpieces of any size could be positioned anywhere on the bed, within the physical limits of the machine. In order to position the workpiece accurately it is necessary to place a grinding wheel such that its side face is at the edge of the workpiece and to butt a slotted strip up to the wheel before clamping tight. In order to ensure correct alignment, two strips must be placed, in the above manner, on one side of the workpiece and a third on another, non-opposite side. Strips on the remaining sides can be slackened to enable the workpiece to be fitted and removed. No means of preventing the workpiece from rising vertically is required.

5.8.4 Safety System

Operator safety was a major criterion when designing the machine since the robot is capable of high speed and acceleration which could cause severe personal injury in the event of an accident. The machine was, therefore, guarded using perspex screens, Figure 47, which allowed an unobstructed view of the cutting area. These guards are electrically interlocked with the robot, the grinding motor and the coolant pump as shown in Figure 48, such that when the guards are opened or an emergency stop button is pressed, the power to the machine is turned off. The low voltage sensors and safety circuit remain electrically live and emergency stop buttons are situated on the control panel and at the two most exposed corners of the machine. The ammeters, control buttons and no volt release switches, [135], controlling the pump and AC spindle motor are mounted in the control cabinet as shown in Figure 49. Additional guarding below the robot also prevents coolant splashing out of the machine.

5.8.5 Flexible Drive Transmission

A standard flexible drive of a type intended for general engineering applications was selected. This unit is low cost, readily available and of the required length. Initially however, component life was unacceptable since continuous use caused heat build up due to friction, hence softening the outer sheath allowing excessive flexing of the drive core.

Experimental development resulted in the flexible drive being modified which increased its useful life. Essentially a series of modifications helped control friction by limiting the degree of curvature, these modifications were:

a. use of a padded support sleeve bracket to reduce forces on the bearing at the driven end of the drive and to dampen any vibration,

b. use of the strain relieving spring, shown in Figure 43, to produce a smooth curve in the drive as it terminates at the gearbox, and

c. wrapping the drive in layers of insulating tape to stiffen the sheath of the flexible drive shown in Figures 42 and 43.

Chapter 6

Development of the CAM System

Contents

6.0 Introduction

This chapter describes the development of the software that converts CAD drawing files to CNC instruction code for the 5-axis brilliant cutting machine.

Initially a suitable CNC controller was chosen. It is the programming language and functions available with this controller which together with the geometry of the machine tool, (Chapter 5), define the required output of the CAM system.

The CAM system is then developed and consists of individual feature based modules for each type of cut. Each of these individual modules is described in terms of its DXF input, mathematical basis, and programme structure. Programme listings are included in Appendix C.

Developing the CAM brilliant cutting system involved the integrating of machine, tooling and control system. In addition developing the software entailed both the design and encryption of code and also the experimental development of toolpaths and feedrates for the grinding and polishing processes.

6.1 The CNC Controller

6.1.1 CNC Controller Selection

The controller interprets instruction code and produces an output that controls the actuators. Some form of drive or servo-valve is usually required to provide power according to this output. CNC controllers are complex and expensive electronic systems and should, therefore, where possible be purchased in standard form.

The control requirements for brilliant cutting are:

a) independent 5-axis motion,

b) linear interpolation, ie point to point,

c) continuous path motion, and

d) constant velocity control for controlled cutting feeds.

For each of the above control requirements the method by which the function is carried out is not considered a selection criteria. The criteria used to identify a suitable machine controller were:

a) that it satisfy the control requirements,

b) economic price, and

c) compatibility with other system components, such as stepper motors.

The Smart Motion Control Card, (SMCC), marketed by Baldor [136] was selected as being suitable. This system required three controller cards, (ie each SMCC card controls two machine axes), connected by daisy chain to a host computer which acts as the control terminal. This form of construction produces a system that is competitive in terms of cost when compared with other commercially available controllers.

6.1.2 Programming Motion

In common with most CNC controllers the SMCC uses a high level language that offers a large number of path generation functions. In order to rationalise the structure of the CAD/CAM system only two forms of motion are used:

1. Linear Interpolation - This allows straight line motion from a current position to a specified position in a specified time. For curved lines proportional interpolated movement of rotary axes is used.

2. Continuous curves - Continuous curves are specified by a number of points along the length of the curve. The actual path travelled by the grinding wheel, however, does not follow a curve through these points. Instead the curved interpolation function of the SMCC controller moves the grinding wheel through a series of arcs, beginning and ending at the centre point of a line drawn between each point, ie circular interpolation [17]. This effect is illustrated in Figure 50 which is plotted using a pen fixed to the Tilt-axis

support bracket. The spiral path shown in Figure 51 has points approximately 20mm apart. The smooth path is the continuous curve programmed as a series of points. The straight lines are generated by discrete moves between the same data points. The smooth line can be seen to touch the mid-points of the straight lines. The end points of the straight lines are the data points, hence the generated curve is seen to fall inside the programmed path. The plot for an inter-point distance of 3mm is shown in Figure 52. In this case linear interpolated data points are only discernible from the smooth generated curve when the radius of curvature falls within 25mm.

The error in position can be calculated according to the procedure listed in Figure 53. By having the points close together, (ie. 3mm), when compared with the radius of curvature, (which can be a minimum of 37mm with the wheel diameter selected), the positional error is calculated to be about 0.03mm. With regard to the scale of the brilliant cutting process, in which cuts are typically 12mm wide, this error is satisfactory.

6.2 SMCC Instruction Codes

The subset of the SMCC instruction language and syntax adopted for brilliant cutting employs the following rules:

1. The three controller cards within the SMCC have the addresses A0, A1 and A2. When a command is to be received by all three cards the SMCC controller requires the address AA.

2. Each block of instruction code must be headed with the phrase "AAz 800" in order to clear the controller card memory for the subsequent code. The value 800 represents the number of lines of memory cleared, ie it was found that the maximum size of programme that could reliably be stored in the SMCC memory was 800 lines in length. Programmes longer than this length had to be divided into separate programme units.

3. Before positional data is specified for wheel axis movements both the move and acceleration times have to be specified. The move time parameter is expressed as "T", followed by the time for the move in binary milliseconds. For example "T1024" represents a move time of 1024 binary milliseconds which is equivalent to 1 second. The acceleration time uses a lower case "t" and the value for this time is also specified in binary milliseconds. Once set, the move time T and acceleration time t parameters, refer to all subsequent moves until new values are set.

4. Continuous paths and curves use the acceleration parameter to control the rate of change of velocity of the machine. This has the effect of smoothing the changes in feed rate due to variation in the arc distance between control points.

Due to the effect of machine compliance, cut width is sensitive to changes in feed rate. Therefore, to ensure a smooth cut the acceleration parameter should be set to be equal to the move time.

5. Linear moves are specified solely as the destination for each individual move which is expressed as the co-ordinates of each axis. For example:

A0 X100.00 Y 200.00 A1 X100.00 Y180.00 A2 X-13.00

represents the point 100mm along the longer horizontal X-axis and 200mm along the shorter horizontal Y-axis. The second X parameter is the distance that the wheel must travel vertically towards the workpiece, ie the Z-axis. The second Y parameter is the rotation of the grinding wheel about the normal to the glass, (R-axis), and the third X parameter is the tilt T-axis for rotation about a horizontal axis in the plane of the wheel rim.

6. All positions are specified to a maximum of two decimal places which the resolution of the control system and provides acceptable positioning accuracy.

7. The actual path followed by the grinding wheel will not pass through or stop at a specified point unless a forced stop or dwell command is used. This is

expressed as "DWE" followed by the period of the stop. For example "DWE100" represents a dwell of 100 binary milliseconds. This dwell time has been found to be sufficient to allow each SMCC control card to complete its internal servo loop. This function, therefore, ensures a synchronised start to the next move.

8. Curved moves are designated by the command STA which is sent to all cards. Such moves are specified by a series of control points along the length of the curved path. A dwell command must be inserted to take effect after the last point on the curve has been reached. This ensures that the next move is not executed whilst the wheel is still within the workpiece.

9. Having executed a programme the grinding wheel must be moved to its home position using the HOM command This executes a fast traverse and is necessary in order to re-calibrate the open loop control system. The programme unit is then terminated with the command "END".

6.3 The Programming Language

The GW Basic programming language was chosen to write the CAM software for the following reasons:

a. random access data files are supported,

b. the mathematical and trigonometric functions required to calculate the geometry of brilliant cut objects are supported,

c. matrix algebra as required in polar robot applications, [100], are not required since the simple cartesian structure of the machine developed does not require such elaboration,

d. the relatively slow processing speeds of the interpreted GW Basic compared with compiled languages does not present problems since the language is only being used to convert CAD data into a machine control program "off-line" , and

e. the level of accuracy provided, in terms of the number of significant digits supported, is more then adequate for the brilliant cutting process which requires only five significant digits.

6.4 Integrating CAD with CAM

For each of the brilliant cut features described in Section 2.2 a discrete software module was developed. The application of each module is tabulated in Figure 30. All cuts of the same type are grouped into a data file which is then translated to the DXF format in order to provide the input for the respective part programming module. The CAD/CAM method is feature based, [137], that is each feature is defined by a limited number of specified drawing entities. Each part programming module is described in Section 6.5. These modules demonstrate the following features:

1. ability to process a large number of cuts,

2. ability to output to a series of files,

3. ability to process input data that describes cuts drawn in any direction,

4. ability to change the direction of cut at the limits of the machine, eg. to cut spirals,

5. ability to smoothly merge two cuts into a single cut,

6. the use of wheel geometry and glass thickness as parameters in calculating the tool path,

7. sorting of drawing entities according to type into random access memory using the drawing layer as an identifier,

8. the use of a look up table to index curves containing the entity end points as identifiers, and

9. for multi-entity defined cuts the ability to match random order data to retrieve the data for an individual cut.

Cuts may then be saved according to type by allocating each type of cut to a particular drawing layer as shown in Figure 30. This is facilitated using the colour identification and sorting facilities of DesignCAD 2D. This CAD system has the ability to label each colour using a number and can, therefore, identify all drawing entities of a specific colour. These drawing entities can then be sorted and saved on specific drawing layers.

Brilliant cut designs must always be drawn to scale using the CAD functions of DesignCAD 2D. Hence a distance on the design must represent the same distance on a workpiece. The DesignCAD 2D "UNITS" command also enables designs to be rescaled to a desired size. Positioning the design on the workpiece is carried out by drawing an outline of a reference workpiece and placing the design on to this outline. The bottom left hand corner of the workpiece is then defined as the (0,0) point using the ORIGIN command. The horizontal direction on the screen is set to correspond to the X-axis of the machine and the vertical direction corresponds to the Y- axis.

The workpiece must normally be clamped to the bed of the machine at a position other than the home position for the machine. Hence, when the machine returns to its home position after completing a programme, the grinding wheel does not obstruct the loading or unloading of workpieces. When the design is processed, therefore, an offset is automatically added to the positions of the X and Y axes which corresponds to the position of the glass.

As stated the CAD design consists of drawing entities held in a file according to the DXF format. This format is a serial ASCII file and all relevant data is held in a section of the file labelled with the characters "ENTITIES" and terminated with the characters "ENDSEC". Each entity record is separated by a field containing the character 0 and each field is separated by a space character. The next three fields contain an identifier for the type of entity, an unspecified system code and the drawing layer the entity is stored on. There then follows a series of data co-ordinates and identifiers that define the entity according to its type.

6.5 Software Development

The following sections describe how the DesignCad 2D drawing data is represented in the DXF file and the methods used to convert each type of brilliant cut object to CNC part programmes. Illustrations of the features produced show how each technique has been applied.

6.5.1 Mitred and Oval Punts

Both mitred and oval punts are defined by centrelines as described in Section 2.1.2. Hence the software programmes required to process them are identical in terms of positional information. Differences only exist in the data parameters used to control cutting and wheel geometry.

The centrelines for both types of cut are defined within the DXF file by a record of the type shown below, ie:

0 LINE 8 LAYER1 10 X_1 20 Y_1 11 X_2 21 Y_2

This represents a line, on drawing layer one, from position X_1Y_1 to position X_2Y_2. A line on layer 1 denotes a mitred punt and consequently the file will also contain records describing two arcs for each centreline. These arcs are ignored by the part programming software since they are used only to illustrate the shape of the finished punt. Oval punts are stored on layer 7 and contain ellipses to represent the finished shapes of the brilliant cut object.

The flow chart shown in Figure 54 represents the structure of the software programme. The position of the grinding wheel Tool Centre Point (TCP) in the X and Y axes is calculated using the mid-point of the centreline shown in Figure 55. The R-axis position is calculated using the direction of the centreline which points from position 1 to position 2. Although the R-axis is limited to a maximum rotation of 180 degrees, the centreline of a CAD drawing may point in any direction throughout 360 degrees. In cases where the centreline does not correlate directly to a feasible R-axis position, the positions are exchanged such that the cut then points in the opposite direction, which will be an acceptable R-axis position. Overcoming the geometric limits of the machine through the transposition of data points in this manner is possible since the geometries of brilliant cut objects are independent of the direction of cutting.

The depth of cut, which is the distance moved by the Z-axis beyond the surface of the glass, is calculated using the wheel radius and the length H of the centreline as illustrated in Figure 56. This length represents the chord of the grinding wheel required to cut a punt of that length.

It is necessary to control the plunge rate such that as the wheel moves further into the surface of the glass, a constant volume of material is always removed per unit of time. Depth of cut, d at successive positions d_t seconds apart is given by:

$$d_{t+dt}^3 = d_t^3 + V \qquad (4)$$

Where:

d_t = depth at time t,

d_{t+dt} = depth at time t + dt, and

V = an empirical constant

The above equation ensures that plunge rate is reduced as depth of cut increases and hence has the effect of reducing cutting loads as depth of cutting increases. When feed rates have not been reduced the increased load has been shown to stall the machine. In addition, to avoid dulling the wheel, the control programme must ensure that diamond grains always cut under appreciable pressure. This is achieved by programming the wheel to move away from the workpiece surface by 0.02mm once it achieves the full depth of cut. Hence cutting forces are not allowed to gradually diminish whilst the wheel is touching the work surface.

From the results of actual cuts the following values for V where found to yield satisfactory cutting conditions, ie:

1. Mitred cuts: V = 1 for dt = 1,

2. Oval punts: V = 0.4 for dt = 1, and

3. Round punts: V = 5 for dt = 10, see section 6.4.2, below.

Figure 57, which is approximately full size, illustrates the type of product that can be achieved using this method. Figure 58, in contrast uses shallow cuts, which because of the geometry of the wheel, are slender in proportion. Figure 59 illustrates the variation in size of oval punts that it is possible to cut.

6.5.2 Round Punts

Round punts are defined using a circle and are represented in the DXF file by a record of the form shown below, ie:

0 CIRCLE 8 LAYER6 10 ***X*** 20 ***Y*** 40 ***R***

Here the centre of the circle is at the ***X,Y*** position and the radius of the circle is ***R***. The depth of round punts are calculated in an identical manner to that of mitred and oval punts. However, round punts require the rotary axis of the grinding wheel to perform an oscillating, corkscrew motion in order to generate the circle.

The part programming routine for round punts was developed from that of the mitred punt routine, (Section 6.5.1). It was found necessary to use an array to store DXF data in order to improve processing time by reducing file access delays.

The rotating grinding action used to produce round punts produces a fine surface finish which is easier to polish than other brilliant cut features. Figure 60 shows the lens effect of this type of cut.

6.5.3 Panel Cuts

Panel cuts are defined by straight lines of the same format as mitred punt centrelines. The programme shown in Appendix C is capable of performing orthoganal cuts in which the motion of the cutting wheel is a simple plunge, traverse and retract.

6.5.4 Curved Linework

Linework is the technique of producing narrow cuts of curved shape where the wheel is not tilted and cutting depth is held constant. This programme can also be used to generate part programmes for cuts of differing depths which use either round or mitred wheels.

These types of cuts are described by entities generated by the DesignCAD functions CURVE. Curves can be in any direction and of any length. In addition a number of individual curves can be joined into a single curve using the JOIN command. Arcs and circles may be drawn by using the DesignCAD commands ARC-V and CIRCLE-V which generate data similar to that produced by CURVE. When the ends of a cut meet to form a closed loop the part programming software ensures that these ends are joined smoothly such that no joint mark is visible.

Figure 61 illustrates a design produced by the above functions which contains several curved features some of which have been built-up from separate curved features. A more traditional design, also featuring punts, is shown in Figure 62. Figure 63 illustrates the effect of polishing round punts and highlighting them against matt cuts.

It can be seen in Figure 63 that the relative widths of each flank changes along the length of each mitred cut. This 5-axis motion is generated by a parametised mathematical function:

$$t_i = t_o + ((i/L) . T) \qquad (5)$$

Where:

t_i = tilt at distance i along cut ,

L = length of cut in the X-Y plane,

t_o = start angle and

T = angle of tilt motion.

The above equation can be used to cut shapes that are either difficult to draw using the CAD system or for producing particular effects. For example the design shown in Figure 64 has been produced using this module.

The DXF output is in the form of a polyline consisting of a large number of co-ordinate points on the curve. The distances between successive points varies according to the radius of curvature of the curved line. For typical brilliant cut curves this separation varies between 0.25mm and 1.5 mm. Also included in the list of co-ordinate points are the original points used by the designer to define the curve. These points may be separated from CAD-calculated points by as little as 0.0001mm and may also be separated in one dimension only. When the direction of the curve is calculated the inclusion of such points can cause errors of the order of 45 degrees in direction to be produced. These discontinuities are avoided by calculating the direction at a given point from the position of the previous and following points

The software module selects points from the curve that are approximately an equal distance apart. By using data from the CAD file the positional accuracy of the cut is retained. However the result is data of slightly variable separation, which results in slight variations in feed rates.

The effect of discontinuous data on cut quality was investigated by generating a number of separate cuts with each cut being a simple "feed in - traverse - feed out" cutting cycle. The path traversed by the grinding wheel was through a series of points that are equidistant except for two points which were set closer together than the others. This had the effect of generating a variation in the feed rate. The traverse speed and acceleration parameters were varied for each cut. It was found that variation in feed rate had a noticeable visual effect, ie the width of cut at the glitch was increased by up to 0.3 mm on a 3mm wide cut.

This variation may be attributed to the compliance of the machine under different reaction forces due to variation in feed rate.

It was observed from this work that the feed rate needed to be progressively changed over this distance such that any change in width was sufficiently gradual as to be undiscernable by eye. This was achieved by:

1. increasing the pitch between points, ie the greater the number of DXF points between those selected, the smaller the variance in pitch between the selected points and the smaller the variance in feed rate, and

2. by specifying a long acceleration time parameter such that the variation in feed rate occurs over a longer distance, hence Rule 4, Section 6.1.3.

The part programming process is illustrated in the flowcharts shown in Figures 65 and 66. The basic steps involved in this process are as follows:

1. The DXF data for the curve is loaded into computer memory.

2. The programme then calculates the separation of the data points.

3. The distance chosen between output points is either input or a default distance is selected by the software. This distance may be varied in order to suit curves of unusually large or small radii. If the step length is greater than five data points apart then the maximum variation in feed rates between steps is no more then 20%.

4. The programme selects points from the data which are no more than the chosen distance apart.

5. A nominal R-axis position is calculated that corresponds to the true direction of these points. This is the R-axis position that will be used if up-cut grinding is employed.

6. The mode of grinding is determined, ie if either up-cut or down-cut grinding is used.

7. If the direction of cut requires the down-cut mode of grinding then the appropriate R-axis position is stored in a parallel array to the nominal position.

The R-axis position for down-cut mode grinding is the opposite direction to that used for up-cut grinding.

8. If the wheel needs to be tilted then the angle of tilt is calculated.

9. If the toolpath is of such a length that the SMCC instruction code will not fit onto the file already open then a new instruction code file is generated.

10. The instruction code is calculated and written to a data file. This is performed by examining the points in sequence and selecting appropriate R-axis positions. If necessary, changes in the mode of grinding are carried out at this stage.

This module uses both upcut grinding and downcut grinding. Upcut grinding is used for R-axis positions that lie between -5 and 185 degrees. When the toolpath passes beyond this limit the wheel is raised, rotated 180 degrees and the cut continued using down-cut grinding. Down-cut grinding is used for R-axis positions between 175 and 365 degrees. A 10 degree hysteresis has been provided in order to prevent excessive numbers of direction changes when programming curves, such as vine motifs, which repeatedly cross the horizontal. The criteria for a direction change are that either the point under consideration is outside the hysteresis band or due to a tight radius of curvature, the following point is outside the actual limits of the machine.

Changes in the mode of grinding are made over a distance of two point separations according to Figure 67 which shows the positions specified in the

SMCC instruction code as round symbols, and the actual toolpath as a line. There are three consecutive data points A, B, C and the change in mode of grinding takes place at point B. The commands sent to the controller are:

Continuous path through:
Point A at normal cutting depth,
Point B at normal cutting depth,
Point C1 at 0.25mm above C
Point C2 at 5mm above the glass
Pause then fast traverse and rotate to A2
Continuous path through A3, B and C

Figure 67 illustrates how the motion caused by the CNC controller actually misses the control points. The result of this error is that when the wheel is at point B it is not at its required cutting depth. However, this problem is satisfactorily overcome by programming the wheel to return along the same path and on this second pass the deflection of the machine structure is reduced, hence enabling additional material to be removed. The actual depth of cut at B is controlled by the relative height of C1 and A3 and it has been found that a depth of 0.25mm is suitable for a 2mm to 3mm wide "V" shaped cut. The result is a variation in width that is imperceptible to normal view, but influenced by errors in the positioning of the apex of the "V" of the grinding wheel which may be introduced through dressing. In addition, when for example brilliant cutting ellipses, the 10 degree hysteresis provided has the effect of moving the change over point away from the horizontal extremes. The change over point is then cut on the flanks of a feature rather than on its apex. This has the effect of hiding the join by placing it in a less obvious position.

Smooth joins may be obtained when either a curve forms a loop or the function CIRCLE-V is used since the ends of the curve are automatically considered as point B, the second point as C and the second to last point as A.

6.5.5 Symmetrical and Asymmetrical Edge Cut Segments

These types of brilliant cut objects are defined using a curve that can be constructed using the ARCV function to generate a symmetrical segment and the CURVE function to generate an asymmetrical segment. A straight line may also be drawn between the ends of such curves in order to allow the designer to visualise the cut shape.

Although segment cuts may be constructed in any orientation, in order to simplify the logic of the part programme software curves must be drawn on the CAD system according to Figure 68, that is with increasing Y co-ordinates.

Segments are described within the DXF file by data of the format:

Line 1: 0 POLYLINE 8 LAYER11 62 1 6 CONTINUOUS

Line 2: 0 VERTEX 8 LAYER11 62 1 6 CONTINUOUS 10 ***XA*** 20 ***YA***

Line 3: 0 VERTEX 8 LAYER11 62 1 6 CONTINUOUS 10 ***XB*** 20 ***YB***

Line 4: 0 SEQEND 8 LAYER11

Line 5: 0 POLYLINE 8 LAYER11 62 1 6 CONTINUOUS

Line 6: 0 VERTEX 8 LAYER11 62 1 6 CONTINUOUS 10 ***XA*** 20 ***YA***

Line 7: 0 VERTEX 8 LAYER11 62 1 6 CONTINUOUS 10 ***X2*** 20 ***Y2***

Line 8: 0 VERTEX 8 LAYER11 62 1 6 CONTINUOUS 10 ***X(N-1)*** 20 ***Y(N-1)***

Line 9: 0 VERTEX 8 LAYER11 62 1 6 CONTINUOUS 10 ***XB*** 20 ***YB***

Line 10: 0 SEQEND 8 LAYER11

Lines 1 to 4 describes a line from ***A*** to ***B*** and the remaining lines a curve from ***A*** to ***B*** which lies on points ***2*** to ***N-1***. The quantity and distribution of the data obeys the same rules as described in Section 6.1.2.

The data stored within the DXF file is processed to generate a CNC part programme according to the flowchart shown in Figure 69. All positional data for the curves contained within a design are initially loaded into a data array. An address list which contains the position of the cut data in the first data array is then stored in a second data array. With reference to Figure 70 each individual curve is then processed as follows:

1. Select Equidistant Points

Points are determined at equal intervals along the straight line L1 between the two ends of the curved line L2.

2. Interpolate Corresponding Point on Curve

For each of these calculated points, both the normal to L1 is calculated, (ie L3), and the point of intersection (ie P_{IX}, P_{IY}) of L3 with the curved line L2. The distance between A' and P_{IX}, P_{IY} represents the cross section of the cut and from this a wheel position may be calculated as described below.

The point P_{IX}, P_{IY} is calculated as the intersection between line L3 at the selected point and the line between the two consecutive points, (ie x_1y_1 and x_2y_2) of the curve which lie either side of (P_{IX}, P_{IY}). The points x_1y_1 and x_2y_2 are deduced by substituting their co-ordinates into the equation of the normal which is of the form "y = mx + c". The line between the points is referred to as an elemental line and if the co-ordinates of the two points are x_1,y_1 and x_2,y_2, the equation for this elemental line, of gradient m_e and intercept c_e, is :

$$Y = (m_e . X) + c_e \tag{6}$$

Where:

$$m_e = (y_2 - y_1) / (x_2 - x_1)$$

$$c_e = y_2 - (m_e . x_2)$$

And the equation for the normal is:

$$Y = (m_n . X) + c_n \qquad (7)$$

The co-ordinates of the point of intersection, P_{IX} and P_{IY}, are then as follows:

$$P_{IX} = (c_n - c_e) / (m_e - m_n) \qquad (8)$$

$$P_{IY} = (m_e . P_{IX}) + c_n \qquad (9)$$

3. Calculate the Cross Section of the Cut

Edge cuts are normally of constant depth and variable cutting angle in order to produce a uniform depth, ie a standard depth of 0.5mm has been found to be acceptable. In order to prevent the path of the grinding wheel from overshooting the desired cut, the depth along the cut is trapezoidal, ie at the ends of the cut, the wheel is ramped in then out of the work surface. At each selected point, should the narrowness of the cut width cause the angle of tilt to exceed the maximum control limits, the depth of cut is progressively reduced.

Hence, the corresponding angle is within the tilt control limits and overshoot does not occur.

The geometry of the cut section is initially determined by considering the cut section A'BC as shown in Figure 71, in which with reference to Figure 70, A' is the point on L1, C the intercept point P_{IX},P_{IY} on L2 and B the deepest point of the cut.

If d_{ix} is the distance between A' and C in the X direction and d_{iy} is the distance between A' and C in the Y direction, A'C is calculated as such:

$$A'C = (d_{ix}^2 + d_{iy}^2)^{0.5} \tag{10}$$

The distance a, which is normally 0.5mm, measured along A'B is derived from a trapezoidal depth function. Since, angle A'BC is a right angle, BC may be calculated as such:

$$BC = (a^2 + A'C^2)^{0.5} \tag{11}$$

Hence:

$$T = \tan^{-1} (a / BC) \tag{12}$$

If T is greater than 15^o then T is fixed at 15^o and a is recalculated as such:

$$a = A'C \sin(T) \quad (13)$$

4. Calculate the X and Y Axis Positions of the TCP

With reference to Figure 72, the position of the TCP is point E. If the width of the wheel is *w*, point E is at a distance *w*/2 from B measured along BC, hence:

$$A'E = a.\sin(T) + ((w / 2).\cos(T)) \quad (14)$$

The cartesian co-ordinates of E in the X-Y plane may be calculated by similar triangles as such:

$$E_x = A'_x + ((d_{ix} / A'C) . A'E) \quad (15)$$

$$E_y = A'_y + ((d_{iy} / AC) . A'E) \quad (16)$$

Where: E_x, E_y = X and Y co-ordinates of E respectively.

5. Calculate Z-axis Position

The distance of the TCP from the surface of the glass at point E equals *d*, where:

$$d = (BC - (w / 2)) . \sin(T) \quad (17)$$

6. Determine R-axis Orientation

The R-axis direction is calculated from the end points of line L1 in Figure 70. If x is the distance in the X direction between the end points and y the distance in the Y direction then:

$$\text{for } x > 0 \qquad R = \tan^{-1}(x/y) + 90^{\circ} \qquad (18)$$

$$\text{for } x < 0 \qquad R = \tan^{-1}(y/-x) \qquad (19)$$

7. Convert Geometry to CNC Paths

The direction of rotation of the T-axis can then be determined from the normal vector, ie dix, diy. Having calculated the five axis co-ordinates for each point, offsets are added for the position of the glass in the X, Y and Z directions and the information inserted into a CNC programme as described in Section 6.2. The cut begins and ends with the wheel either exactly touching or just above the extreme points of the curve.

The procedure described above was tested using the data listed in Figure 73. It can be seen that an accurate representation of the actual CAD drawing has been achieved.

6.5.6 Circular and Arc Edge Cuts

Edge cutting in a curved path requires that the side face of the wheel is perpendicular to the radius of curvature of the inner edge of the cut. This has the effect of sweeping the wheel such that only the edge of the wheel grinds the glass as illustrated in Figure 74.

The five axes tool path for circular and arc edge cuts is generated theoretically from the polar parameters of a specified circular cut. Arcs are generated by superimposing a depth varying function on a curved path. Cuts produced by this software are illustrated in Figure 75. The data specified consists of the inner and outer radius of the circular cut, the nominal depth of cut, and the co-ordinates of the centre of the cut. The toolpath is calculated in the following manner:

1. Calculate Cut Geometry

The method adopted assumes that the wheel can be considered as a thick disk and the surface of the glass as a horizontal plane. The plane intersects only two faces of the wheel to form the wheel imprint shown in Figure 74. Points A', D, D', E and C lie in the plane. Point B is the position at which the maximum depth of cut occurs and is the deepest point of the wheel. The rotary axis, along which the TCP lies, passes through point E which itself may be either side of C on the extended line A'C.

Assuming a continuous cut through an arc, the generated cut will have:

a) an inner edge of radius r_1 through D,

b) a deepest point at radius r_2, and

c) an outer edge of radius r_3 that passes through the parabola DCD' at the point furthest from O. It must be assumed that the radius is such that this point is approximate to C. It is possible that a small error might result in cases where the curvature of the cut relative to the width of the cut causes this furthest position to diverge from O.

For the wheel to pass through the glass such that only the surface DBC is cut, the chord DD' must either be tangential to the inner edge that is located at radius r_1 or at an obtuse angle. The software developed assumes the simplest case in which angle DDO=90^o.

Consider a section in the perpendicular plane through A, B and C, as shown in Figure 76. B' is defined as a point vertically above B in the horizontal plane. The distance A'B will be assumed to be set at a value ***a***. In practice the value of a is set at a nominal 0.5mm. Note that ***a*** is not the true depth of the cut in the Z direction, which is B'B, nor is it the length of the slope AB but a distance measured along the face of the wheel.

Considering the sideface of the wheel, shown in Figure 77, it may be seen that:

$$A'D = \quad (r_w{}^2 \ - \ (r_w - a)^{\,2}\,)^{0.5} \qquad (20)$$

where:

r_w is the radius of the wheel.

With respect to the horizontal plane in Figure 78.

$$R_3 = \quad r_3{}^2 \ - \ A'D^2 \qquad (21)$$

$$A'C = \quad (\,R_3 \ - \ r_1)^{0.5} \qquad (22)$$

These equations define the position of two points of the triangle Figure 76. It is known that A'B = a and that angle A'BC = 90^o, hence:

$$T \ = \ \sin^{-1}\,(a/(R_3 - r_1)) \qquad (23)$$

where: T = angle of the Tilt axis

$$BC \ = \ (R_3 - r_1)^2 - A^2 \qquad (24)$$

2. Calculate wheel position from cut geometry

Defining d as the distance of the TCP below the surface of the glass and w as the width of the wheel, Figure 72 holds true. Hence, the depth d corresponding to cut parameters is given by:

$$d \ = (BC - (w/2))\,\sin T \qquad (25)$$

Where an arc cut is required a depth varying function may be superimposed, ie:

$$Z_i = Z_o + d(\sin(i \,.\, 180^o / (i_2 - i_1))) \qquad (26)$$

Where: Z_i = Z-axis position at angle i^o

Z_o = Z-axis position at surface of glass

This type of function provides a smooth curve as illustrated in Figure 75.

$$EC = (BC - (w/2)) \cos T \qquad (27)$$

As $0 < T < 15^o$, cos T is always >0.

Therefore, EC is negative if BC < w/2.

With respect to the horizontal plane in Figure 79:

$$R_E = R_3 + EC \qquad (28)$$

$$r_E = R_E^2 + A'D^2 \qquad (29)$$

Where :

r_E is the radius of point E, the TCP.

3. Calculate toolpath

A parametric toolpath of radius r_E is calculated by calculating that angle that corresponds to a specified step size, and calculating a series of X, Y, Z and R positions using trigonometry.

6.5.7 Symmetrical and Asymmetrical Crescent Edge Cuts

An individual crescent edge cut, whether symmetrical or asymmetrical, is defined using two curves. Each of these curves may be derived using either the ARCV or CURVE drawing functions. In order to identify each pair of curves that belong to a specific cut they must have common start and end points. Consequently, because the module can process many cuts at once, no two cuts can share both start and end points.

It is also necessary to differentiate between which curve represents the stepped edge of the cut that is nearest to the centre of curvature and which curve represents the other edge. In order to achieve this the curve corresponding to the stepped edge is designated the primary curve and placed on drawing level 13 and the other curve is designated the secondary curve and placed on level 14, ie as specified in Figure 30, Panel II. Curves must be drawn using the CAD system with ascending Y co-ordinates according to Figure 80.

During the design stage of the brilliant cutting process, drawing entities are continually being created, deleted or modified. When the data is output as a DXF file the entities are listed in the order that the data was created or modified. A pair of curves that represent a single cut may, therefore, be some distance apart in the file. In order to rematch pairs of curves, all curve data points are loaded into memory and an address array is used to store the location of the end points. Then for each primary curve a corresponding secondary curve is found and its number stored in the address array.

A flowchart illustrating the steps involved in calculating the toolpath is shown in Figure 81. The initial task is to identify step points along the primary curve which are approximately a chosen distance apart using the method described in Section 6.1.2.

The gradient of the primary curve is determined for each selected point by calculating the slope between the DXF data points immediately prior to and after the selected point. This slope is used as the gradient of the tangent at the selected point, D as shown in Figure 82. The nominal depth of cut, ***a***, is determined by the same technique as for edge cut segments described in Section 6.5.5. From this nominal depth, position A' is calculated as shown in Figure 70. The perpendicular from A' intersects with the secondary curve at C, which is calculated as described in Section 6.5.5. The positions A', D, C and depth a describe the wheel imprint as described previously in Figures 74 and 76. As with segments, the nominal depth of cut will be reduced if the angle of tilt is beyond the limit available and positions A' and C would be recalculated.

The wheel position data is then calculated as described in Section 6.5.6 for circular edge cuts except that R-axis and T-axis directions must be calculated for each point respectively. The data is then output in the form of SMCC code and the process repeated for the next cut.

Cuts produced by this module, such as Figure 83, require all 5 axes of continuous motion and are shallow with delicate ends that are at the limit of the cutting ability of the machine tool. The toolpaths for these curves use computer generated curves obtained from two curves of a 2-D CAD drawing, a nominal depth parameter and tool and workpiece offsets.

6.5.8 Mitre cuts of variable depth and tilt

Mitred cuts of variable depth and tilt are defined by three curves. This module is derived from the crescent module, (Section 6.5.7), and operates in the same manner. The three curves must be drawn between the same end points and no two curves can possess common end points. The primary curve which lies in the centre of the three is drawn on layer 18 and the two secondary curves on layer 19.

The data is read and stored in addressed arrays and the curves are again matched according to their end points. For each cut, points are selected at a regular distance apart along the curve. At each selected point the normal to the curve is calculated. The intersections of this normal with the two secondary curves, together with the selected point define a section of the cut, as illustrated in Figure 84. The X and Y axes positions of the TCP are defined as the position P. The R-axis direction is derived from the gradient of the primary curve at the point P.

The Z and Tilt axes are calculated by considering a nominal triangular cut section as illustrated in Figure 84. The section will have an angle of 140^o at the apex, which is the standard angle designed for the brilliant cutting machine. The primary point, P, is defined in two axes only and can be considered to represent the perpendicular from the apex onto the surface, thereby separating the line ST, into two lengths, a and b, and the apex into two angles A and B respectively. Let the length of the perpendicular be d.

$$A + B = 140^o \tag{30}$$

$$\tan (A + B) = \tan(140^o) \tag{31}$$

$$\tan (A + B) = \frac{\tan A + \tan B}{1 - \tan A.\tan B} \tag{32}$$

$$\tan A = a / d \tag{33}$$

$$\tan B = b / d \tag{34}$$

Hence :

$$\tan 140^o = \frac{a/d + b/d}{1 - a.b / d.d} \tag{35}$$

$$(a + b) / d = (1 - a.b/d_2). \tan 140^o \tag{36}$$

Multiply by $d^2/\tan 140^o$

$$(a + b). d / \tan 140^o = d^2 - a.b \tag{37}$$

$$d^2 - (a+b)/\tan 140^o .d - a.b = 0 \tag{38}$$

Solving the quadratic:

$$d = \frac{1}{2}\left(\frac{(a+b)}{\tan 140^{o}} + \mathrm{sqr}\left(\frac{(a+b)^2}{(\tan 140^{o})^2} + 4.a.b \right) \right) \qquad (39)$$

The positive root is taken in order to ensure that d is positive.

Subject to the correct orientation,

$$\text{Tilt angle} = 70^{o} - \tan^{-1} (a/d) \qquad (40)$$

The SMCC code is then generated as described in Section 6.2.

Figure 85 illustrates cuts produced by this method. These cut shapes can only be produced using a five axis machine. These cut types are complex in shape but can be reproduced accurately using the developed machine tool. The toolpath for these cuts is generated by the computer programme from three 2-D curves and tool and workpiece offsets.

It will be noted from the above paragraphs that the CAD/CAM software, the CNC controller, the actuation system, the structure of the machine, the transmission and the tooling all have a part to play in the quality of surface finish and geometric accuracy of the cut. To research BC and to concentrate on only one aspect is to fail to appreciate the complexities of the problem. The situation is analogous to the diamond grinding of glass. The system is a web of relationships, not a chain of command. In reaching and experimenting with a system that covers CAD to marketing the finished product this project evaluates the entire concept of CAD/CAM automated BC. Though qualified in its scope, and occasionally eschewing the state of the art in favour of the reliable and economic, this project demonstrates that it is possible to automate BC. At worst the system developed is capable of producing ready to polish panels in volume, thereby removing a large proportion of the skilled elements of BC. At best it can produce finished goods with some types of cut polished and some types of cut with an attractive matt finish. The potential for a truly proficient system is clearly there. Commercial viability depends on a lot more.

Chapter Seven

Discussion

Contents

7.1 Brilliant Cutting

Brilliant Cutting is an art form inhibited by the practical limitations of the process. Brilliant cut products at the high end of the quality market have great aesthetic impact. However, high volume, low cost production is not possible of products that contain the full range of engraved features possible with manual engraving. There currently exists a stylistic gulf between the manually produced products and products produced using automated equipment. This has the effect of limiting the high quality brilliant cutting designs to a select, luxury market.

Brilliant cutting has received renewed interest due to increased demand for products such as decorative mirrors and window panels. Of the four market sectors for brilliant cut products identified from the market survey (Section 2.5) those reliant on manual production are experiencing problems in terms of matching supply with demand. Market demand for products produced by skilled manual techniques continues to expand whilst the ability of manufacturers to satisfy that demand is falling due to a shortage of skilled craftsmen and the long processing times required leading to high manufacturing costs.

In order to overcome supply problems in these market sectors a feasible solution is the use of automation using CAD/CAM technology that is able to produce, at an acceptable cost, the full range of brilliant cut patterns required to satisfy customer requirements for traditional decorative styles.

The CAD/CAM route is necessary in order to simplify the control of the automated system to a level comprehensible within the glass industry. This solution has already been successfully introduced into other flat glass markets where several large organisations are using CAD/CAM to produce high volumes of products with simple designs for the furniture industry. Two main problems prevent this equipment being extended to markets currently dependent on manual processing techniques. Firstly, no machine has been found to be capable of reproducing the full range of patterns and cut types that current manually brilliant cut products demand and secondly in order to purchase existing machines a high level of capital investment is required. For any system to satisfy the potential market, it must have technical sophistication and possess a satisfactory capital expenditure payback period.

The work undertaken has required the combination of several technologies, ie CNC, CAD, glass diamond grinding and polishing and the automated engraving of glassware. The work has also required the development and demonstration of mathematical models for enabling automated tilted wheel engraving to be accomplished.

The scope of the project was divided into four areas:

1. Determining the CAD requirements of brilliant cut designs.

2. CAD/CAM derivation of CNC control code.

3. Design and manufacture of a prototype CNC machine.

4. Evaluation and sourcing of appropriate grinding and polishing tooling.

It was essential that the key features of each area and its integration with its adjacent levels, were demonstrated in sufficient detail to justify the technical viability of a potential commercial system and that any technology or knowledge required to manufacture such a system be investigated.

7.2 CAD for Brilliant Cutting

The work undertaken has ensured that the CAD environment is the sole source of creative input to the system and can, therefore, be used to derive a complete geometric definition of the intended workpiece design.

It has been found that a three dimensional brilliant cut object containing the full range of traditional techniques can be adequately defined as a two dimensional design. This has been possible since the depth of cut, ie. the third dimension, is implicit in the standardised techniques used. Although variation of third dimensional parameters is readily possible, the effect on the nonquantified operational characteristics, that are empirically compensated for at standard settings, will be to reduce the accuracy of the cut features.

A further significant development that occurs in this project is that the drawing produced is intended as a blueprint for the finished product, ie the human operator does not impose the path of the wheel. When cutting with a tilted wheel in the brilliant cutting system, the TCP path is offset from the CAD data entities in three dimensions and two directions. In addition, the degree of offset varies with the diameter of the wheel in all five axes. This method is more appropriate, then previous glass engraving CAD/CAM systems, [13,20].

The work carried out has shown that by grouping geometric data into features that are predefined conceptually, the logic required to interpret the data is reduced to those core features pertinent to the process. By minimising the complex 5-axis motion of brilliant cutting into features the experience of the craftsman may be modularised and encrypted into a computer programme.

A commercial CAD package has been found to facilitate the design of brilliant cut products at the design and planning stages. The CAD package assists the interactive process between brilliant cutter and customer when generating the design.

DesignCAD 2D was chosen as the CAD package since it was inexpensive, "easy to use" and provides the essential features required to support CAD/CAM for brilliant cutting. Since the CAD system is intended for use by non-technical personnel the ease of use of the DesignCAD was considered most important in its eventual selection.

The main advantage of using DesignCAD is the availability of ergonomic aids, such as on screen and pallet icon menus and macros. In addition, DesignCAD possesses built-in languages for parametric programming. These features have been used to tailor DesignCAD 2D for the brilliant cutting process. The use of icons to develop a purpose built menu system, (Figure 31), greatly simplified the construction of brilliant cut designs and reduced the time required.

Parametric design macros have been written for mitred and oval punts. This facility allows accurate representation of the proportions of the punt, makes the system easier to use and reduces the time taken to produce a detailed visualisation of the product.

It has been demonstrated that only a small number of the total CAD functions available on commercial CAD systems are required for brilliant cutting, therefore commercial CAD packages are, in general too sophisticated. There are contradictory arguments as to whether this is beneficial. An advantage is that the designer has considerable freedom and power to construct elaborate designs in a number of different ways. However, as Solaglass Ltd have identified, it becomes difficult to train personnel to use the system.

In addition the use of a CAD system has provided the following benefits, ie:

a. designs to be more practical and cost effective at an earlier stage in the design process,

b. reduced the time taken to produce a working design,

c. reduced the level of skill required on the part of the brilliant cutter,

d. the use of rough sketches and verbal descriptions to be avoided, hence leading to higher levels of customer satisfaction and removing a major source of discontent,

e. improved cost and processing information provided to customers,

f. repetitions of a design to require no further drawing or marking and each subsequent reproduction of a design to be as accurate as the first,

g. hard copy of designs to be provided to customers.

The programming language and functions available within the SMCC controller, together with the geometry of the machine tool, (Chapter 5), defined the required output of the CAM system.

A subset of the SMCC instruction language was derived to enable a logical structured approach to be developed when communicating with the SMCC. This approach required only two types of move, linear and circular interpolated motions. A similar programming approach was adopted for each type of move resulting in the routines that generate the code being simplified. It was not necessary to employ all of the programming capabilities of the SMCC since the concentration of control lies with the CAD and CAM systems.

In order to match the calculated tool path with the CAD illustrated cut the CAD/CAM software uses the data points output by the DXF file rather than calculating a parametised equation or using a mathematical technique to represent the curve. The result, despite the inability of the SMCC controller to follow a path through points, is satisfactory. To recalculate a set of spaced points from the CAD output would compound errors introduced by the CAD system and unless the CAD/CAM software uses exactly the same mathematical process to determine the curve the calculated tool path cannot accurately produce the cut intended by the designer. This will be applicable when editing of the design remains at the CAD system level. Where the design is modified beyond an error detection level within the CAD/CAM system then a recalculated smooth cut may be required.

7.3 Generation of CNC code

The key function of the CAD/CAM software is to generate the CNC code from the CAD output. The use of 2-D designs has enabled the DXF file to be used to provide dimensional data for the generation of CNC code. DXF file structures have several advantages, ie they are drawing entity orientated and it is easy to retrieve and interpret dimensional data. Individual modules have been developed for all the main types of features involved in brilliant cutting. Each of these modules has been described in terms of its DXF input, mathematical basis, and programme structure. These modules demonstrate the following features:

a. ability to process a large number of cuts,

b. ability to output to a series of files,

c. ability to process input data that describes cuts drawn in any direction,

d. ability to change the direction of a cut at the limits of the machine, eg. to cut spirals,

e. the use of wheel geometry and glass thickness as parameters in calculating the tool path,

f. sorting of drawing entities according to type into random access memory using the drawing layer as an identifier,

g. the use of a look up table to index curves containing the entity end points as identifiers, and

h. for multi-entity defined cuts the ability to match random order data to retrieve the data for an individual cut.

Developing the CAM brilliant cutting system involved the integration of machine, tooling and control system. The development of the software entailed both the design and encryption of code and also the experimental development of toolpaths and feedrates for the grinding and polishing processes.

7.4 Brilliant Cutting using CAD/CAM

7.4.1 Plunge Grinding Techniques

Mitred and oval punts are the simplest form of cut and are generated by the profile of the wheel in a plunging action. A "declining feed rate" technique was developed to control the plunge rate in order to ensure that machine overloading does not occur due to the large grinding surface area possible.

Both mitred and oval punts are defined by a single line or vector. However, this does not allow visualisation of the finished article. Hence, additional CAD entities have been provided, ie curves and ellipses, using the macro function facilities of the CAD system. This facility enables designers to visualise the effects of changes to the dimensions of objects by making such changes easier to accomplish. In addition, the use of the CAD system is made less complex.

Round punts are defined using a circle and involve complex rotary movement of the workpiece. Consequently a high level of manual skill is required to produce a visually circular indentation. The CNC machine, however, overcomes this problem since it is able to mechanically generate these shapes accurately. The oscillatory technique developed has two advantages over a simple plunge approach. Firstly, the wheel need not be accurately profiled to the shape of a sphere in order to produce the circular cut required. Secondly, the combination of the continuous alteration of the direction of the passage of grains with the fine feed rate of the declining feed rate technique produces less rough surfaces than other cutting techniques, ie surface finishes of approximately 1 micron RA are possible which are readily polished, (Figures 60 and 63).

Consideration must be given to the condition, setting and geometry of the wheel. The grinding forces cause the Z-axis to be deflected from the surface of the workpiece. Hence, a punt can develop lobes because the deflected Z-axis will then sweep in an arc rather then rotating. This problem is increased if the tip of the wheel is not co-incident with the TCP, as can occur if the wheel is not mounted in the correct axial position, or if successive wheel dressings have distorted the shape of the wheel. Development of the punt grinding process determined that lobing is reduced by employing a number of zero-feed oscillations and reducing the grinding forces by maintaining the wheel in a sharper condition. Zero-feed grinding has a tendency to dull the diamond grains, hence, reducing the sharpness of the wheel. This process is, therefore, more costly than other techniques in terms of grinding time, operator input and wheel wear.

7.4.2 Traverse Grinding Techniques

Panel cutting, is unique among the traditional brilliant cutting techniques in that it is the only one where uniformity and accuracy are essential. As such the process is ideal for a cartesian machine tool in which the availability of straight guideways and accurate depth control enable superior panel cuts to be accomplished than can be obtained through manual practices. The work undertaken has identified the effect machine stiffness has on the quality of panel cuts. If the machine does not possess sufficient stiffness then the width of a panel cut can vary between the plunge and the traverse phases of the cutting cycle (Figure 86). The reaction forces differ in both direction and magnitude subject to the specific feed rates and depths used, resulting in an appreciable mechanical deflection. A "gradual depth feed" motion was developed in which the dominant motion is transverse. Consequently the net reaction vector is stable and approximately along the direction of travel such that mechanical deflections have less effect on accuracy.

The range of techniques available to the flat glass brilliant cut industry has been extended by the development of a module that is able to produce linework. This is the technique of producing narrow cuts of curved shape where the wheel is not tilted and cutting depth is held constant or varied along the length of the cut. The module developed includes the following features:

a. when the ends of a cut meet to form a closed loop, the part programming software ensures that these ends are joined smoothly such that no join mark is visible.

b. when the R-axis of the machine reaches the end of its travel, the wheel is raised, turned 180 degrees and cutting resumed along the feature such that no join mark is visible, and

c. the module varies depth of cut and tilt angle of the grinding wheel according to a parametised mathematical function, hence shapes that are either difficult to draw using the CAD system or of a particular shape can, therefore, be cut.

The intersection of two cuts, generated by grinding actions of differing resultant forces, (ie upcut and down-cut grinding), without a join is due to careful development of the brilliant cutting process. As described in Section 6.5.4, the cut geometry is the result of blending the beginning of one section of cut with the end section of the second cut, using the compliance of the machine and the circular interpolated motion to control the amount of material removed at the join. By empirically determining parameters to suite a given cut width, (ie 3 mm), and building these values into an encrypted control algorithm, a consistent non-visible join is maintained. As with round punts, although the form accuracy of the wheel is relevant, the effect of the point of the mitred wheel not being coincident with the TCP is reduced by this gradual blending technique. This module was also used to develop the curved path programming techniques described in Section 7.1.2

7.4.3 Three Dimensional Grinding Techniques

Edge cutting is the most frequently used three dimensional grinding technique in traditional designs. This is because the flexibility of form possible with edge cutting allows a great number of effects to be achieved. The technical and aesthetic complexity of edge cutting demand a high level of skill and care from the craftsman, which requires time to execute. The CNC machine can perform, in single passes, delicate and accurate cuts quickly, (ie at speeds of 4mm/s), resulting in surface finishes that are easily polished.

Control of five axes is a complex problem, not aided by the comparative complexity of the motions, in which yaw and pitch can vary with translation in a variety of unpredictable manners. Hence, sudden and extreme changes in acceleration and direction can be created. The Circular and Arc edge cut module has been developed which employs a parametised route to establish CNC code. Here the design is defined mathematically, augmented by operator defined parameters, with the toolpath being calculated as a function of these parameters.

Several categories of three dimensional continuous edge cuts have been identified, ie:

a. symmetrical segments, which can be represented by a straight line and an arc,

b. asymmetrical segments, which require a straight line and a curve,

c. symmetrical crescents, which can be represented by two arcs, and

d. asymmetrical crescents, which can be represented either by two curves or a combination of a curve and an arc.

An individual segment edge cut, whether symmetrical or asymmetrical, is defined using a single curve which is defined in the DXF file as a continuous string of data points. The system attempts to reproduce the design exactly using the data directly from the DXF file CAD output. It is possible to cut any shape within the envelope parameters, (eg. maximum width), of the technique. The system is, therefore, flexible and capable of producing designs that are open to artistic adaptation and development.

In removing the limitation of the straight line, a Crescent Edge Cut module was developed that represents a departure from formula parametisation. Here the main limitation is the need to define a step depth in order to be able to employ a 2D CAD system.

As with segment edge cuts the system attempts to reproduce the design exactly using the data directly from the DXF file output. The advantage of this system is that no limitations are placed on the designer to conform to a precept ideal. Although freedom of line is encouraged it is still possible, through the functions of the CAD system, to dictate that a geometrically pure shape is used as and when required.

During the design stage, drawing entities are continually being created, deleted or modified. When the data is output as a DXF file the entities are listed in the order that the data was created or modified. A method was devised of using an address array to store the identifying location of the end points for individual cuts. This then enabled the individual lines that made up a continuous cut segment to be linked for the generation of CNC code.

Mitred cuts of variable depth are produced by tilting the wheel such that one of its flanks moves further to the horizontal and hence becomes broader than the other flank. In manual cutting problems arise when the wheel needs to be tilted at pronounced angles in order to produce such an edge cut. The brilliant cutting machine developed is able to produce features with a high degree of tilt and tight radius. These types of cut, if produced manually, would require a violent sweeping motion of the glass relative to the wheel. Manually these cuts are associated with long process times since they require care and skill, hence they are expensive. The use of the brilliant cutting machine reduces the time and cost required to produce such features. Hence, this technique is more available to the designer, thereby enhancing the brilliant cutting process.

7.5 Five Axis Grinding Machine

A design process was used that started at basic principles and developed a series of concepts into the final machine. As few assumptions as possible where made during this process. A fundamental design consideration was that the machine had to be capable of reproducing all of the techniques that could be employed manually. Hence, the need for a machine with five degrees of freedom.

The design of the machine reflects the perceived needs of the quality end of the market rather than the bulk production of low quality goods. The diameter of the cutting wheel is 75mm which allows smaller scale, more detailed work to be undertaken. The width of the brilliant cutting wheels are 12mm which ensures that the brilliant cutting machine is capable of producing normal scale brilliant cutting features. The main limitation of the brilliant cutting machine when compared with commercial four axis machines is the relatively low rate of material removal which is due to the small wheel diameter and low cutting speeds adopted.

A small size of cutting wheel was selected and a maximum cutting force specified which determined the payload of the machine. The structure of the machine was then designed around this payload, ie the size of payload determines both the size and cost of the machine with an increase in payload having an exponential affect on cost. By minimizing the mass of the payload the weight of the machine was minimised and hence the cost of the actuating system.

Although the main cost of the machine is the actuating system, this cost is primarily a fixed cost and does not increase significantly with increases in the lengths of the X and Y axes. These axes determine the maximum size of workpiece that can be processed. It was, therefore, possible to design a machine capable of producing panels of realistic size ie, 1000 x 600mm.

The resolution of the brilliant cutting machine is 0.01mm on each linear axis and 0.01 of a degree on each rotary axis which has been found to be satisfactory for grinding most brilliant cut features. Positional problems were experienced with cuts that required five axis motion. These wheel positioning problems have been attributed to sixth axis wear adjustment using spindle spacers. A further complication is the greater demands on accuracy made when polishing and the relationship of positioning accuracy with the mechanical compliance of the machine.

Machine rigidity was identified as a key factor in achieving accuracy, hence the brilliant cutting machine was designed to be sufficiently robust such that compliance offsets are not needed. For most forms of brilliant cutting, however some measure of machine compliance is an aid to polishing, an example is the polished swan motif illustrated in Figure 64. This design was rough cut using a diamond grinding wheel and polished using a wooden wheel with pumice and a felt wheel with rouge. Despite great care the three wheels could not be adjusted to the TCP with absolute accuracy, mainly because wheel wear resulted in changes in diameter. The compliance of the machine, aided by a small increase in Z-axis position allowed the polishing wheels to be forced into the cut and, therefore, to make contact with both flanks of the cut. A more rigid machine would have required a greater accuracy of wheel positioning to achieve the same result.

The means of achieving the resolution of the machine is the actuation system, which for the brilliant cutting machine consists of microsteppers. This technology was chosen mainly because of its power to cost ratio. In practice it has performed well and is impervious to abuse. The vibration generated by stepper motors has not been detrimental to brilliant cutting and could assist in the grinding process, ie ultrasonics has been shown to improve grinding with diamond wheels.

7.6 Tooling

Previous research on the diamond grinding of glass concentrates on the use of metal bonded wheels which reflects their dominance in the field. The research has identified the following benefits when using diamond grinding abrasives:

a. they remove glass more efficiently and therefore, more economically than other abrasive materials,

b. machines using diamond abrasives require smaller spindle motors, therefore, have smaller payloads and are consequently less expensive,

c. they require less frequent dressing which is of benefit in an automated system,

d. diamond wheels are sintered, consequently the range of profiles required for brilliant cutting can be accommodated with minimal cost penalty, and

e. diamond abrasive is available in a variety of grit sizes and concentrations, consequently the grinding characteristics of the wheel may be tailored to the demands of the application.

Alternative methods of manufacturing diamond wheels were evaluated experimentally in order to identify the most suitable for the brilliant cutting process. All methods examined used a metal base onto which is bonded the diamond grinding medium. It is the method by which the bonding is accomplished that differentiates methods and also has a significant effect on the grinding process. In this respect, electroplated wheels possess rough surfaces due to the uneven manner in which the nickel and diamond composite coats the surface. This was found to produce a surface that exhibited considerable subsurface damage that was visible to the naked eye. Although the material removal rates possible using this wheel type were high, ie with feed rates of 160mm/second possible, this type of wheel was unsuitable for polished brilliant cut features. Sintered diamond wheels have proven suitable in terms of the surface finish produced which can be easily polished.

In terms of the glass grinding process itself, previous research has concentrated on the relationship between a small number of the many variable parameters involved in glass grinding. Little previous work relates to the type of wheel engraving found in brilliant cutting, ie in which the grinding wheel feeds through the material and removes large volumes of glass. Most references concentrate on specific relationships between a few significant parameters, whilst fixing the many other parameters at arbitrary values and consequently disguising the dominant relationships. In order to overcome the difficulty in comprehending the relationships between grinding performance variables contained in the published literature, a unified system model, (Figure 26), has been constructed to indicate both the variables involved in glass grinding and the relationships between these variables.

Glass grinding is a dynamic feedback system and the resultant parameters will constantly change as the grinding process proceeds. Not enough is known about the individual relationships to develop this qualitative model into a quantifiable mathematical model. Mathematical relationships have been published for some of the parameters, however most contain empirical "constants" which rely on the experimental conditions for validity, for example the use of lead crystal glass. Furthermore some important relationships, such as those that determine the stability of the system, are not known. For this reason, the model developed must be considered to be applicable only under normal grinding situations and only as a general help in abnormal conditions.

Chapter 8

Conclusions

8.0 Conclusions

Within the brilliant cut industry, a significant market niche exists for high quality, low cost designs. However, there currently exists neither the craftsmen nor the technology to adequately supply this market. A CAD/CAM system has, therefore, been developed to overcome such supply problem by possessing the capability of producing the full range of features currently available using manual techniques. In order to develop this machine the following objectives have been achieved, ie:

1. The basic types of cuts that make up all brilliant cut designs have been identified, ie these are:

a. mitred and oval punts,

b. round punts,

c. panel cuts,

d. curved linework,

e. symmetrical and asymmetrical edge cut segments,

f. circular and arc edge cuts,

g. symmetrical and asymmetrical crescent edge cuts, and

h. mitre cuts of variable depth and tilt.

2. The process requirements for generating each of the above basic types of cuts using a grinding wheel have been determined in terms of wheel profiles required, number of degrees of freedom on the grinding wheel, angle of tilt, and wheel diameter requirements.

3. From a knowledge of the above grinding process requirements, a 5-axis CNC gantry type grinding machine has been designed and built which is capable of grinding all the basic types of brilliant cut features listed above. This machine tool possesses the following features:

a. the axes are X, Y, Z, Rotation and Tilt of the wheel,

b. the workpiece remains stationary whilst the grinding wheel moves,

c. a flexible drive is used to power the grinding wheel motor in order to reduce the payload at the grinding head,

d. the wheel diameter (75mm) is small enough to allow intricate engraving, yet the wheel width (12mm) is wide enough for most brilliant cutting cuts, and

e. The machine can produce panels of 1000mm x 600mm which covers the great majority of Brilliant Cut panels currently produced.

4. Part programming modules have been developed for each of the above basic types of cut. A detailed study of the kinematics of brilliant cutting was carried out in order to convert the process into mathematical relationships for use by the CAD/CAM system. The programme modules developed use data from the DXF of a 2D CAD system.

5. In order to facilitate the design process, improve design efficiency and enable designers to visualise the end product, a CAD user interface has been developed that provides a specialized brilliant cutting design system. This interface has the following features, ie:

a. use of "on screen" icons that activate those functions most used for brilliant cutting,

b. additional lines to aid visualisation of the actual brilliant cut designs, and

c. parametric design features.

The use of CAD has been found to facillitate the design of brilliant cut products at the design and planning stages. In addition, the interactive process between brilliant cutter and customer when generating the design has been assisted.

5. A model has been constructed that qualitatively illustrates the relationships between the many variables involved in the glass grinding process. This model illustrates that the process of the diamond grinding of glass is a complex dynamic system in which a small change in a single parameter can have profound results.

6. The most effective way of grinding glass has been found to be using diamond wheels.

7. A number of polishing techniques have been demonstrated with qualified success. The fastest method used an impregnated polymer wheel. However, improved polishing performances were produced when the vertical, Z, axis was disconnected and gravity used to provide constant polishing pressure. For round punts traditional rouge and felt wheel polishing was found to be effective at producing a high quality finish.

The benefits gained using the CAD/CAM system are:

1. The high degree of skill currently required on the part of the craftsman is no longer be required.

2. The quality in terms of the geometric smoothness of curves, accuracy of form and position and consistency of surface finish are greatly improved.

3. The common practice of using multiple passes of the grinding wheel, ie initial passes to remove the majority of the material and subsequent passes to finish the cut geometry, in order to ensure accuracy of form and position, are no longer be required. Hence, reductions in overall processing time when compared with manual brilliant cutting can be achieved.

4. The problem of removing material in error does not arise.

5. Cut shapes will not be poorly formed saving the large amounts of rework time that are currently needed to remove this problem.

6. Less reliance is placed on the need for experienced craftsman and long training periods to achieve acceptable quality levels.

7. The consistency of surface finish may be controlled by dressing the rough cutting wheel, hence, assisting in the reduction of subsequent polishing times.

8. The ability to tilt the wheel allows a wide variety of decorative effects to be produced.

9. The system meets the needs of the high added value end of the market rather than the bulk production of low value goods.

Chapter 9

Further Work

Contents

9.0 Further Work

9.1 Software Integration.

There is a need to simplify the system by integrating the discrete software modules into a single unit. Integration is required at two levels, firstly the separate system modules should be combined, secondly the multiple stage process of generating a programme needs to be simplified.

As the system was designed for integration, with an inbuilt method of distinguishing between different types of cut, integrating the modules is made relatively easy. Simplifying the CAD/CAM process, which uses three separate application programmes and a number of intermediate data files, is more complex as the inherent limitations of the MS DOS computer operating system cause delays and demand operator intervention. Some streamlining is possible using Batch and Response file techniques but these limit the user to a top down CAD/CAM process.

The Windows environment offers a new approach to the CAD/CAM process, as it is now possible to move from one programme to another with greater efficiency. Furthermore it becomes possible to imbed a CAD system, CAD/CAM engine, production control software and even CNC control, within a host interface programme. Such a system would overcome some of the few limitations found with the present system.

9.2 Wheel wear compensation

It has been found that wheel wear can have a significant effect on the accuracy of the product and that continuous adaptation to allow for wheel wear is vital to effective polishing. Real time wheel wear compensation would offer significant advantages in reduced CAD/CAM time, as has been shown with four axis CNC brilliant cutting machines.

9.3. Automated wheel dressing facilities

Accurate wheel dressing is required to maintain the form and cutting characteristics of the wheel without causing unnecessary wheel consumption.

9.4 Automated wheel changing

Brilliant Cutting is a multi tool process and wheel changing has been found to consume a significant proportion of production time with the present design. Automated systems have been shown to be effective on other machines and are desirable in this instance. It should be noted that this may pose a significant challenge due to the need to tilt the wheel 15 degrees.

9.5 Polishing wheels

This research has shown that composite polishing wheels are suitable for Brilliant cutting but much research is required to develop an ideal grade that offers long life with optimum surface finish.

REFERENCES

In order of reference.

1 DUTHIE, A.L.
Decorative glass processes
1908
Archibald Constable & Co. Ltd

2 SPILLER, B.
Victorian public houses
1972
David and Charles

3 GIROUARD, M.
Victorian Pubs
1975
Studio Vista

4 HEDDLE, G.M.
A manual on etching and engraving glass
(Pub by:)Alec Tiranti
London, 1961

5 ALLAN, Rosemary E. & BROWN, Ian C.
Beamish, The Great Northern Experience
Souvenir Guide Book, ISBN 0 905054 04 0
North of England Open Air Museum, Stanley, Co. Durham.

6 BEST R.J.W.; STOCKTON D.J.
Brilliant cutting using CAD/CAM
Proceedings of the 28th Matador international conference
UMIST, Manchester, 18-19 April 1990

7 STOCKTON, D.J,; BEST, R.J.W.
Brilliant cutting of flat glass CAD/CAM
Proceedings of the 6th int conf. on production research.
University of Strathclyde, Glasgow, 5-7 Sept 1990

8 BEST, R.J.W. and STOCKTON, D.J,
Generating 5-Axis Positional Co-ordinates from 2D CAD Drawings,
Proceedings of the 7th National Conf. on Production Research,
Hatfield Polytechnic, Sept. 1991.

9 BS 952: Part 2 1980

Glass and glazing: Part 2, terminology for work on glass

10 Anon
Great illustrated dictionary
Readers Digest
1984

11 MATCHAM, Johnathan; DREISER, Peter
The techniques of glass engraving
1982
B.T. Batsford Ltd, ISBN 0 7134 2536 9

12 Anon. brochure
Joker AF/2 Combined Machine
Interdima Ltd,
Unit 7, Salisbury Place
Great Brickkiln Street
Wolverhampton
West Midlands WV3 O3B

13 Anon. brochure:
"CAT" glass engraving machinary
Interdima Ltd, as 12

14 Anon. brochure
Intermac Masterglass machine
EborLtd. as 34

15 Anon
Advertisement: "Aton/90-CNC" Brilliant Cutting machine
(Placed by:) Interdima Ltd
(In:) Glass age magazine
Sept 1990, v33 n9, back page

16 WHEATON, Mike
A change for the better
Engineering
June 1984

17 MARTIN, S.J.
Numerical control of machine tools
1978
Hodder and Staughton Educational

18 DIJKEMA, H.A.; DIJKER, H.C.
The market of brilliant cutting
Student report
School of Mechanical & Manufacturing Engineering
Demontfort University 1993

19 Anon
Technometal
Euroglass
Autumn 1990 edition 1 p26

20 EDWARDS, P.R.
The computer aided design and manufacture of cutting patterns on crystal glassware
PhD. thesis, 1987 University of Nottingham

21 EDWARDS, P.R.; HOWARTH, M.
Computer integrated crystal glass pattern cutting
(Internal document, Undated, from Department of production engineering, University of Nottingham)

22 ESCHENBACHER, M
Acid polishing of crystal glass
Glass technology
v28 n4 August 1987 pp168-170

23 MAYFIELD, M
Ergonomic redesign of a glass cutters workpiece
PhD Thesis, Nottingham University, 1982

24 HOECKER, H.
Hand grinding of lead crystal glass
Industrial diamond review
v41 n483 Feb 1981 pp71-74

25 Anon. brochures:
IUS/LS GN90 Glass working Equipment
The Flextol IUS/LS Power Tool, by:
Flextol Power Tools
Cottage Lane Industrial Est
Broughton Astley, Leicester, LE9 6PD

26 Anon.
The West Window of Coventry Cathedral
(undated)

English Counties Periodicals Ltd.

27 WILLIAMS, H.C.N.
The latter glory - The story of Coventry Cathedral
1985
The Whitethorn Press, Manchester

28 Anon
Brochure- "Mirrors for elegant homes"
Image glassware Ltd
Unit 2, Globe Mills, Victoria Road, Leeds, LS11 5PJ, UK

29 Anon
Price List- Gray and McDonnell Ltd.
Feb 1990

30 Anon
Catalogue No. 10
Andy Thorton Architectural Antiques Ltd.
Ainleys Ind. Estate, W. Yorkshire, HX5 9JP, UK

31 HERBERT, Stan.
Reflections on Solaglass
Industrial Diamond Review
v47 n521 1987 pp157-158

32 Anon
A handbook of grinding
1961
The carborundum company Ltd. Manchester

33 Anon.
The grinding data book
1989
Universal grinding wheel company Ltd

34 Anon
Ebor glass equipment Ltd Catalogue No. 4
Ebor glass equipment Ltd, James Hill Street,
Littleborough, Lancashire, OL15 8AE, England

35 WILLS, David B.
Grinding- using diamond
SME technical paper

series MR, MR 79-375,1979

36 LISSAMAN, A.J.; MARTIN, S.J.
Principles of engineering production, 2nd Ed.
1982, p265, ISBN 0340 28173 1

37 KOBAYASHI, A.
Recent development in diamond wheel grinding
Annals of the C.I.R.P.
v18 n1 Apr 1970 p31-47

38 HUERTA, M.; MALKIN, S.
Grinding of glass: Surface structure and fracture strength
American society of mechanical engineers (paper)
n75-prod-1 for meet May 18-21, 1975

39 AMMEL, P.
Use of diamond profile grinding wheels on cut glass
Ind. Diamond Rev.
Dec 1975 pp 438-443

40 Anon
"Diamond wheels are key to quality lens output."
Diamonds in industry - glass.
(undated booklet published by:) De Beers Ind. Dia Division
Charters, Sunninghill, Ascot, Berkshire, SL5 9PX

41 BS 2064:Part 1 1976
Diamond abraisive products:
Part 1: Specification for diamond abraisive grinding wheels

42 ISHIDA, Yasuhiro; OGAWA, Genji. On precision grinding of optical glass
Journal of mechanical laboratory of Japan
v8 n1 1962

43 HERBERT, Stan
New flexible tool cuts costs, time and effort
Industrial Diamond Review
July 1976 pp237-239

44 FERRONATO, S.
Increasing the use of flexible diamond tools
Industrial Diamond Review
v48 n529 Jun 1988 pp261-262

45 TOMLINSON, P.N.
Fundermental aspects in carbide grinding with resin bonded diamond wheels
Industrial diamond review
Dec 1976 pp426-432

46 BLACK, T.W.
Grinding with diamonds: research, production results.
Machinery
v73 n3 pp96-100 1966

47 BURMAN, L.L.; PIGURNOV, E.V.; VETROV, A.G.
Relationship between diamond grain size and magnitude of ground off layer of glass
Glass & Ceramics (STEKLO I KERAMIKA)
v25 n11-12, Nov-Dec 1968 pp716-720

48 RADFORD, J.D.; RICHARDSON, D.B.
Production engineering technology
3rd Edition, 1980, ISBN 0333 29398 3 Pbk

49 DAWKINS,G.B.; BRIGHTY, D.N.
Use and abuse of diamond grinding tools - Their effect on economic lens and prism production.
Proceedings of the society of Photo-Optical instrunentation Engineers v163
Proceedings of a symposium on advances in optical production technology, London, April 24-25 1979.
Publ. by SPIE, Bellingham Wash 1979

50 HUERTA, M.; MALKIN, S.
Grinding of glass: The mechanics of the process
American society of mechanical engineers (paper)
n75-prod-1 for meet May 18-21, 1975

51 SCHIKER, M.G.; DOLL, W.
Basic investigations into the high speed processing of optical glasses with diamond tools
SPIE v381
Symposium on optical surface technology
April 12-14 1983, W. Germany

52 KHAIT, O.D.
Optimizing the process of diamond grinding

Glass & Ceramics (STEKLO I KERAMIKA)
v39 n9-10 Sept-Oct 1982 pp431-433

53 KONIG, W.; SCHIMITZ-JUSTEN, C.L.; KOCH, N.
Grinding optical glasses with fine diamond
Industrial diamond review
v50 n536 Jan 1990 pp20-25

54 BURMAN, L.L.; EFANOVA, V.V.; PEREROZIN, M.A.
Bevelling of flat glass using synthetic diamond tools
Glass & Ceramics (STEKLO I KERAMIKA)
v42 (1982) n7-8 (July/August) p307-310

55 WOLK, John, R.
Fluids for glass grinding duties
Glass
November 1988

56 REHM, W.
Effects of coolant purity on glass polishing quality
Sprechsaal
v110 n5 May 1977 pp252-254,256

57 TREAT, L.H.
Grinding fluids and diamond wheels
Abraisive engineering
v16 n4 Apr1970 p30

58 SALTER, N.D.; PEARCE, T.R.A.; HOWES, T.D.
A fundermental investigation of workpiece burn in creep grinding
Milton C. Shaw grinding symposium
Nov 17-22 1985
ASME

59 WRIGHT, D.; LIMERICK, T.
Surface finish and diamond wheel efficiency in the edging of plate glass
Industrial diamond review
Sept 1978 p323-328

60 SANATULIN, A.Z.; DROZHZINOV, V.A.
Improving the quality of goods by diamond tool treatment

Glass and Ceramics 1984 Vol41 Parts 11-12 pp535-537

61 "Put your coolant where your work is."
Diamonds in industry - glass. (undated booklet published by:)
De Beers Ind. Dia. Division
Charters, Sunninghill, Ascot, Berkshire, SL5 9PX

62 MATUSEK, M.; SIKOLA, C.
Diamond grinding of glass for contume jewellery
Industrial diamond review
May 1978 pp172-181

63 TAEYAERTS, Jan
Guidelines to determine diamond concentration required to grind glass.
Ind Dia Rev. Feb 1976 pp48-51

64 Anon
Undated brochure: "ATON/90-CNC" glass engraving machinary
Interdima Ltd,
Unit 7, Salisbury Place
Great Brickkiln Street
Wolverhaampton
West Midlands WV3 O3B

65 Anon
De Beers diamonds in the glass industry
undated booklet published by:
De Beers Ind. Dia. Division
Charters, Sunninghill, Ascot, Berkshire, SL5 9PX

66 YU, A.; BRODSKI, I.; PRUSLIN, G.S.H.
Grinding of glass sitals with diamond wheels of different strengths.
Glass & Ceramics (STEKLO I KERAMIKA)
v25 n11-12 Nov-Dec 1968 pp660-662

67 SHUL'MAN, V.P.; ROGOV, V.V.
Machinability of optical glass in cutting with diamond wheels
Soviet journal of superhard matter
v5 n6 1983 pp73-76

68 TANAKA, Y.,IKAWA, N & TANAKA, T
Preprint of Ann. Meet. Japan Soc. Precis. Engng.
p4 (1969)

69 TKHAGAPSOEV et al

Thermoelastic stresses arising in diamond crystals during the dressing of diamond wheels
Soviet journal of superhard matter
v6 n4 1984 p76-80

70 KHIMACH, O.V. ET AL
Automatic dressing of diamond wheels for the finishing of glass
Glass & Ceramics (STEKLO I KERAMIKA) v44 n11-12 Jul 1988 pp161-462

71 WAPLER, H
The preparation of a diamond wheel- its necessity and costs
Industrial diamond review
May 1976 pp164-167

72 BARRETT, Chris.
Wheel profiling using EDM
Industrial Diamond Review
v47 n521 p156 1987

73 HARADA, Masashi
Dressing of grinding wheel by ultrasoonic and low frequency Vibration
Bull. the Japan Soc. of Prec. Engg.
v2 n1 1966

74 LARSON, Paul D.
Ultrasonics- machining the unmachinable
Automation (Cleveland), USA
v22 pt2, Feb'75 1975

75 TYRELL
Rotary ultrasonic machining
SME creative manufacturing seminar, technical paper,
Non traditional machining seminar, Jan 27-29 1979
paper MR70-516

76 MATUSHEK, M. (with an H)
Mechanism of the glass grinding process
Glass & Ceramics (STEKLO I KERAMIKA)
n11 Nov 1984 pp28-29

77 HERBERT, Stan
Glass Decorating Today
Industrial Diamond Review Feb 1983 pp81-83

78 GALEN, Edward E.
Better glass bevelling
Proc. of Super Abraisives '85
Chicago, USA 1985

79 ROGOV, V.V.; DENISENKO, A.P.; CHAIYI, V.T.; PETRUSHA, I.A.; MALOGOIVETS, V.G.; RYABININA, O.B.
Tribochemical phenomena developing during diamond polishing of optical glass
Soviet journal of superhard matter
v5 n2 1983 pp55-59

80 AHEGAR, K.H.
Mirror glass edging with diamond wheels
Industrial Diamond Review
v41 n484 Mar 1981 pp120-125

81 Anon
Product data sheet - Cerium Oxide
London & Scandinavian Metallurgical Co.Ltd.
UK sales office
Ullerton road
Rotherham, UK.

82 SILVERNAIL, W.L.; GOETZINGER, N.J.
Use of rare earths in glass polishing
Rare earth research conference
10th proceedings papers
Carefree, Arizona, USA, Apr 30- May 3 1971
v2 pp652-661
(Pub by:) AEC, TEC Int Cent, Oak ridge, Tenn, USA, 1973

83 DELINGAT, E.W.
The production of optical surfaces: survey of present techniques and preview on new developments
SPIE v381
Symposium on optical surface technology 1983

84 COOK, Lee, M.
Chemical processes in glass polishing
Journal of Non-crystaline solids
120 (1990) pp152-171
(Pub by:) Elsevier Scientific Publishers
North Holland, USA

85 COOK, Lee, M.
Chemical processes in glass polishing
Proceedings of the 10th University conference on glass science. Jun 7-9 1989

86 ALLEN, Lynn N.
Precision figuring of optics by ion machining processes
Summaries of papers presented at the Conference on
Lasers and Electo-Optics, Baltimore, April 24-28, 1989

87 AKSENOVA, L.N.
Preparation of a glass surface for metalization
Glass and ceramics, (STEKLO I KERAMIKA)
v39 n9-10 Sept-Oct 1980 pp419-421

88 BAYLY, A.R.; TOWNSEND,P.D.
Ion beam processing of glass surfaces
Optical laser technology
v2 n3 Aug 70 pp117-121

89 BOINOVICH, L.B.; EMEL'YANEKO, A.M.; ZLOBIN, V.B.; DERYAGIN, B.V.
Production of smooth glass surfaces
Instruments and experimental techniques, (Eng. trans. of:)
PRIBORY I TEKNIKA EKSPERIMENTA
v31 n3 pt2 Dec 1988 pp815-817

90 PERVEYEV, A.F.; IL'IN, V.V.; MIKHAYLOV, A.V.
Ion polishing of glass
Soviet Journal of optical technology
v39 n10 Oct 1972 pp622-624

91 MROZINSKI, Henryk
Correlation of the results of SIMS and ellipsometric investigations of polished optical glasses
Optic (Stuttgart)
v75 n2 Jan 1987 p82-84

92 HAEUSLE, G.
Scattering of totally reflected light at polished glass surfaces
Optic (Stuttgart)
v34 n4 Jan 1972 pp421-427

93 HAEUSLER, G.; HOBERG, G.
Measurements of scattered light at polished glass surfaces
Optic (Stuttgart)
v30 n4 Jan 1970 pp437-441

94 TANASHCHUK, M.P.
Effect of phase rotation upon the reflection of light by a polished glass surface
Soviet Physics Journal
v22 n6 Jun 1979 pp639-644

95 CROCE, P.; PROD'HOMME, L.
Analysis of polished surfaces by the spacial distribution of scattered light
Optics Communications, (France)
v35 n1 Oct 1980 p20-24

96 CROCE, P.; PROD'HOMME, L.
Light scattering investigation of the nature of polished glass surfaces
Nouvelle Revue d'Optique
v7 n2 Mar-Apr 1979 p121-132

97 ANTHON, Eric,W.
Scatter measurements made with ultraviolet light
(paper presented at:)
"Measurement and effects of Surface defects and quality of polish",
Los Angeles, USA, Jan 21-22, 1985
Proceedings of SPIE v525 pp181-188

98 ABENNET, Jean M.
Measurement and interpretation of fine form errors in optical surfaces.
Symposium on optical surface technology Apr 12-14 1983
Garmisch- Partenkirchen, W. Germany

99 GROOVER & ZIMMERS
CAD/CAM
1984, Prentice Hall International

100 MCKERROW, P.J.
Introduction to robotics.
1991
Addison-Wesley Publishers Ltd. ISBN 0-201-18240-8

101 NARAYANAN, O.H. & DUNDAR, R.

Use of HPGL to transfer cad and graphics information
Proceedings of the 28th Matador international conference
UMIST, Manchester, 18-19 April 1990

102 Anon
CAD support; improving cross platform drawing exchange
CADCAM August 1991 pp11

103 DesignCAD 2D Manual, Undated, American Small Business
Computers Inc. 327 S. Mill St. Pryor Oklahomar 74361

104 CLAYPOLE, Jack
Pondering on parametrics
Professional Engineering
March 93

105 KROONANBURG
Methodisch ontwerpen.
Kivi Leergang 1974
Koninklijk Instituut van Ingenieurs

106 WIER, L.
Notes for B.Eng Engineering Technology
Leicester Polytechnic, 1987

107 NAGARAJAH C.R.
A CAD/CAM approach to crystal glass manufacture
PhD. thesis, 1985
University of Nottingham

108 KNIGHT, J.A.G.; EDWARDS, P.; TAYLOR, T.
To develop a manufacturing sytem for the production of the decorative
patterns on crystal glassware
Proceedings of the ACME conference.
Salford 1986

109 STRANDRING, P.M.; EDWARDS, P.
Computer aided crystal glass cutting
Proceedings of ACME research conference, Nottingham University,
1988

110 Anon. brochure
Unimatic Engineers Product Guide
Published by: Unimatic Engineers, Granville Road Works,
22 Granville Rd. Cricklewood, London NW2 2LN

111 "The silicon chip takes a byte at glass decorating"
Diamonds in industry - glass. (undated booklet published by:)
De Beers Ind. Dia. Division
Charters, Sunninghill, Ascot, Berkshire, SL5 9PX

112 MAYERS, C.C
Automatic glass cutting Procedures
Glass
Feb 1986

113 Anon
De Beers industrial diamond division: CNC grinder
Glass Technology
v27 n1 Feb 1986

114 BRUCKNER, L.K.; GAAL, B.
On geometrical problems of automatic glass grinding
Proceedings of CAD'86, the 7th int. conf. on the computer as a design tool 1986
pp78-88

115 RENNER, G.
A computational method for designing curves on rotational surfaces
Software for discrete Manufacturing
(Edited by:) CRESTIN & McWATERS
(Pub. by:) Elsevier Science Publishers BV
North Holland, USA, 1986

116 "The generation game discovers the microchip."
Diamonds in industry - glass. (undated booklet published by:)
De Beers Ind. Dia. Division
Charters, Sunninghill, Ascot, Berkshire, SL5 9PX

117 UDA, Y.;ONUKI, T.; KAMIGAKI, K.; WATAKAI, M,; KATO, T.; HASHIMOTO
Ultra-precision machine for grinding, turning and measuring aspheric componants
Precision Engineering
Oct 1985 v7 n4 p255

118 UDA, Y.;ONUKI, T.; KAMIGAKI, K.; WATAKAI, M,; KATO, T.; HASHIMOTO

Ultra-precision machine for grinding, turning and measuring aspheric componants
Proceedings of the 3rd int. precision engineering seminar, Interlaken, Switzerland, 13-16 May 1985

119 VENKATESH, V.C; VAN LIGHTEN, R.F
Generation of aspherical surfaces on optical glass lenses by grinding on a CNC machining center.
Proceedings of Superabraisives '85, Chicargo
22-25 April 1985

120 YOSHIOKA et al
Ultra precision grinding technology for brittle materials, application to surface and centreless grinding processes
Milton C. Shaw grinding symposium,(Presented at the winter annual meeting of the ASME, 1985

121 FITZPATRIC, W.J.A.; LEONARD, R.
Precision engraving utilising CAD/CAM/CNC technology
Proc of the 28th Matador int. conf. UMIST, Manchester
18-19 April 1990

122 MCLACHLAN, A.
A cut above the rest
Personal Computing
Jan 1990

123 SHORT, Peter
Evolution of flat glass cutting techniques
Glass international
Sept 1987

124 ZOLOTAREVA, et al
High accuracy finishing of glassware with a complex profile using a diamond tool.
Glass & Ceramics (STEKLO I KERAMIKA)
v42 Sept-Oct 1985 pp427-428

125 Anon. brochure
Standard Diamond Wheels,
Van Moppes IDP Ltd.

126 Anon

Unimatic - Stepping motor applications guide
(Promotional booklet)
Unimatic Engineers ltd

127 ACCARNLEY
Stepping motors

128 Anon.
Berga Lahr using feedback with stepping motors
Eureka
Oct 1988

129 Anon.
Compumotor- programmable motion control
(Promotional booklet)
1987
Parker-Hannifin Corporation

130 KENJO
Stepping motors and their microprocessor controls
1984

131 FORD, C.
Resonance in stepper motors can be overcome easily
Drives and controls
Oct 1987

132 Anon. brochure
"V" plan system,
Cam Systems Ltd

133 Anon, brochure
Hepco Generation II slide system.
Hepco Ltd.

134 Anon, Catalogue
Gears, gearboxes and fasteners,
Hincliffe Precision Componants Ltd.
Storforth Lane Trading Estate, Chesterfield, S41 0QZ

135 Anon
Product data sheet:
No volt release switches (stock no. 340-049)
Data sheet 7499, issued July 1989

RS Componants ltd.

136 Anon
Smart Motion Control Card (SMCC), instructions/operations manual.
Baldor ASR Servotron (UK) Ltd, Unit 13, Charlewoods Road,East
Grinstead, Sussex, RH19 2JB, UK

137 WALKER, H.; WEST, R.
Integrating CAD and CAM through the feature based methodology for
design and manufacture.
Proc. of the 28th Matador int. conf.
Umist. Manchester 18-19 April 1990

BIBLIOGRAPHY

HOYER, Annegret
Transparent Machinable Cutting of Optical Glass
Glastechnishe Berichte
v55 n4 1982 pp66-69

Anon
CADCAM: the design perspective
Engineering
January 1993 pp15-16

Anon
Industrial diamonds; engineering material from another age
Eureka on campus
Autumn 1991

Anon
Diamond; a singular crystal
Eureka on campus
Spring 1992

Anon
Glass
Machine design
April 17 1986 Materials reference issuepp187-188

Anon
The Blue Book 1991, (trade directory)
Roper Davis Ltd, 4 Simon Campion Court, High Street, Epping, CM16 4AU

BESANT C.B.; LUI, C.W.K.
Computer aided design and manufacture, 3rd edition
1986
Hormood

BRAUN, E.
Constellations for manufacturing innovation
Implementing new technologies, (ed. by:) RHODES & WIELD
(Pub by;) Basil blackwell in association with Open University, 1985

BROWN, Norman J.; FUCHS, Baruch A.
Shear mode grinding
43rd annual symposium on frequency control 1989

BS 1089: 1973
Workhead spindle noses for grinding machines: Cylindrical, external, internal and universal types.

CHASEN, S.H. Geometric principles and procedures for computer graphic applications.
1978
Prentice-Hall Inc.

COOK, C.C.; HO, C.Y.
The application of spline functions to trajectory generation for computer-controlled manipulators
Computing techniques for robots, (Ed by) ALEKSANDER, Igor
1985
Kogan Page Ltd

DUNKEN, H.H.
Glass surfaces
Treatise on materials science and technology
v22 1982 pp1-74

DUNKEN, H.
Surface chemistry of optical glasses
Journal of Non-crystaline solids
129 (1991) pp64-75
(Pub by:) Elsevier Scientific Publishers
North Holland, USA

FAUX, I.D.; PRATT, M.J.
Computational geometry for design and manufacture
1979 et seq.
Ellis Horwood Ltd ISBN 0-85312-378-0

GROSSKOPT, Klaus.
Cleaning of sensitive glass surfaces
SPIE v381
Symposium on optical surface technology 1983

GOLDENBERG, A.A.; LAWRENCE, D.L.
End effector path generation
Trans. ASME J. Dym. Syst. Meas. & Control (USA)
v108 n2 pp158-162 June 1986

GOLINI, Donald; JACOBS, Stephen D.
Physics of loose abraisive microgrinding

Applied Optics
1 July 1991 v30 n19

HAMILTON, B.; RAWSON, H.
Deterrmination of the flaw distributions on various glass surfaces from HERTZ fracture experiments
Journal of the Mechanics and Physics of Solids
v18 n2 Apr 1970 pp127-147

HANUSCH, W.; BERGMANN, G.
Diamond tools in the machining of optical glass
Diamonds in industry - glass. (booklet published by:)
De Beers Ind. Dia. Division
Charters, Sunninghill, Ascot, Berkshire, SL5 9PX

HARTMAN, G.; NICHOLAS, I.; SOOGE, A.; WARNER, M.
Computerised machine tools, manpower consequences and skill utilisation,
a study of British and German manufacturing firms.
Implementing new technologies, (ed. by:) RHODES & WIELD
(Pub by;) Basil blackwell in association with Open University, 1985

HORDESKI, Michael F.
CAD/CAM Techniques
1986
Reston Publishing Company INC, Reston, Virginia, USA
ISBN 08359 0620 5

IZUMITANI, Tetsuro; HARADA, Shoichi; ADACHI, Shoji
Polishing mechanism of optical glasses
Journal of Japan society of lubrication engineers
v33 n4 1988 pp267-273

IZUMITANI
Glass hardness, wear and polishing
Encyclopedia of materials science and engineering
Pergammon

JUCHEM, Horst
Diamonds for grinding non metalics
Industrial diamond review
v4 1988 pp158-161

JUCHEM, Horst
Flat glass and diamond grit
Glass

v6 1990 pp308-311

KHALIL, Abid; POWELL, Anne
5 Axis model making saves time and money
Production Engineer, Feb 1987

KIM, K.; KIM, S.S
Interpolation of orientation for precice path generation in industrial robots
Robot computer integrated manufacture (UK)
v6 n3 1989

KIRCHNER, Henry P.
Comparison of single-point and multi-point grinding of glass Journal of American Ceramic Society
v67 n5 pp347-353

KLEIN, Dan; LLOYD, Ward.
The history of glass

KOUCKY, J.; MATUSEK, M
Kinetic interpretation of the glass polishing process
Glass Technology
v25 n5 Oct 1984 pp240-243

KROSS, J.; GERLOFF, H.
Optical investigations on optical glass surfaces
Symposium on optical surface technology
Apr 12-14 1983
Germisch- Partenkirchen W. Germany

KYRIAKOPOULOS, K.J; SARDIS, G.N.
Minimum jerk path generation
Proceedings of the 1988 IEEE international conference on Robotics and information
Philadelphia, PA, USA, 24-29 April 1988
pp364-9 v1
(Pub. by:) IEEE Comput. Soc. Press, Washington DC

LEONARD, R
Elements of cost effective CIM
Int. J. computer integrated manufacturing
v1 n1 pp13-20

LOH, Ernst
Centreing optical lenses

SPIE v381
Symposium on optical surface technology 1983

MACILWAIN, Colin
Computers guide the glass-cutting robots arm
The engineer
20 Nov, 1986

MASELLA, A.; VIREY, F.
Oxygen-Hydrogen burners improve glass surfaces
Glass industry
v69 n5 pp24-25 April 1988

MEKHABUNCHAKIJ, K.; YAMAMOTO, T.; AOKI, Y.
A CSG- based interpretation of 3-view drawings
(Translation of:)
Inst. Electron & Comm. Eng. Japan
Sect E vE69 n12 pp1354-64 Dec 1986

MILAM, D.
Laser-induced damage at 1064nm, 125 psec
Applied optics
v16 n5 May 1977 pp1204-1213

MORRIS, H.I.
Geometrical drawing for art students
1953
Longhams Green and Co.

MULLINEUX, Glen
CAD: computational concepts and methods
1986
Kogan Page Ltd, London

N-NAGY, F.; SIEGLER, A.
Engineering foundations of robots
1987
Prentice Hall International

POWELL
Presentation techniques
Macdonald Orbis 1987
ISBN 0-356-14284-1

PRYCE-EVANS, David
Visual presentation

CADCAM
August 1991

PURCELL, Frank; GIBSON, Ivan S.
The essential elements of CAD/CAM
Proc. of IMC/10
University College Gallway, Sept'93
(Ed by:) NOLAN, P.J. ISBN 090 77563 2

RATTERMAN, E.; CARIUS, A.C.
The use of man made diamond in the glass grinding industry
4th DWMI international technical symposium Nov 14-15 1978, Illinois
(Pub. by:) Speciality Materials Dept
General Electric, Worthington, Ohio, SMD 812-340 (5M)

RENNER, Gabor; POCHOP, Vladimer
A new method for local smooth interpolation
Eurographics '81
pp137-147
North Holland Publishing Company

RHOADES, L.J.
Advances in some specialized grinding processes
Milton C. Shaw grinding symposium
Nov 17-22 1985
ASME

SADRE, A.; KOSSEY, R.; TAYLOR, J.
Motion processing for a robot controller
2nd biennial international machine tool technical conference
proceedings, 5-13 Sept 1984, Chicargo, IL, USA
v3 pp811-817
(Pub by:) Nat machine tool builders assoc. Mclean, VA, USA

SHOHAM, M
A textbook of robotics II, structure and operation
1984
Kogan Page

SWIFT, Howard R.
How surface chemistry affects float glass properties
Glass industry
May 1984

TANZI-MIRA, G.;ZIVIERI, F.; SEMARARO, Q.; ANGLANI, A.

Economic evaluation of alternative CAD/CAM systems: a fuzzy multi attribute decision making model
Proc. of the 28th. Matador int. conf.
UMIST Manchester 18-19 April 1990

TROCH, I.
Time -optimal path generation for continuous and quasi-continuous path control of industrial robots
Journal of intell. robot syst. theory appl. (Netherlands)
v2 n1 pp1-28 1989

VAN VLACK, Lawrence, H.
Materials for engineering: concepts and applications
1982
Addison Wesley Publishing Co.
Reading, Massachesetts, ISBN 1-201-08065-6

VASILASH, G.S.
CAE, CAD & CAM at CMI
Production USA
v102 n5 pp58-59

WAWRO, Michael
Getting more out of CAD/CAM
Professional Engineering
Oct 1989 pp43-44

WHITEFIELD, Andy
An analysis and comparison of knowledge use in designing with and without CAD
Proceedings of CAD'86, the 7th int. conf. on the computer as a design tool 1986

WINSER, P
Interactive 3D graphics for consumer applications
IEE colloquium on "Realistic 3-D image synthesis"
Digest No.11, London, Jan 16 1990

WRIGHT, V.E.
Microcomputer CAD Systems
Chem. Eng. (USA)
v92 n14 8 July 1983 pp 99-102

ZUCKERMAN, Jean
Decorators focus on flat glass
Glass industry August 1990

ILLUSTRATIONS

Figure 1. An example of brilliant cutting combined with embossing produced by Sekon Glass, circa 1988. Original in colour.

Figure 2. A door plate, combining white acid, brilliant cutting and bevelling, designed by A.L. Duthie, circa 1905, [1].

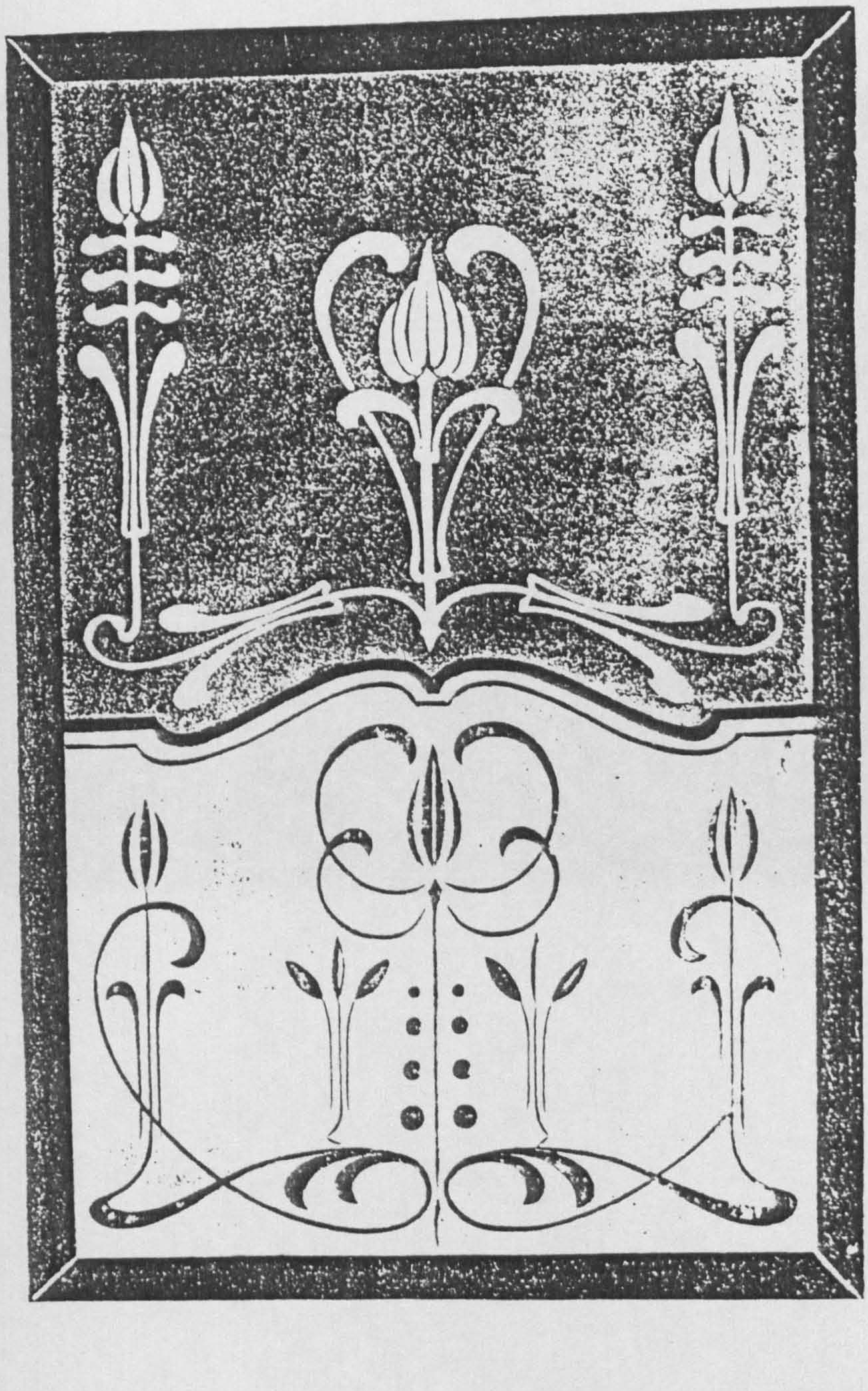


Figure 3. A traditional bar panel from the Sun Inn, Beamish Museum. Photograph by the author. Original in colour.

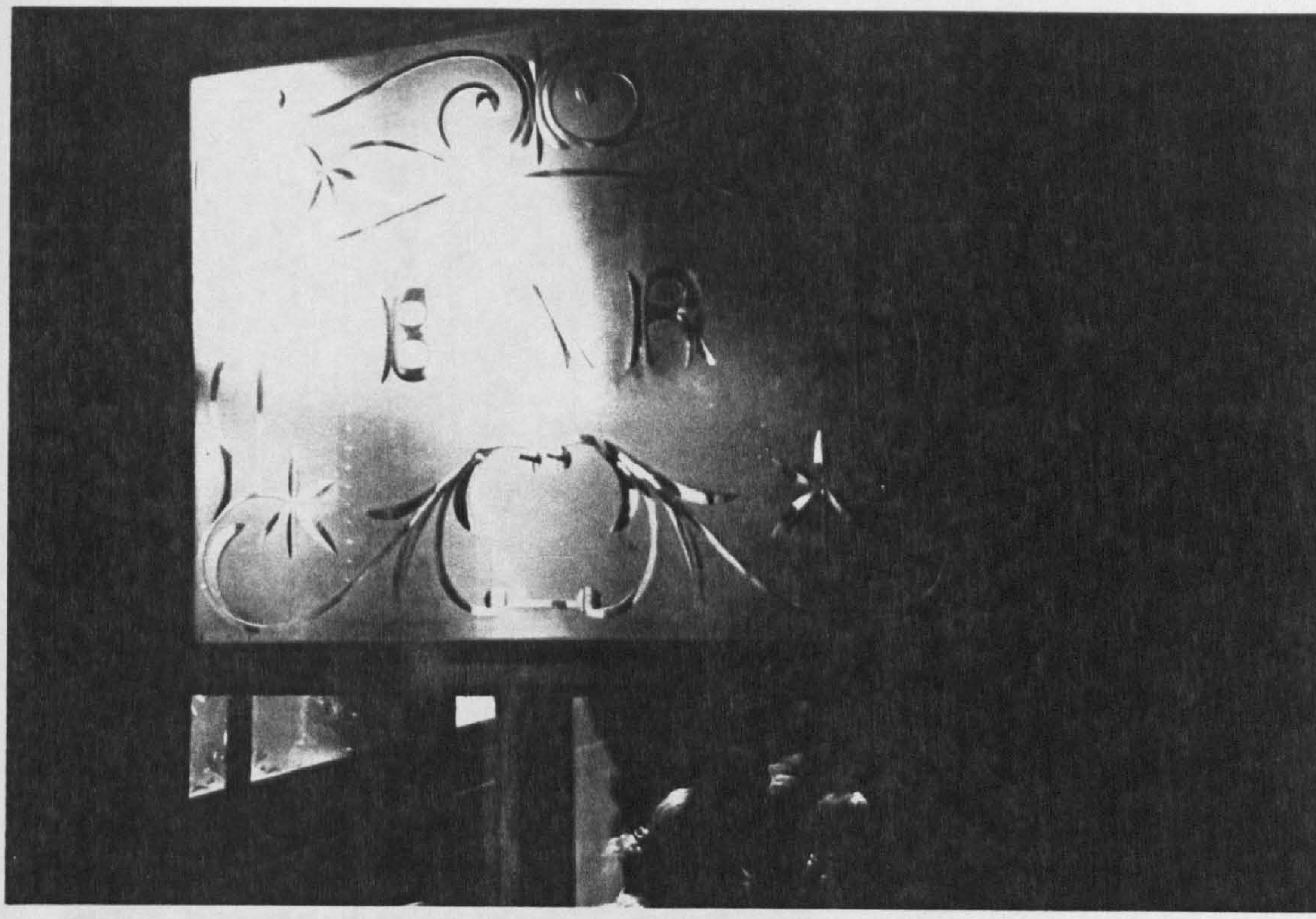


Figure 4. A traditional door panel of ornate design, combining brilliant cutting with frosting, Beamish Museum. Photograph by the author. Original in colour.

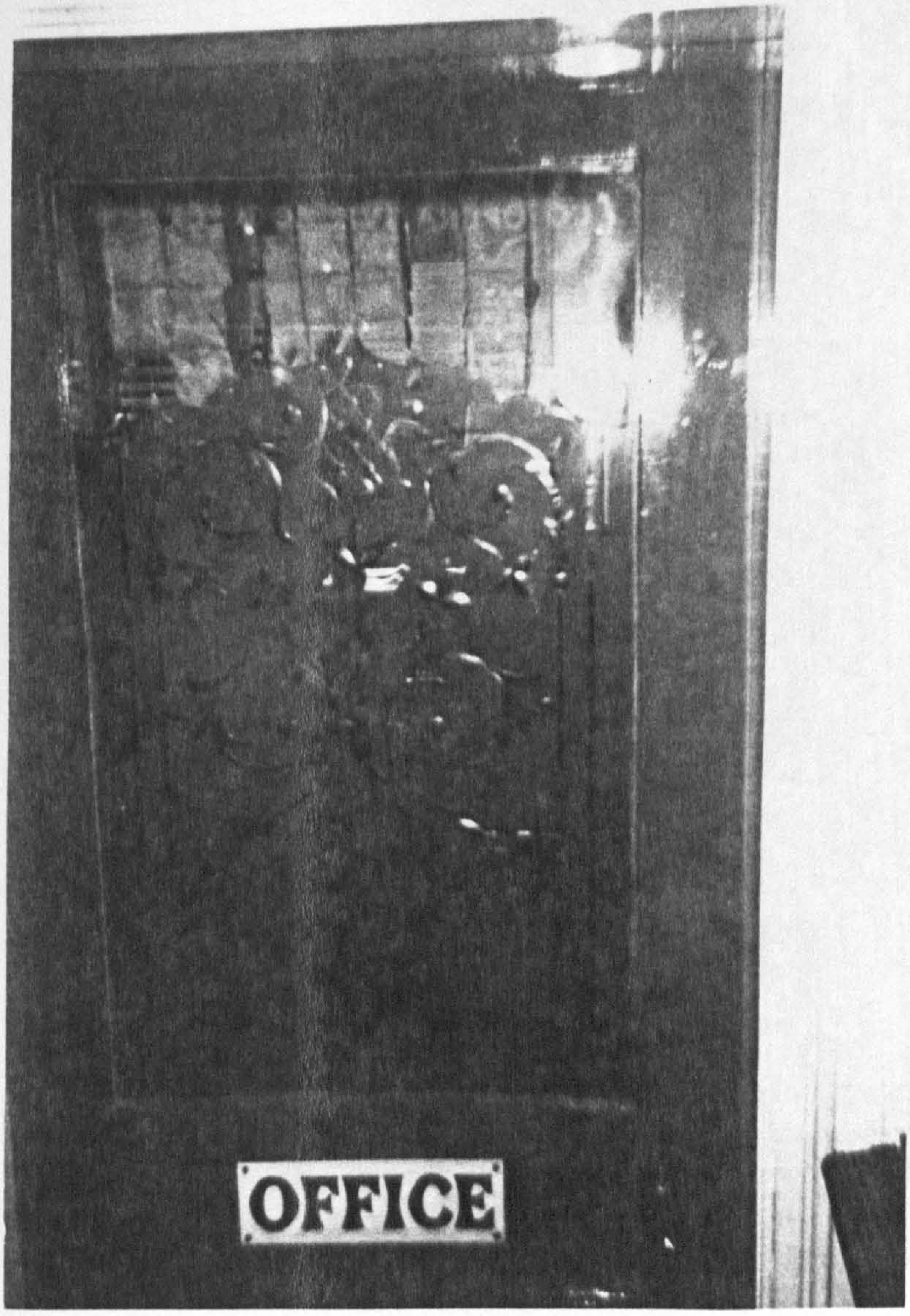


Figure 5. A period door panel of contrasting design, brilliant cut into a frosted panel. This panel was probably frosted by grinding with loose abrasive. Beamish Museum, photograph by the author. Original in colour.

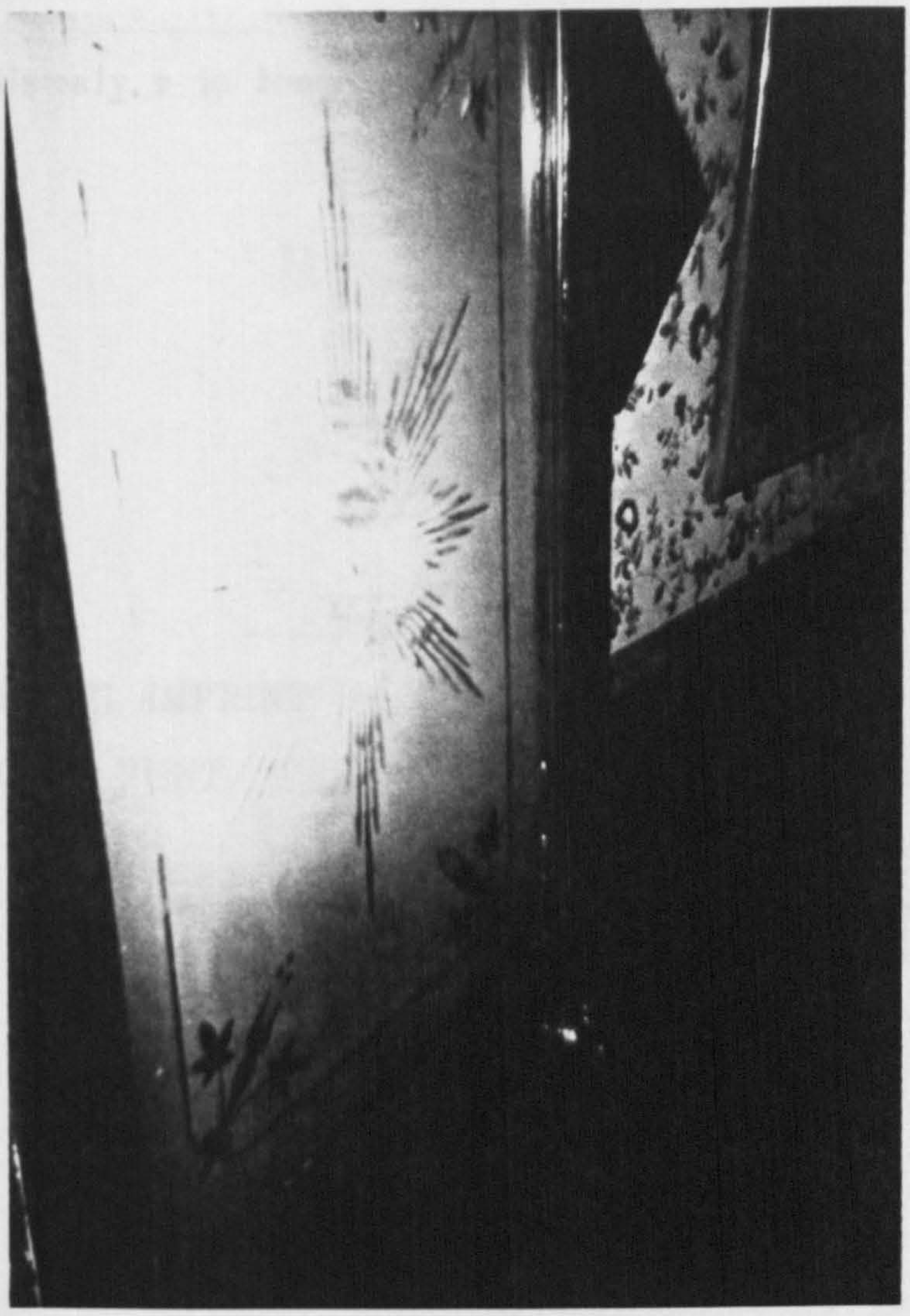


Figure 6. Brilliant cutting with the round edged wheel.

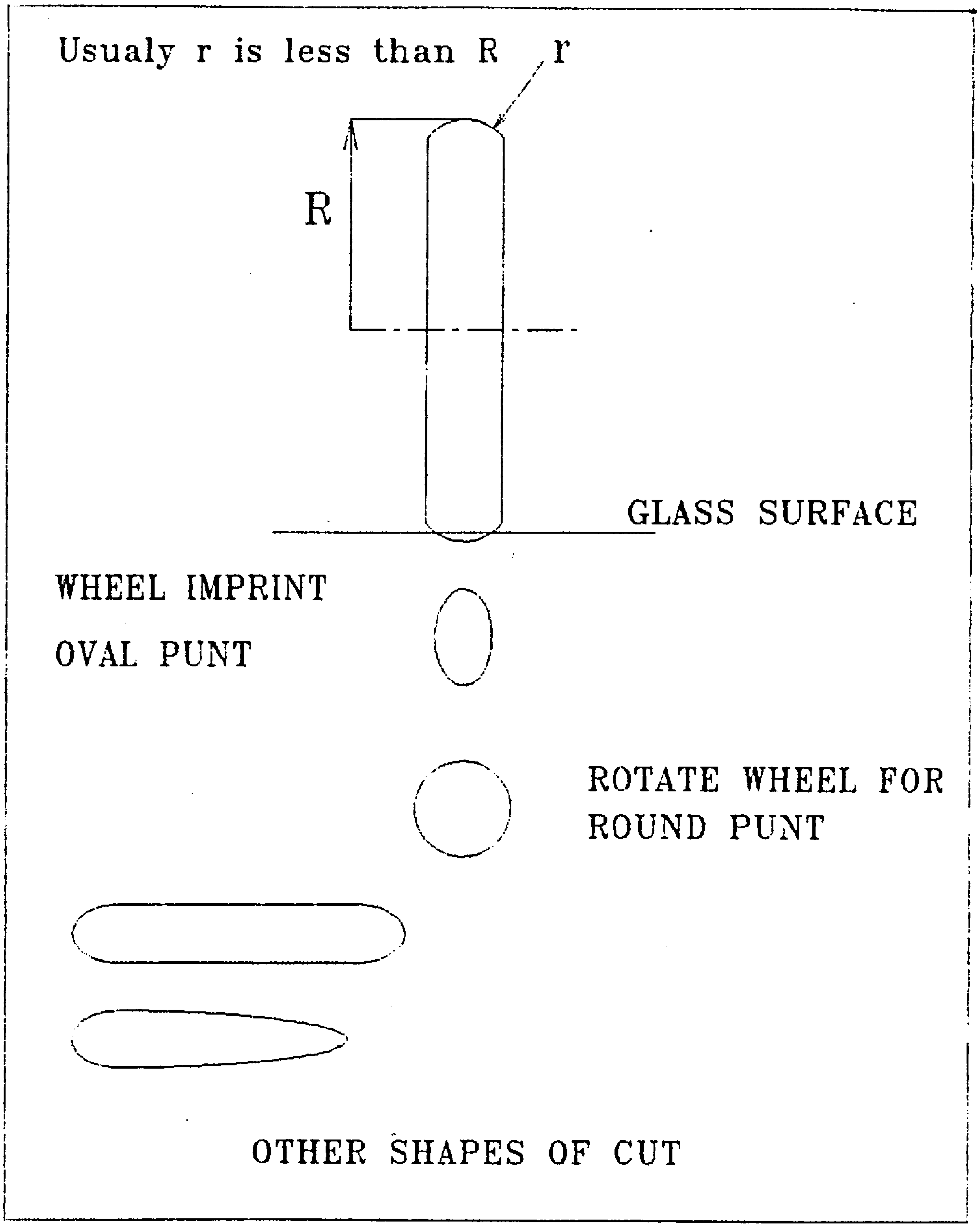


Figure 7. Brilliant cutting with the mitred wheel.

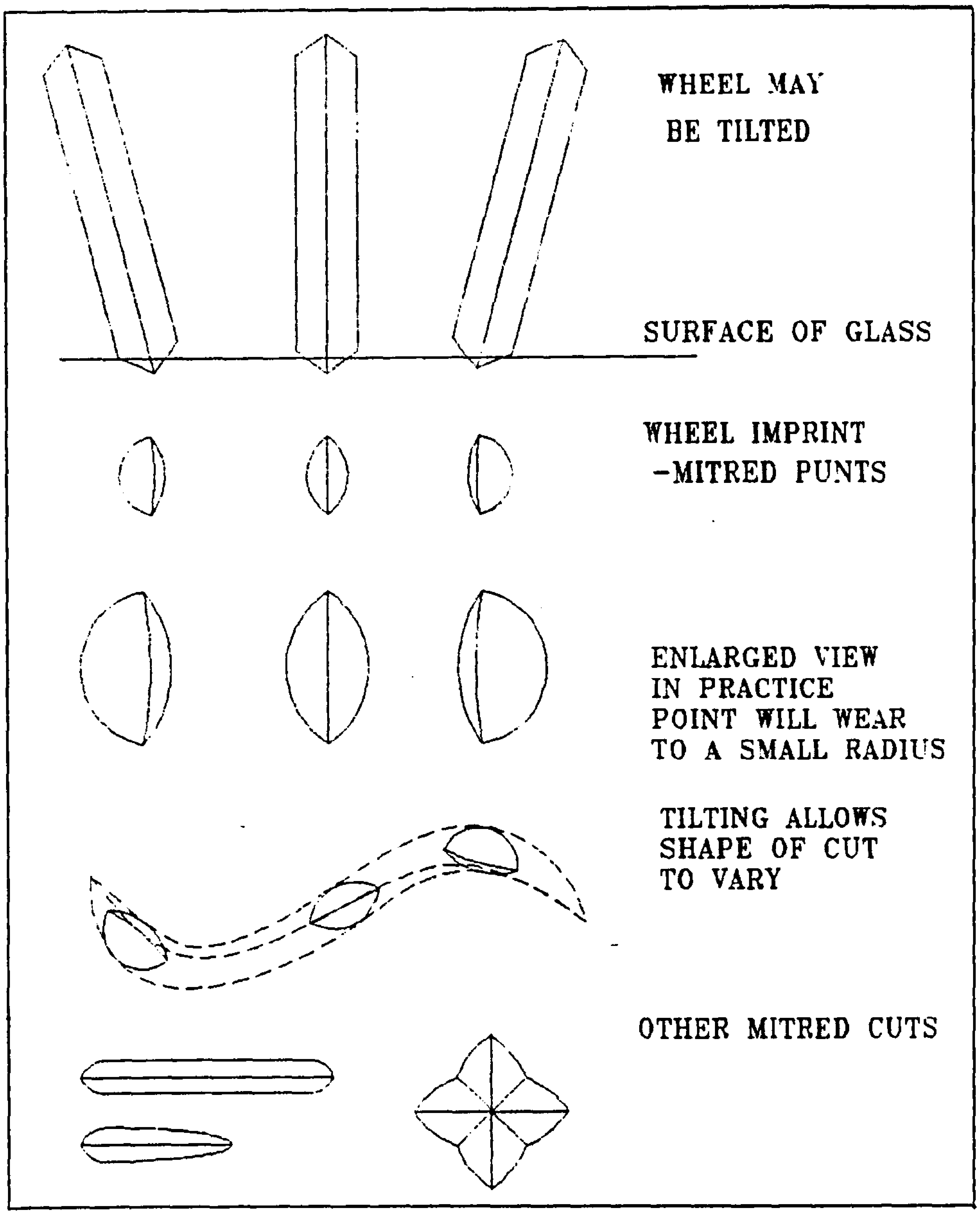


Figure 8. Edge cutting with the square edged wheel or "strap".

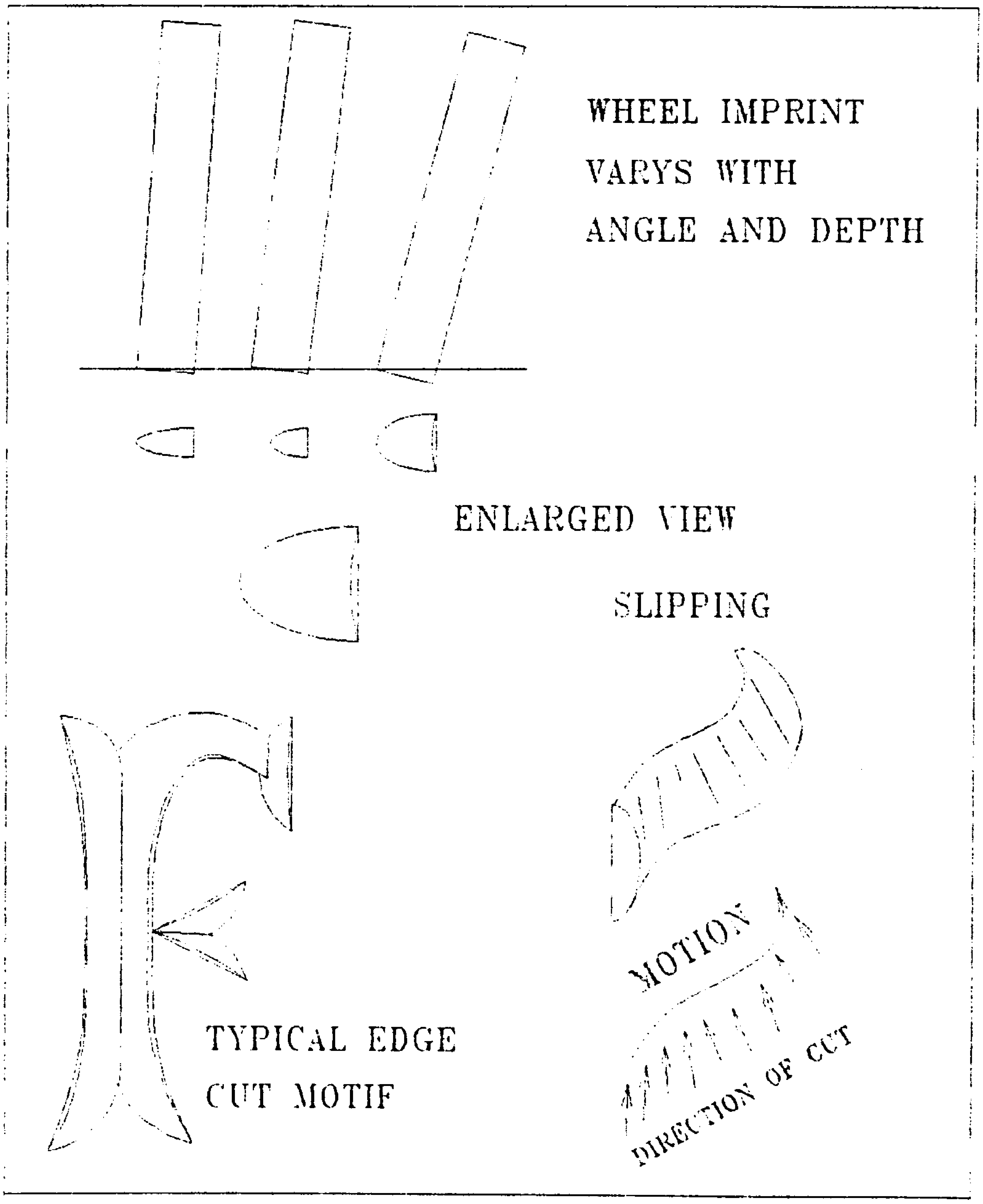


Figure 9. Panel cutting.

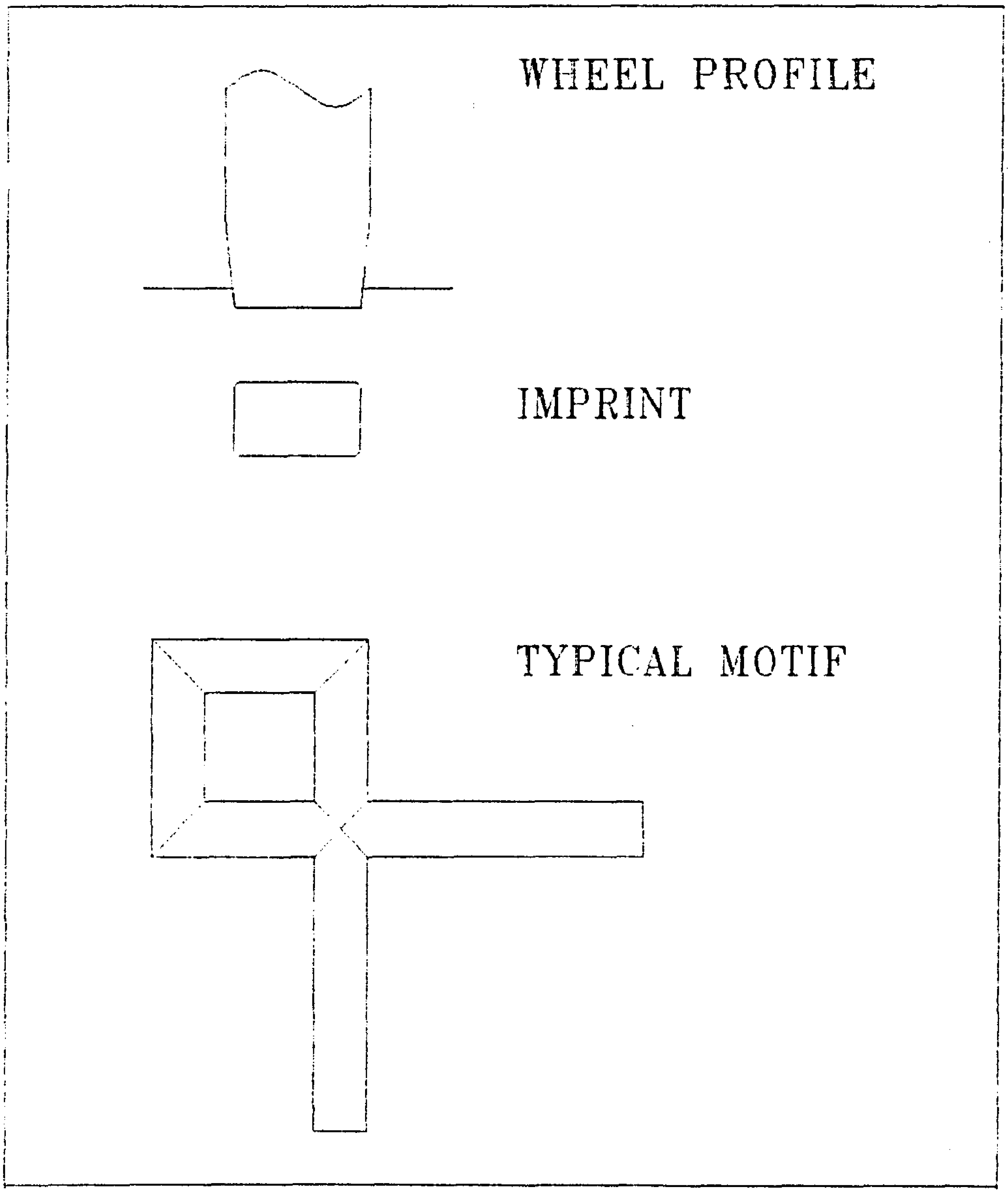
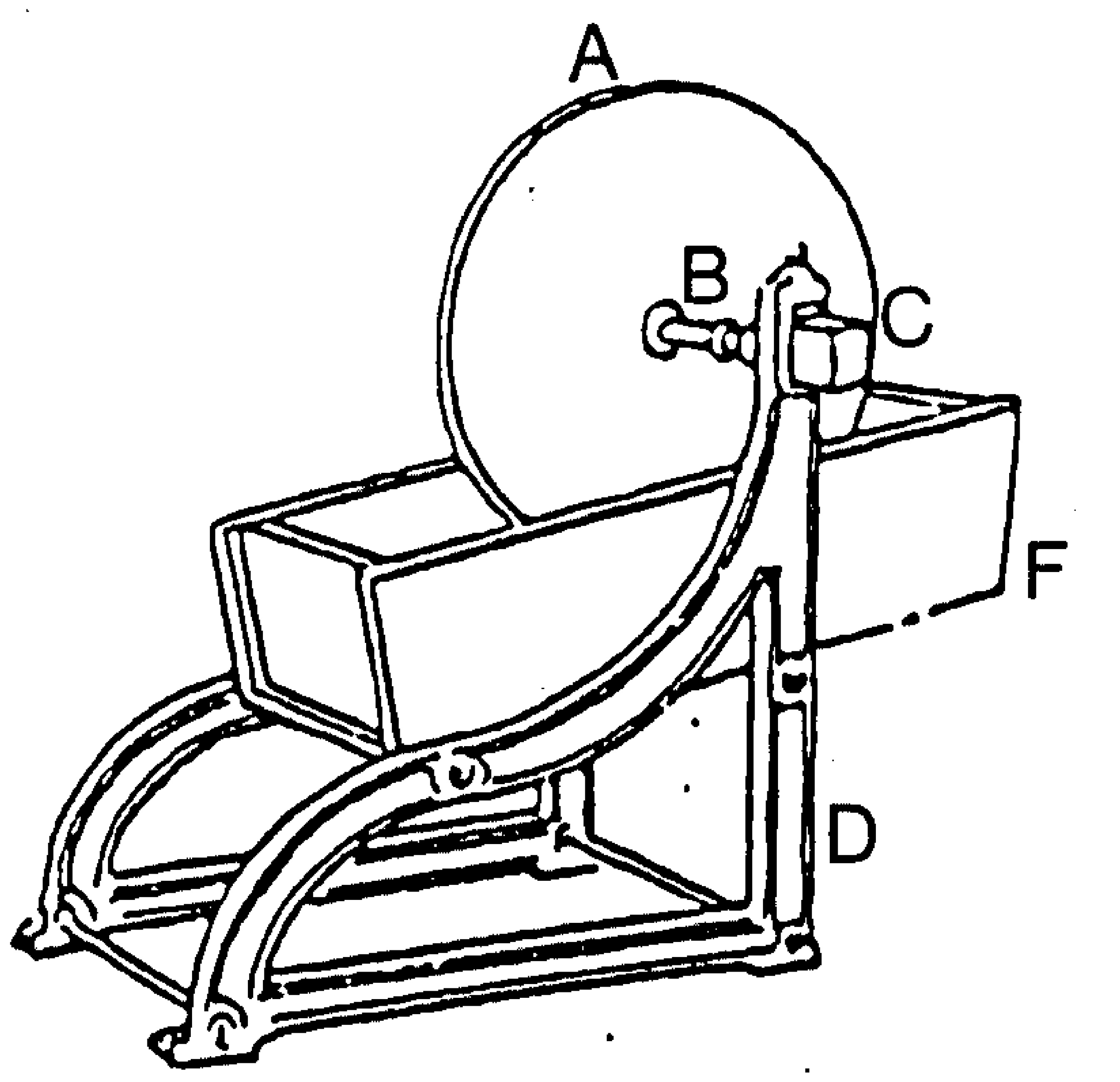


Figure 10. Victorian brilliant cutting equipment, [1].



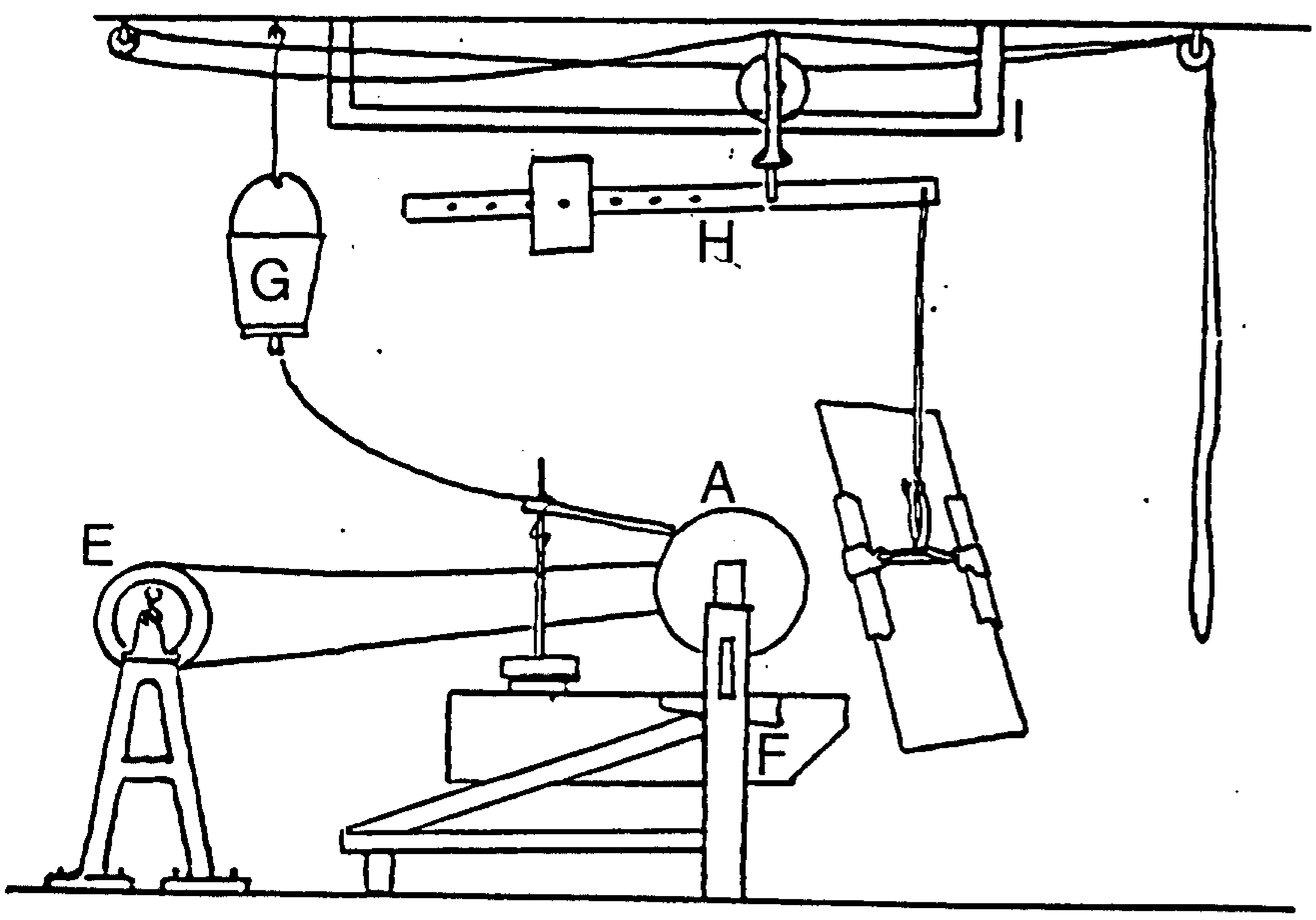


Figure 11. A modern day brilliant cutting workshop, photograph by the author. Original in colour.

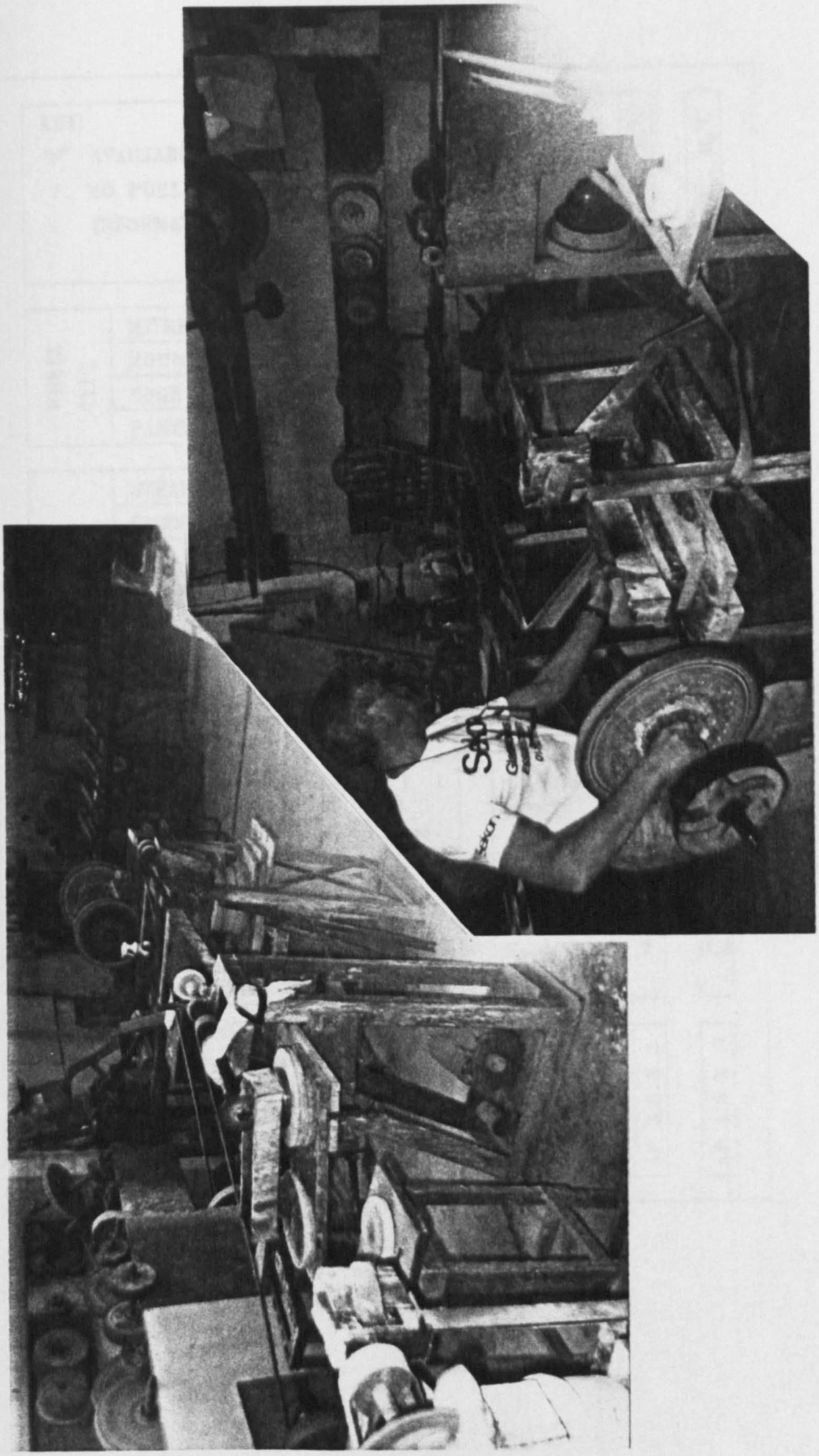


Figure 12. A comparison of glass engraving machines

KEY:
✓ AVAILIABLE
? NO PUBLISHED INFORMATION

		JOKER AF/2	CAT 3M	CAT 4M	CAT 6M	MASTER GLASS	ATON 90-CNC	ALPA 91-CNC	KAM 91-CNC	ET.04 CW CNC	OUR BC. M/C
WHEEL TYPE	MITRED	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	ROUND					✓	✓	✓	✓	✓	✓
	EDGE										✓
	PANEL										✓
CUT FEATURES	STRAIGHT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	CURVED	✓				✓	✓	✓	✓	✓	✓
	VARI.CURVED					✓	✓	✓	✓	✓	✓
	FIXED DEPTH	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	VARI. DEPTH					✓	✓	✓	✓	✓	✓
	TILTED	✓									✓
	VARI. TILTED										✓
	ROUND PUNTS					✓	✓	✓	✓	✓	✓
No. AXES		1	1	1	1	4	4	4	4	4	5
AUTO TOOL CHANGER						✓	✓		✓	✓	
TOOL STORAGE CAP.						3	8		8	3	
No. WHEELS CUTTING SIMULTANEOUSLY		2	3	4	8	1	1	1	1	1	1
FEED RATE (m/min)		?	2	2	4	?	8	?	?	?	0.3
CONTINUOUS FEED		✓			✓						
BED SIZE (m) AP = APPROXIMATELY		N/A	2.2 X 2.2	2.6 X 2.6	2.4 X CF	AP 3 X 1.5	AP 3 X 1.5	3.25 X 1.75	3.25 X 1.75	AP 3.5 X 2	AP 1.5 X .7

Figure 13. A versatile multi-purpose machine, [8].

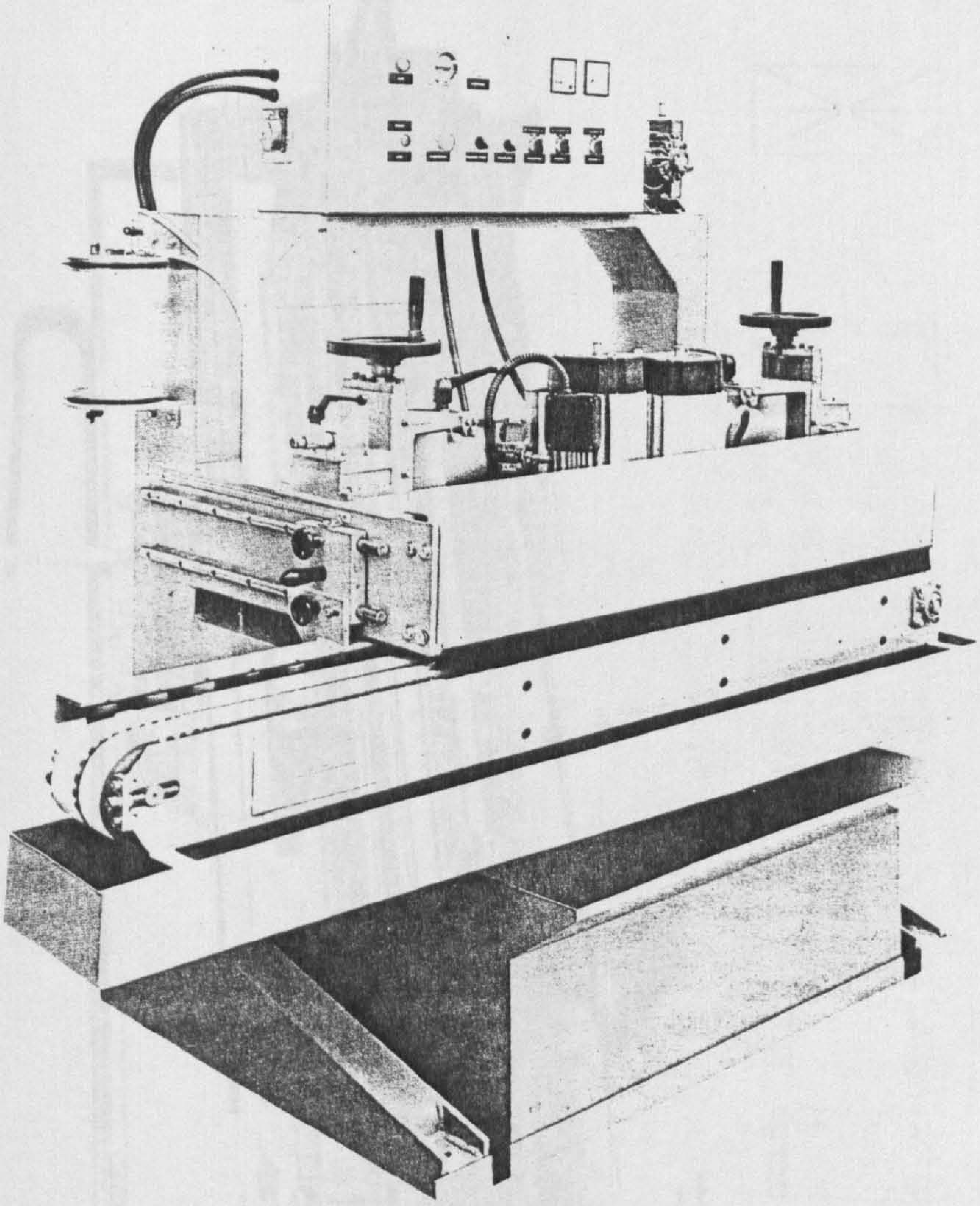


Figure 14. A dedicated straight line engraving machine, [9].

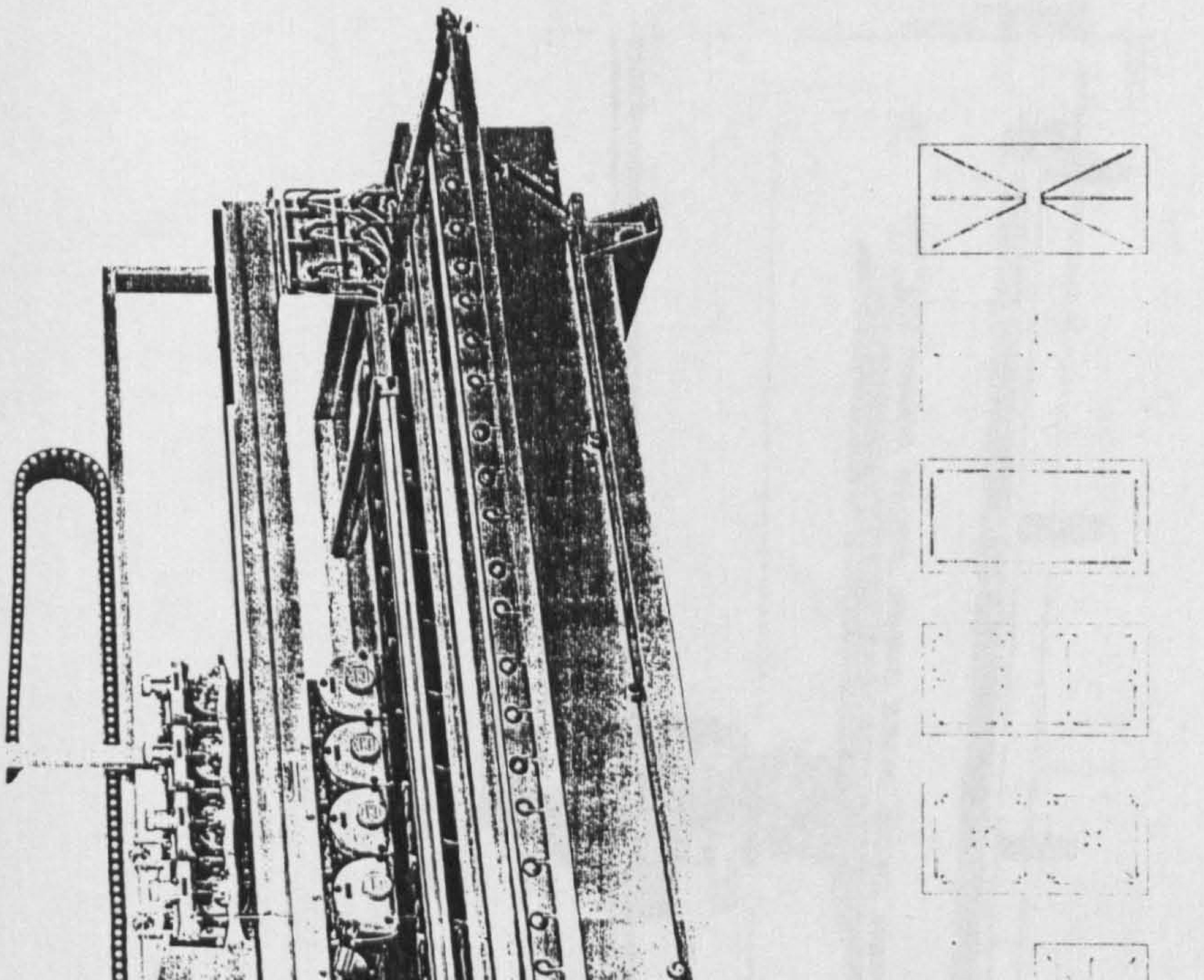


Figure 15. The Intermac Masterglass machine, an example of a four axis CNC brilliant cutting machine, [10].

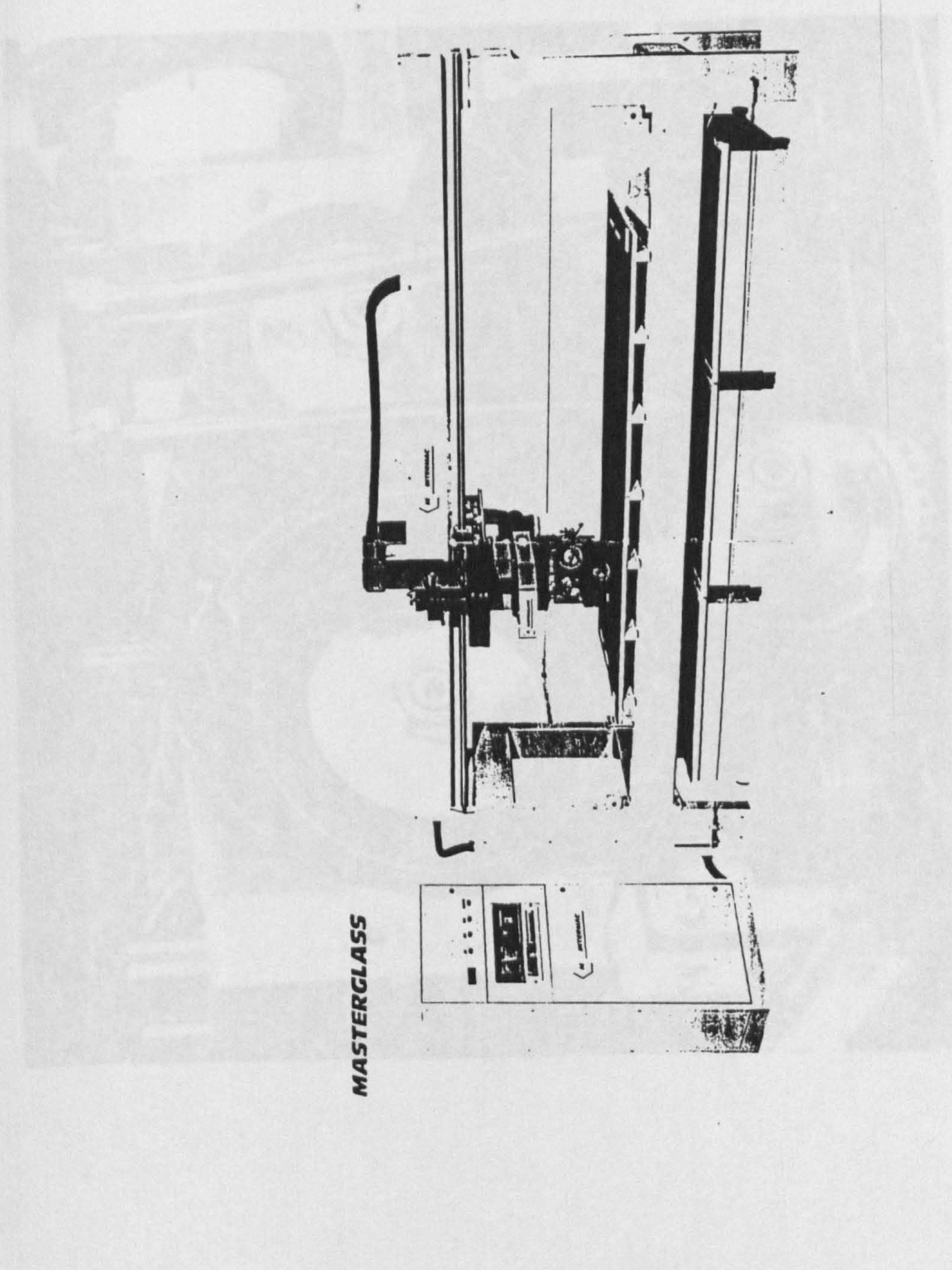


Figure 16. The wheel carousel of the Intermac machine, [10].

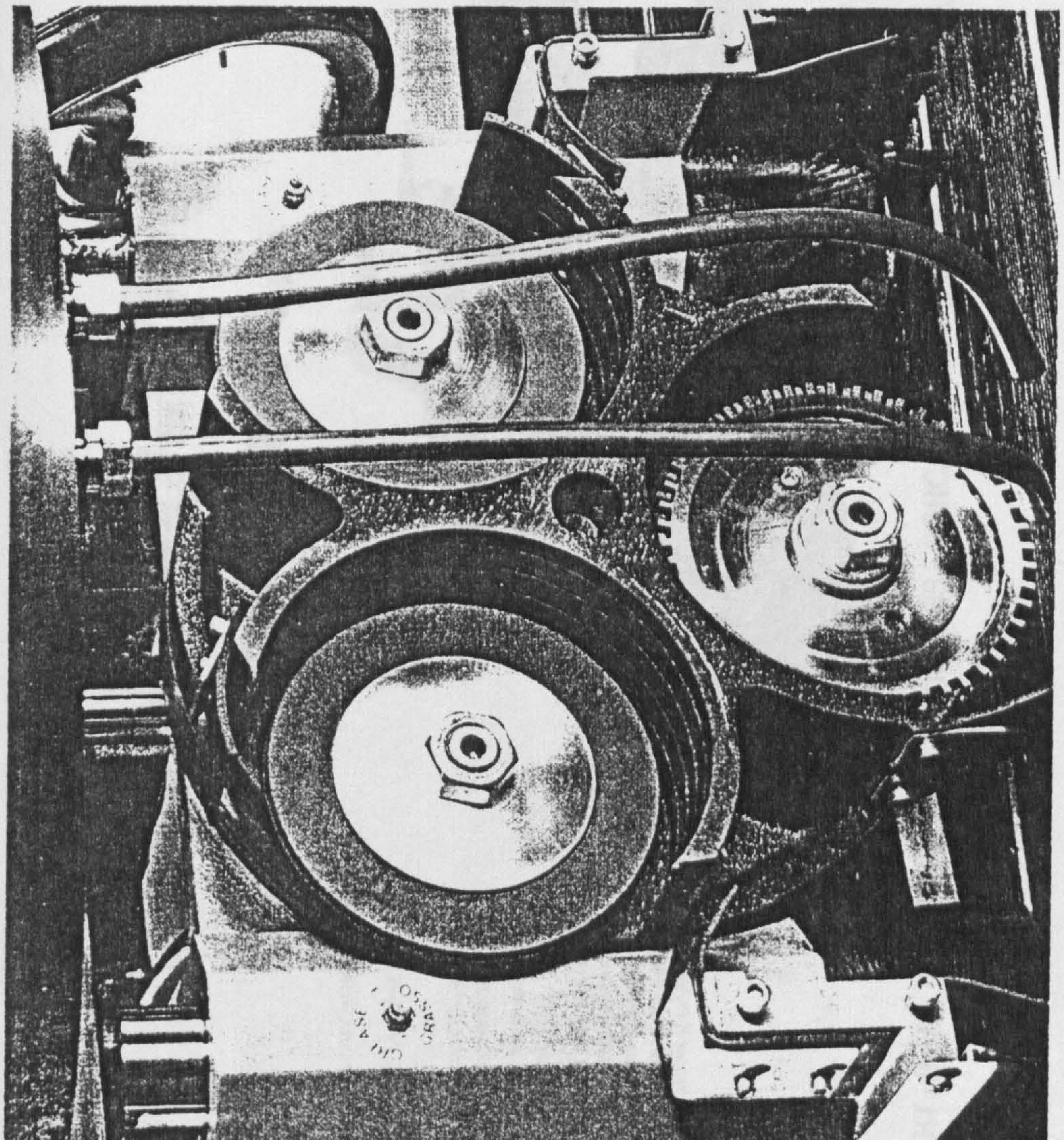


Figure 17. The Aton/90-CNC four axis CNC brilliant cutting machine, [11].

Figure 18. A copper wheel lathe, [7].

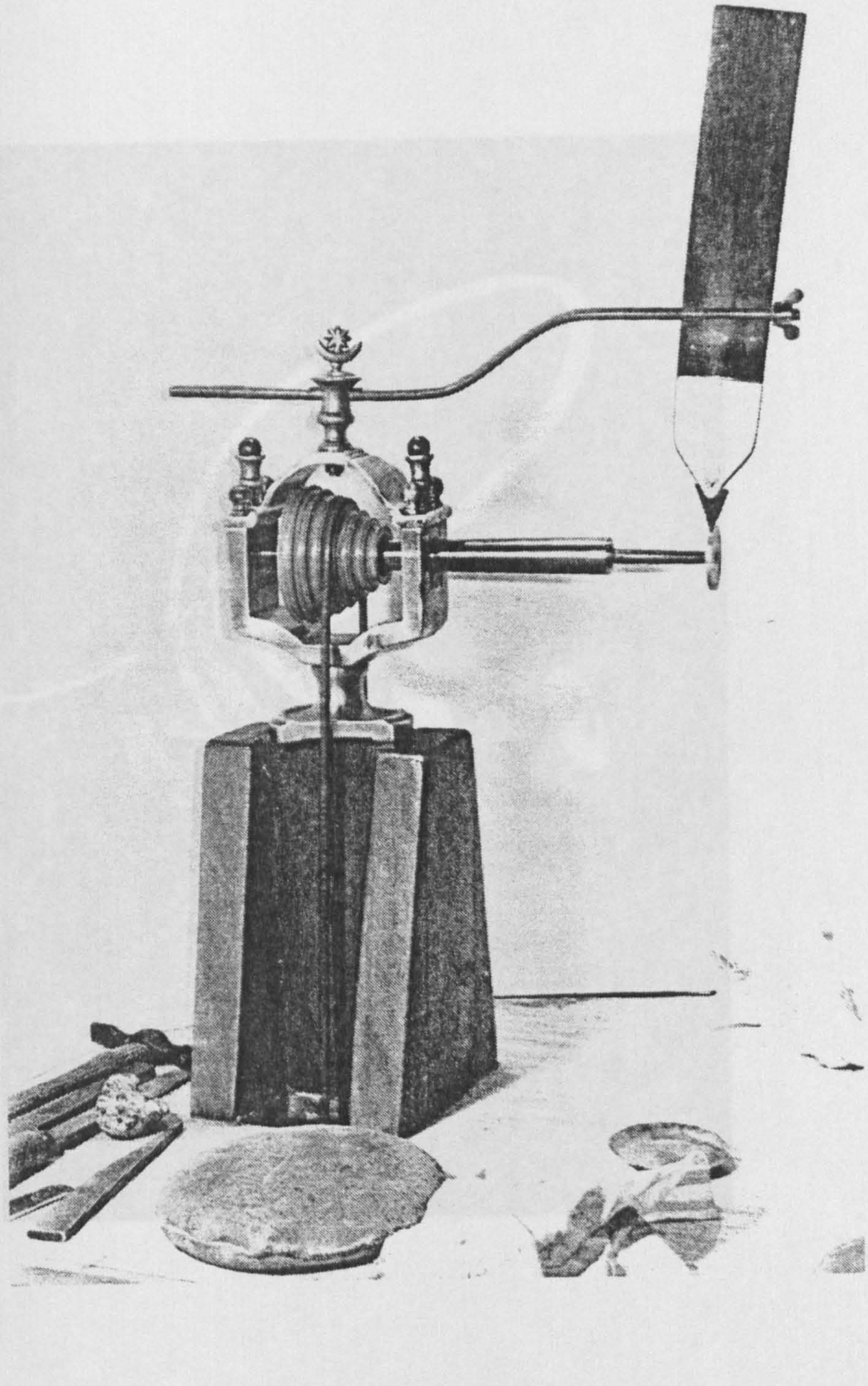


Figure 19. Flexible drive equipment, constructed by the author, photograph by the author.

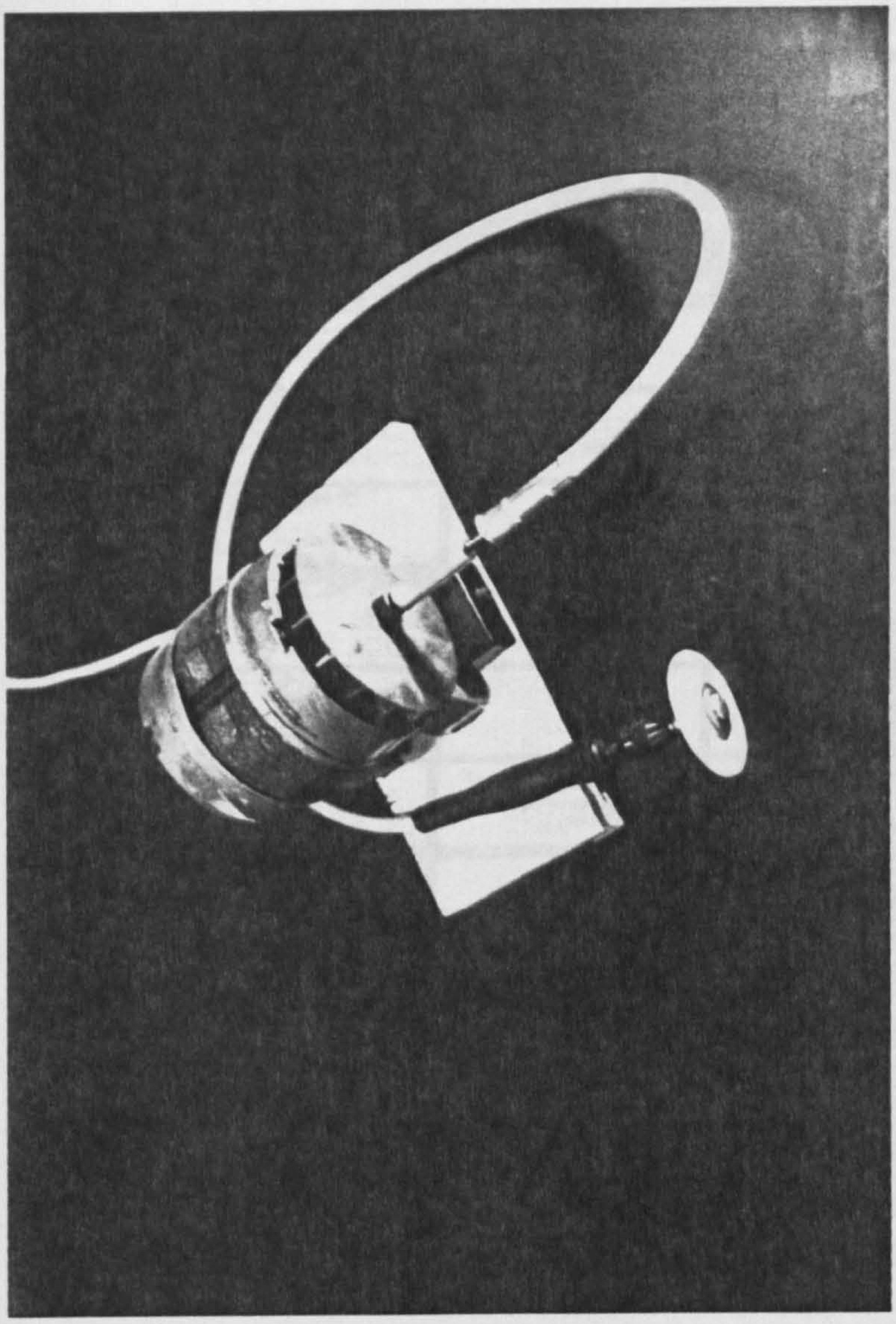


Figure 20. The Great West Window by John Hutton, post card unattributed. Original in colour.

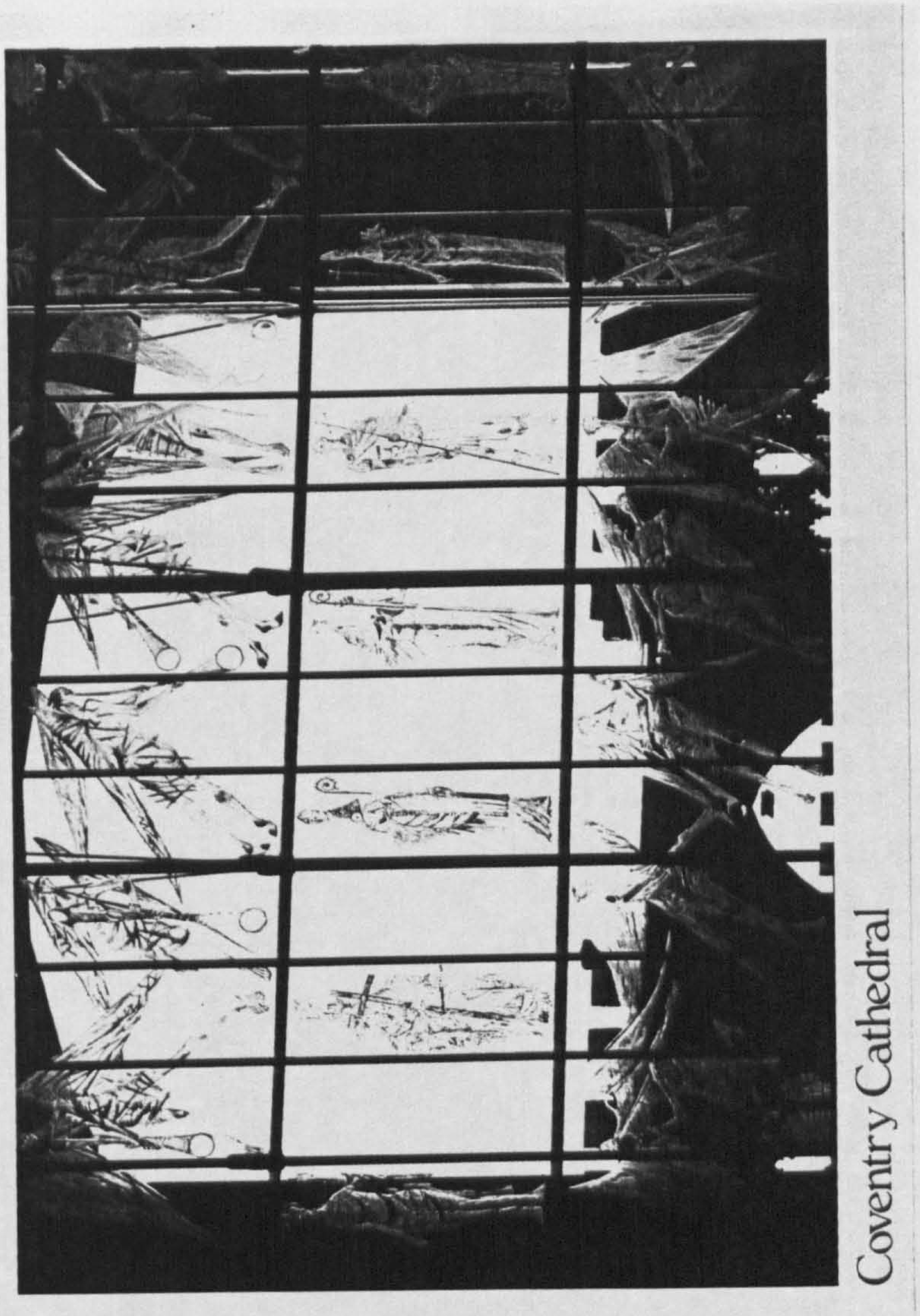


Figure 21. An example of four axis CNC brilliant cutting, photograph by the author.

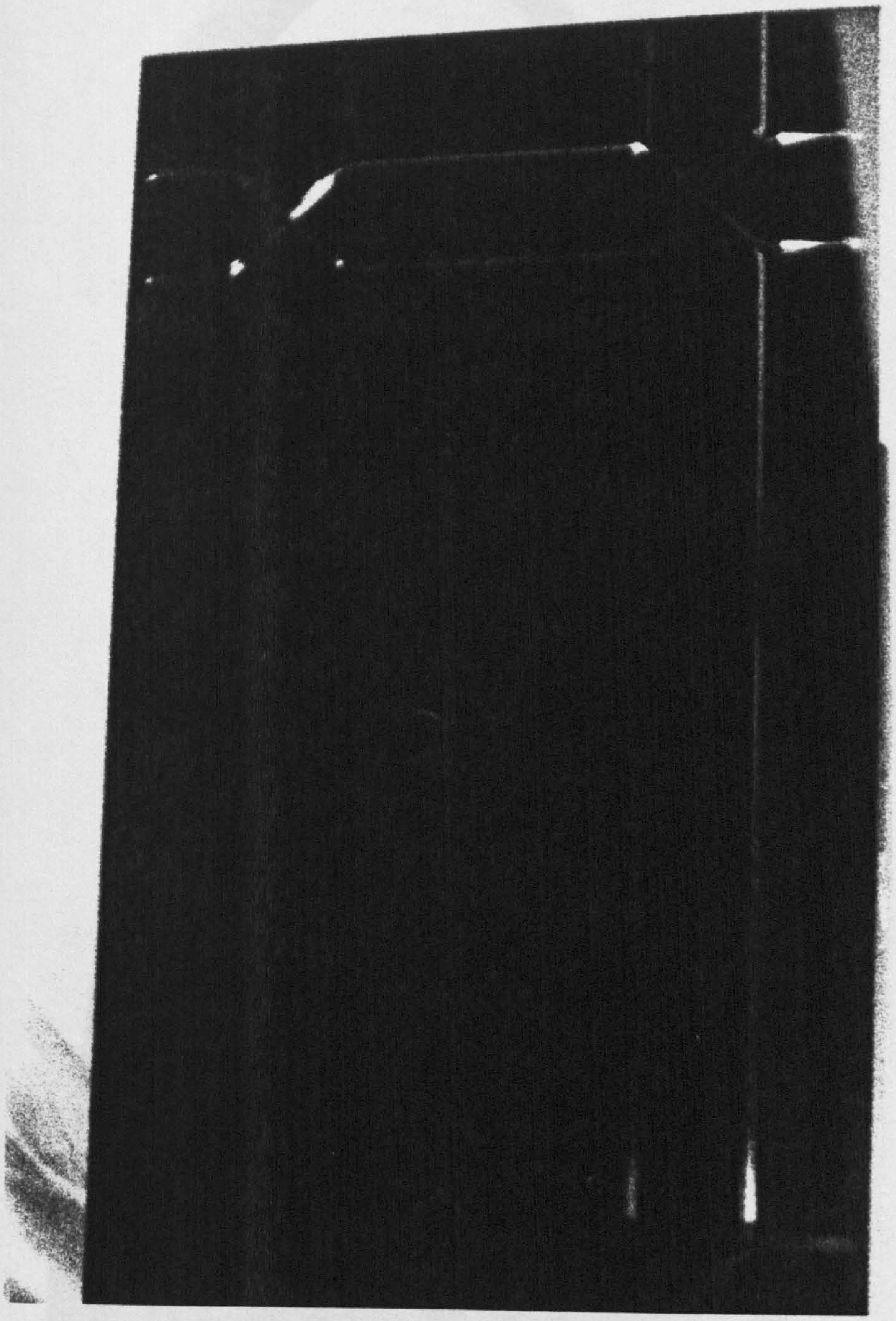
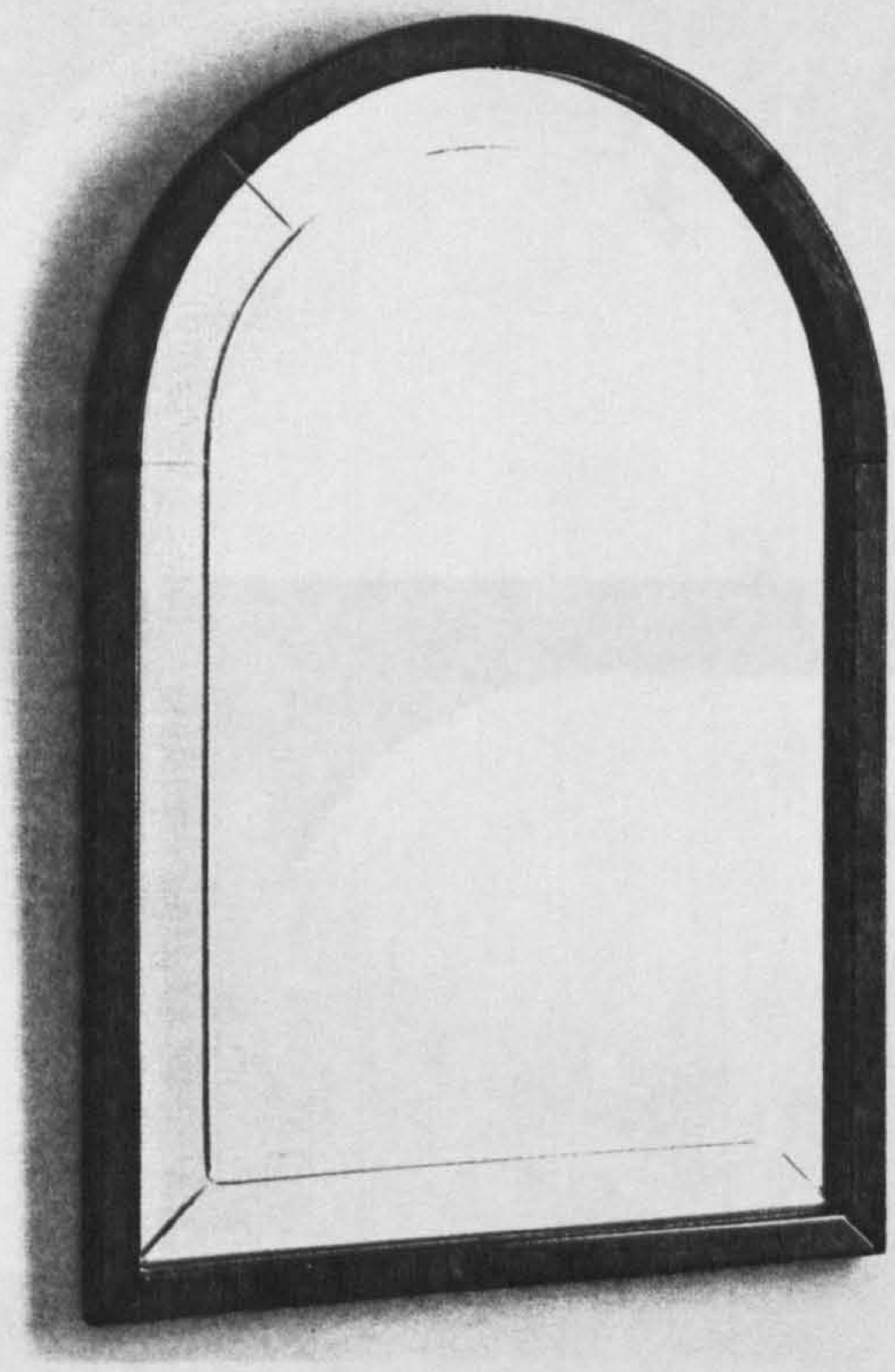


Figure 22.
(Above) An example of a four axis brilliant cut mirror.(Image Glassware Ltd. [25]) Original in colour.
(Below) LP motif designed by the author from "Leicester Polytechnic" logo and produced on the Intermac machine, photograph by the author.



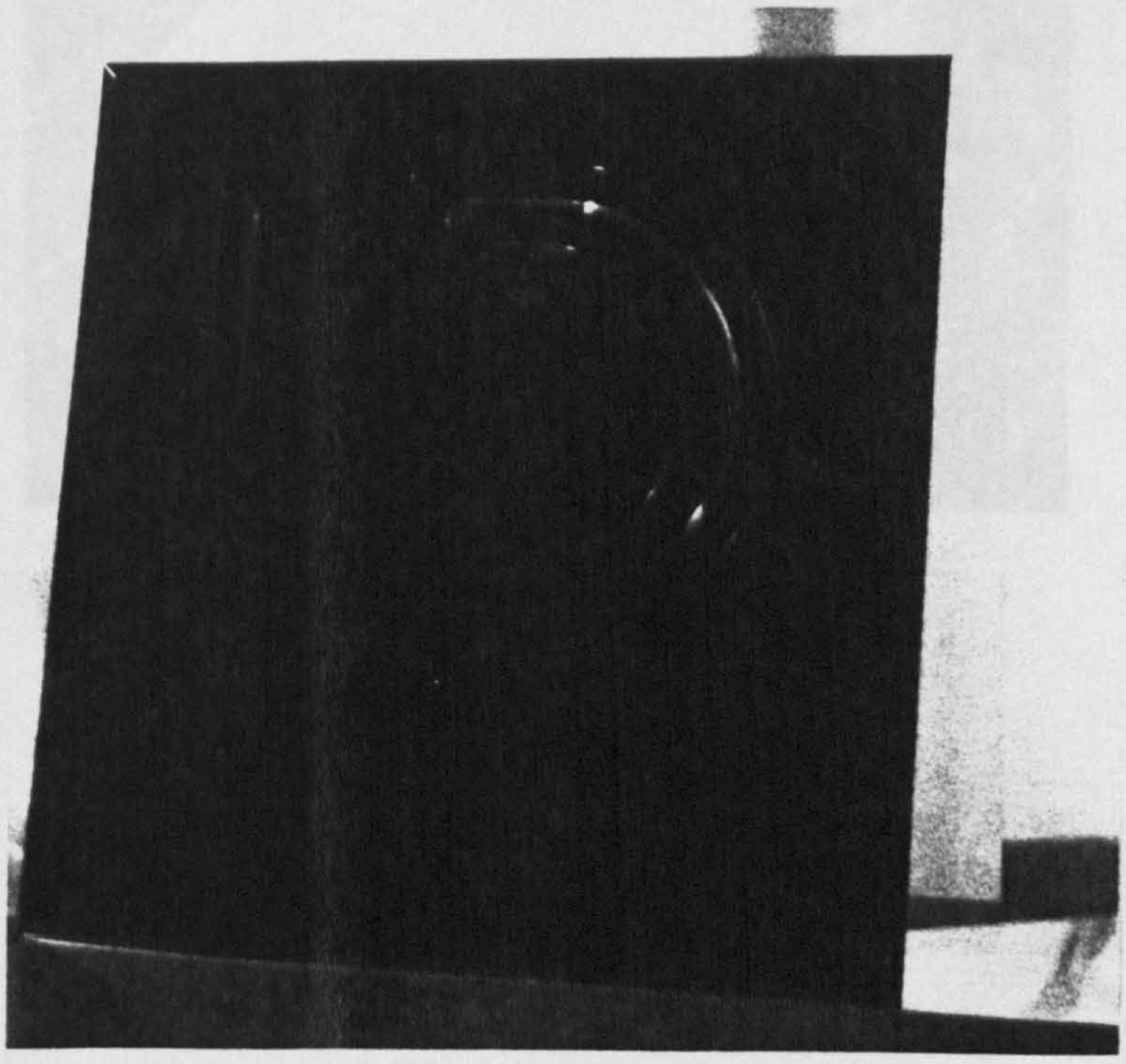


Figure 23. Inexpensive hand cut mirrors, [25]. Original in colour.

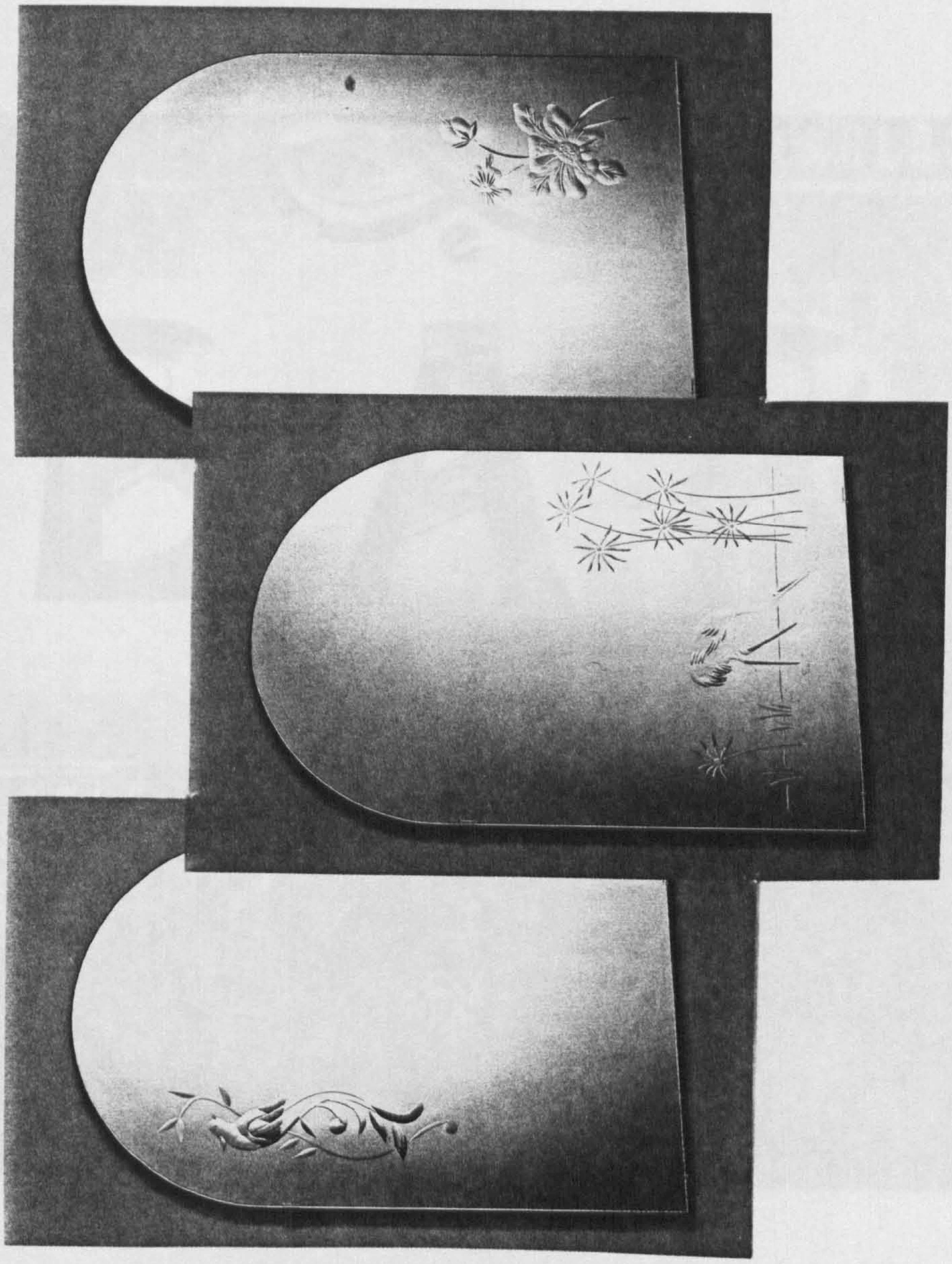


Figure 24. A contempory panel of ornate design produced for an advertisement for Solaglass Ltd. The design of the letters "BAR" is distinctive and unusual.

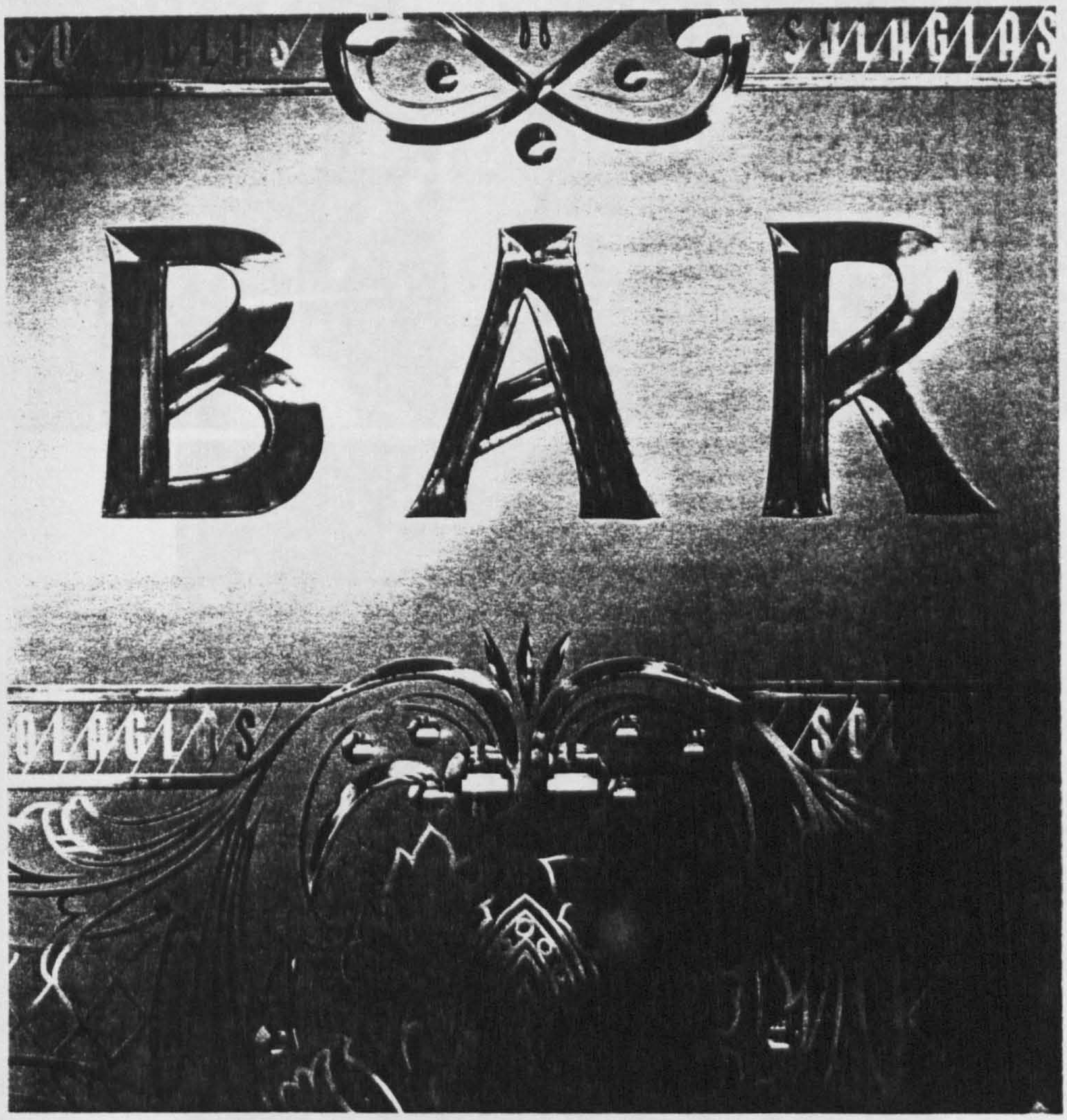


Figure 25. Mirrors of exceptionally ornate design, produced to commission by Sekon glass Ltd., photograph by the author. Original in colour.

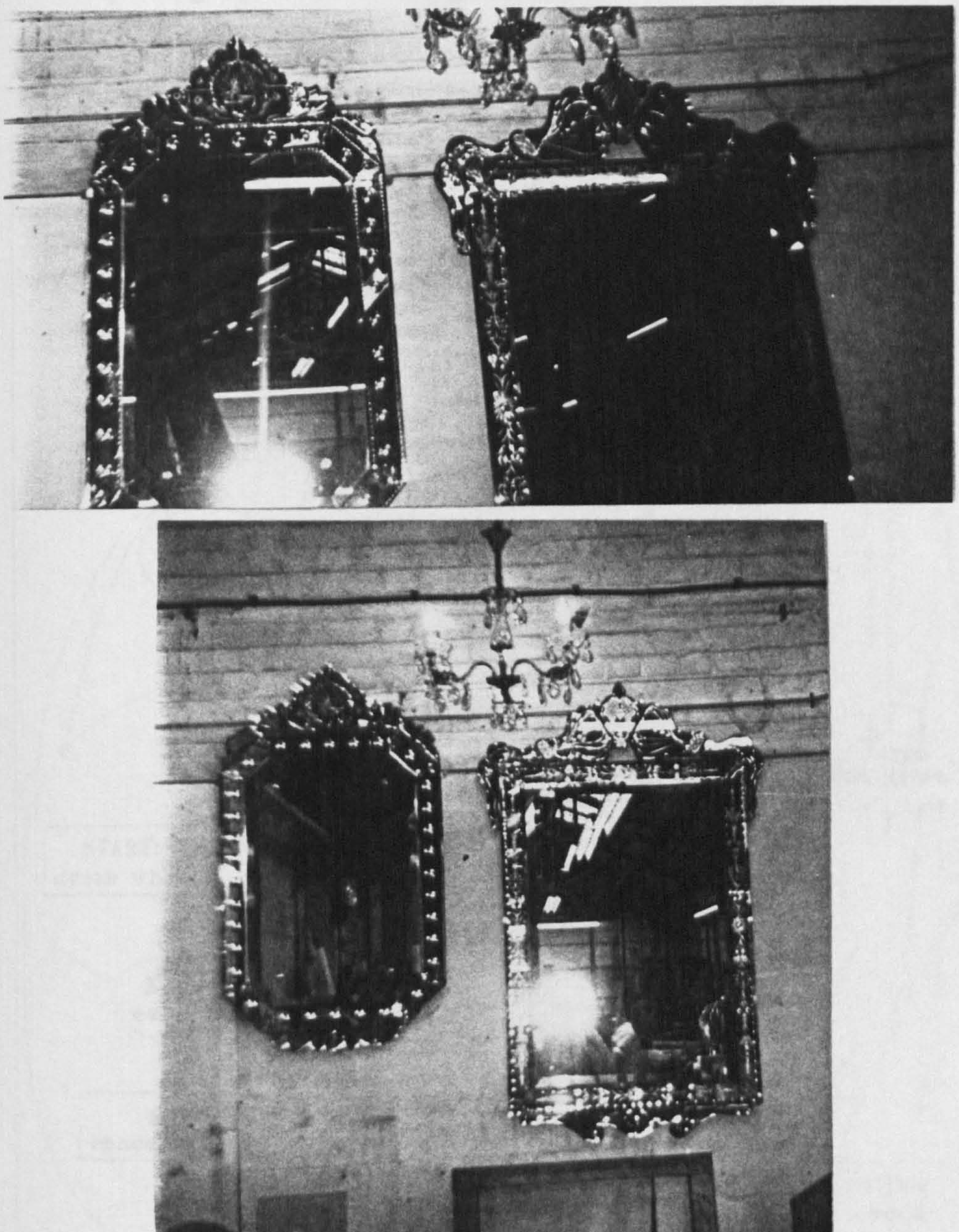


Figure 26. Diagram depicting the relationships between parameters during the grinding of glass with diamond.

Rectangles determined designed, fixed, input parameters.

Ellipses signify resultant cutting parameters.

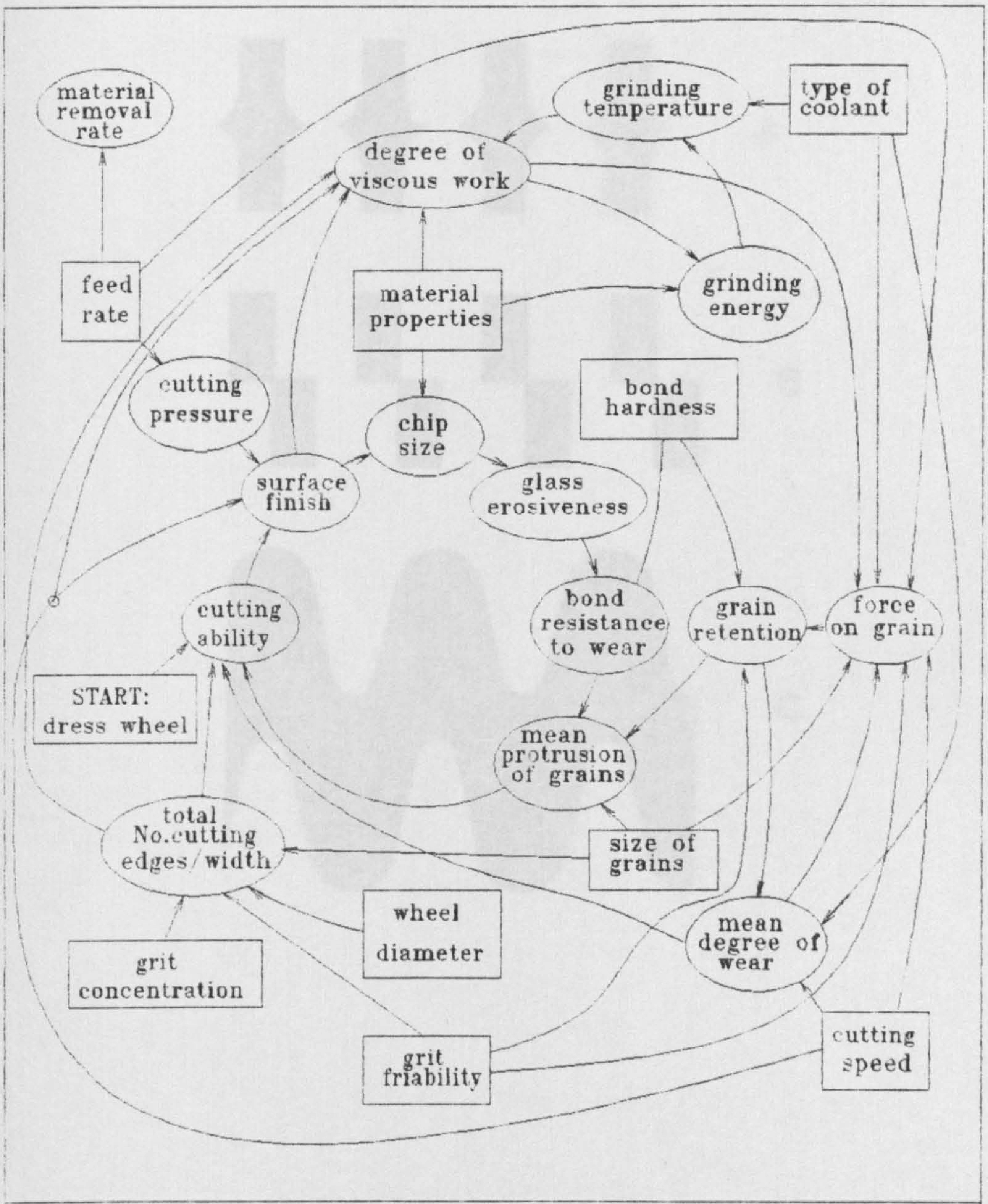


Figure 27. Wheel tread pattern used for metal bonded diamond wheels.

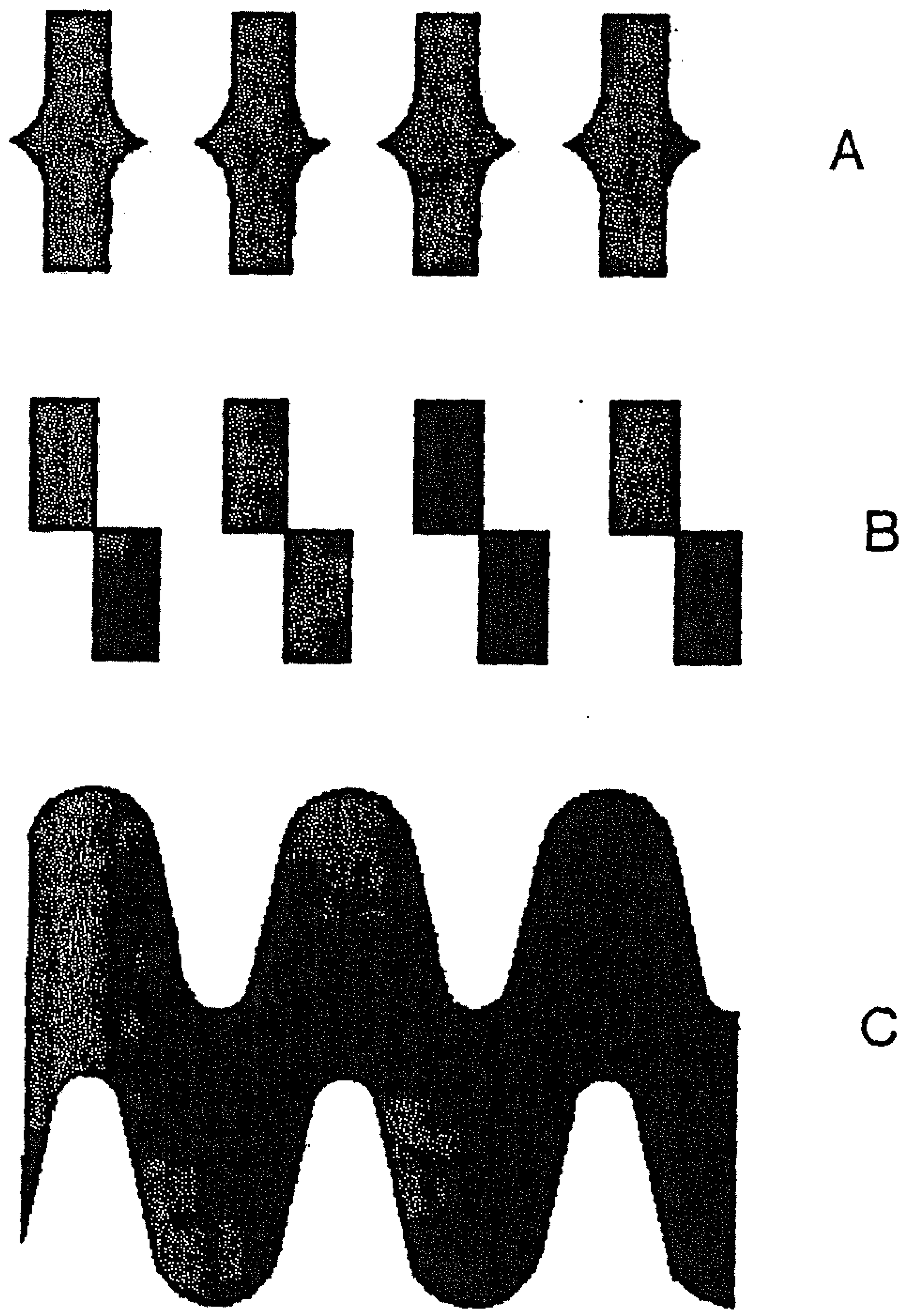


Figure 28. The Characteristic grinding rate/ surface speed curve as determined by Matusek [60]. Matusek measured grinding rate as the thickness of the layer of glass removed in unit time. Different grinding pressures produce curves of similar characteristic shape but different absolute grinding rate.

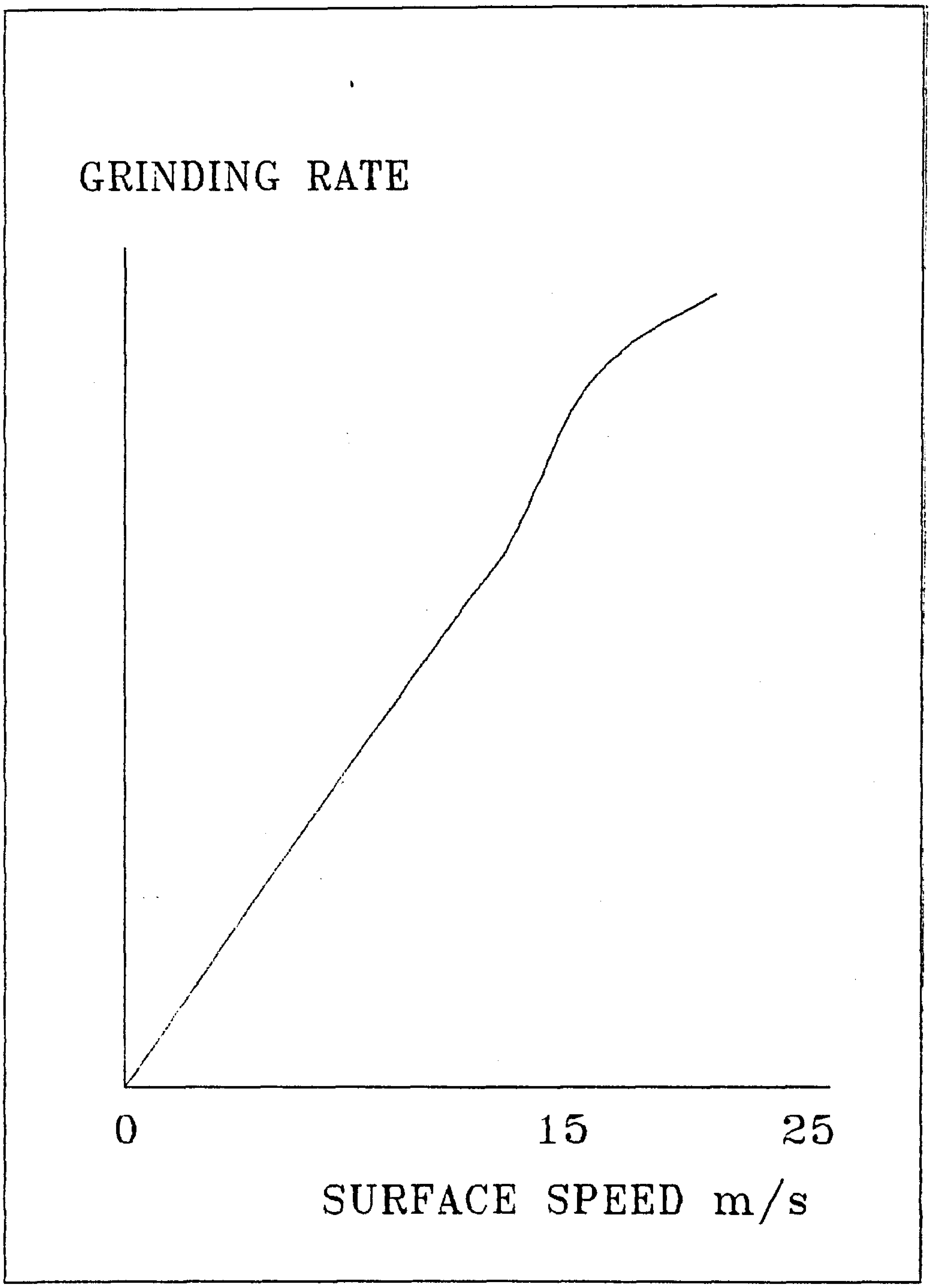


Figure 29. The production of fine finish bevels using cup wheels.

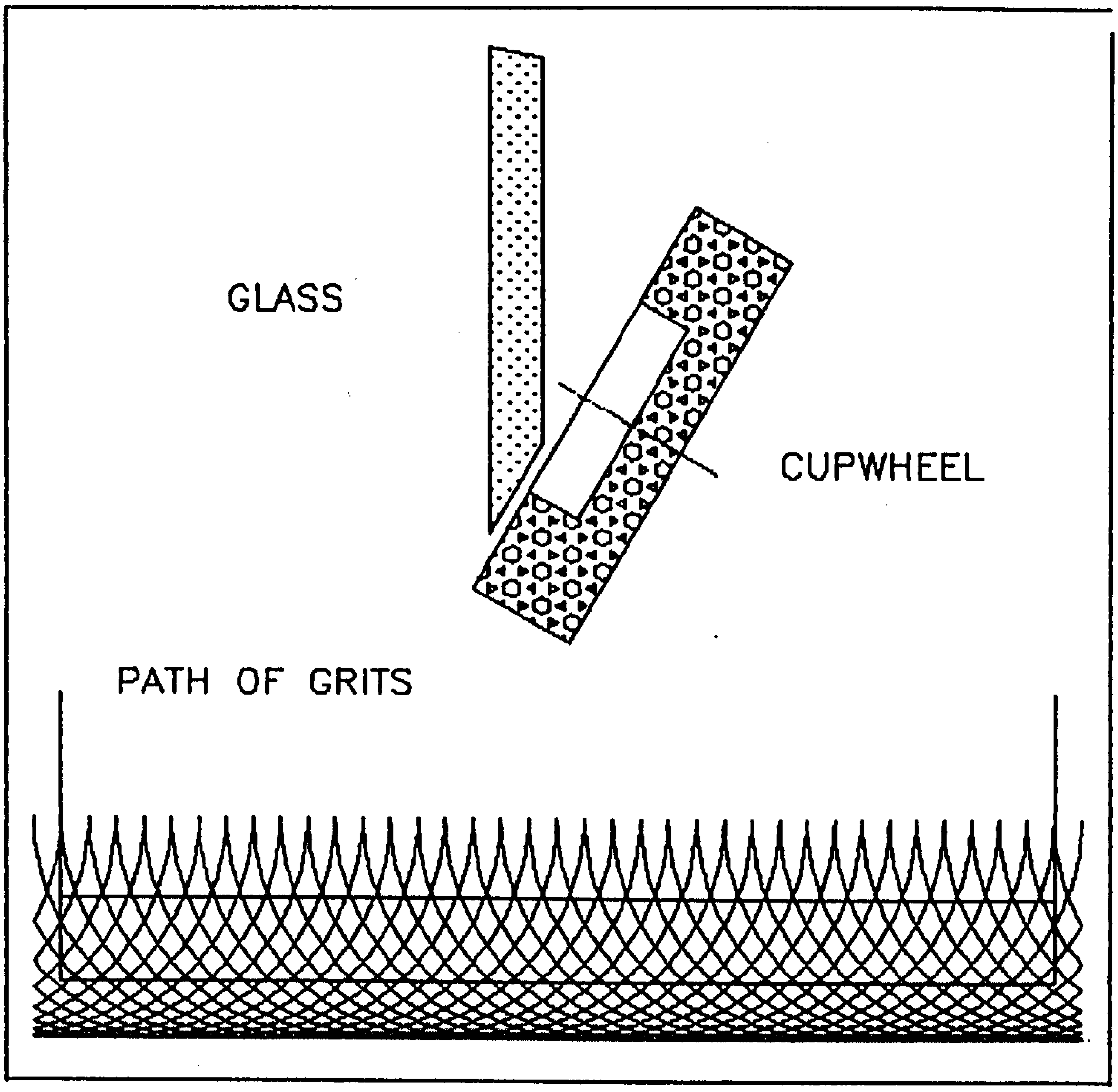


Figure 30 panel (i). Cuts possible with the brilliant cutting CAD/CAM system.

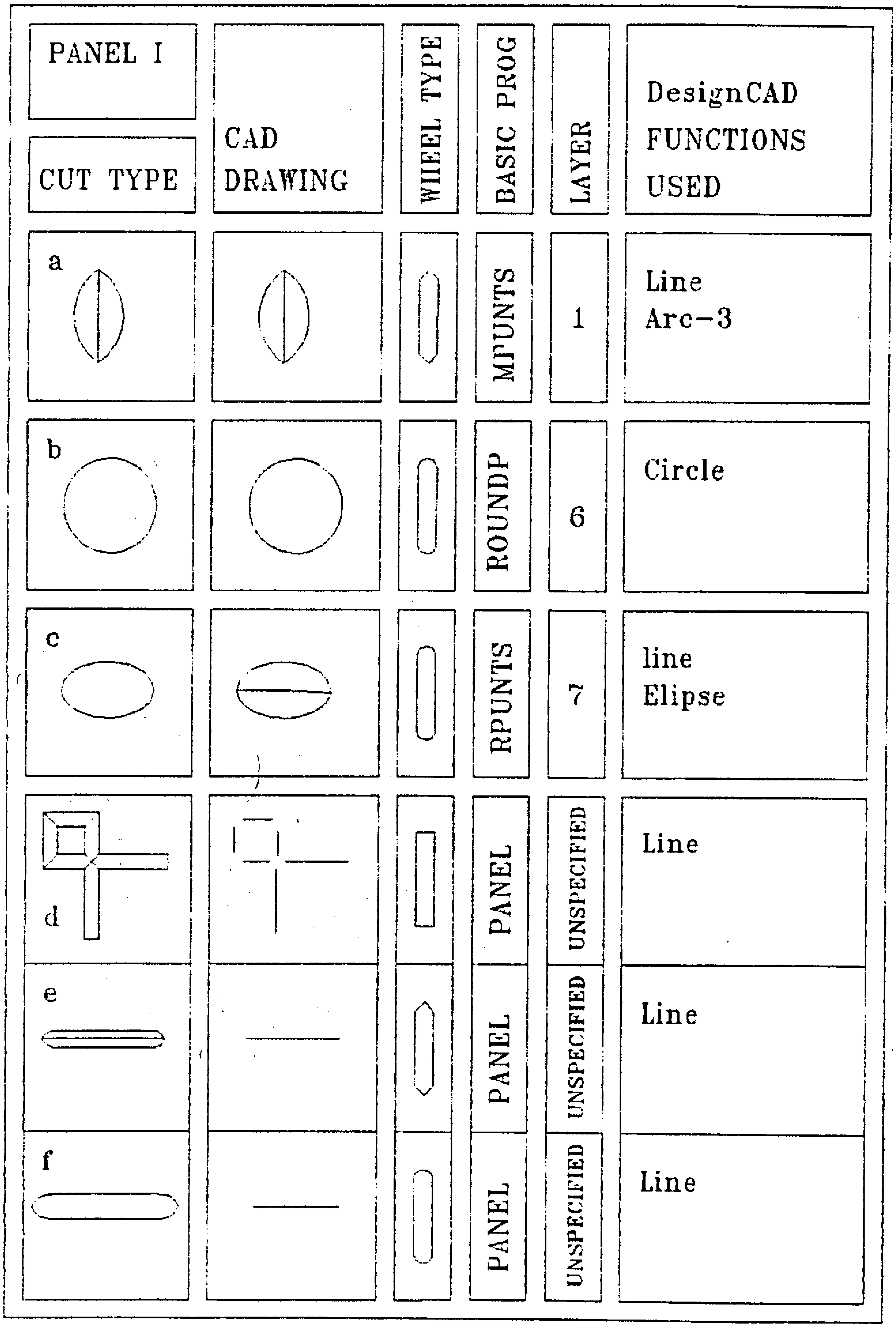


Figure 30 panel (ii). Cuts possible with the brilliant cutting CAD/CAM system continued.

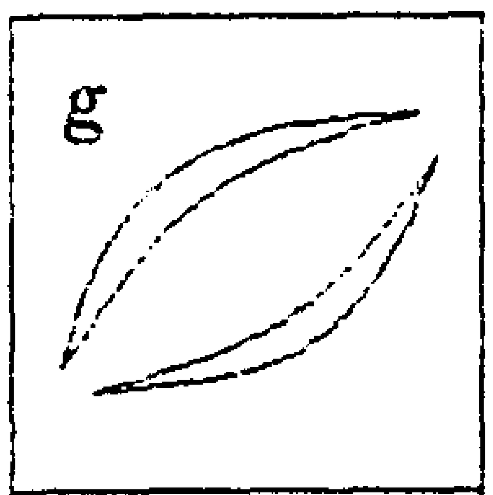
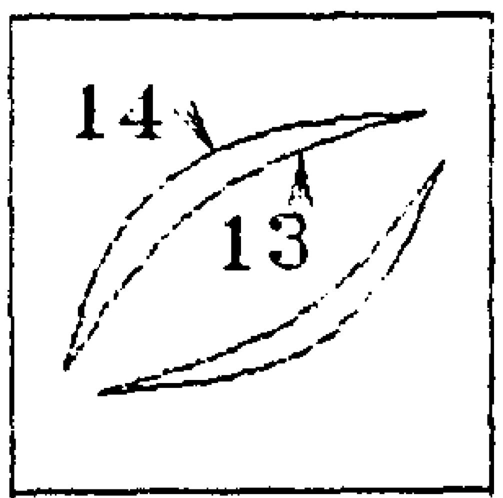
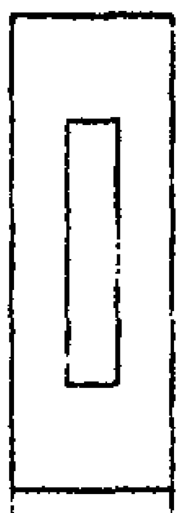
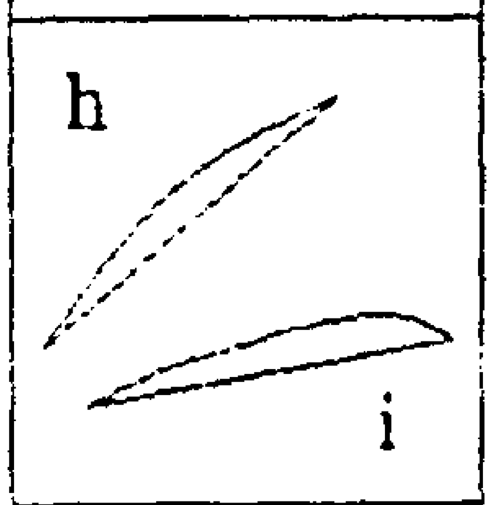
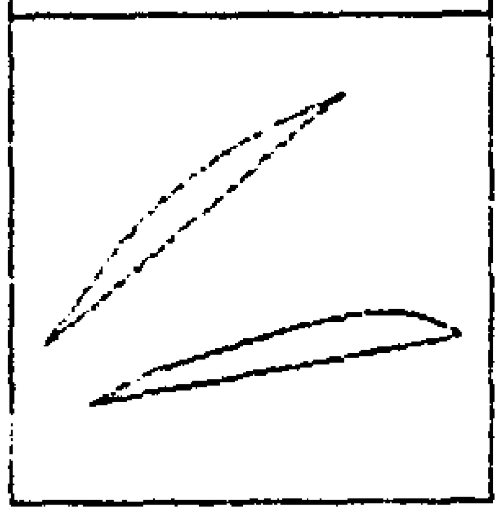
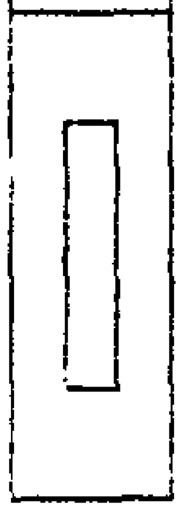
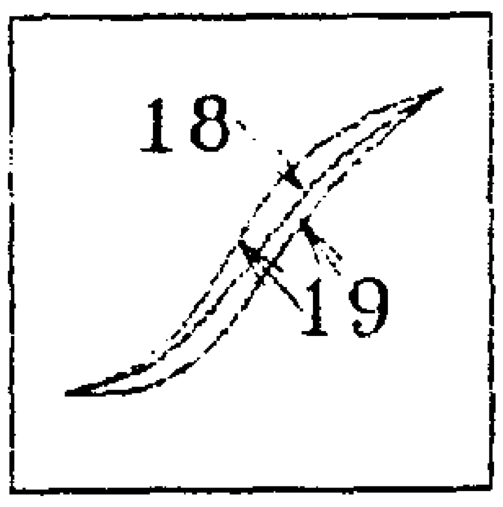
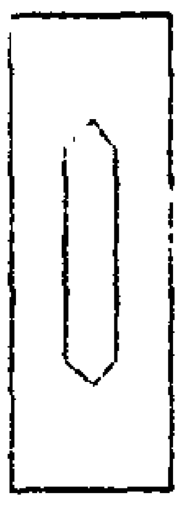
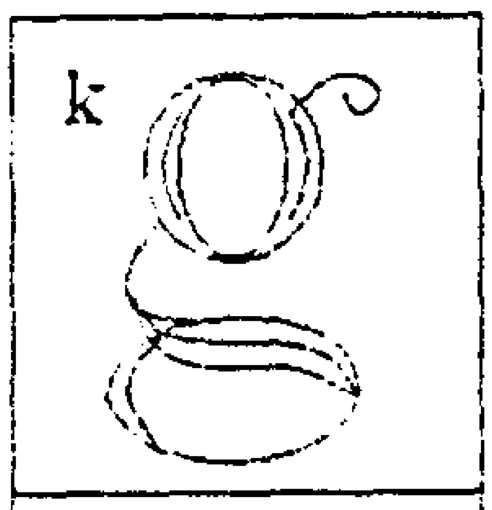
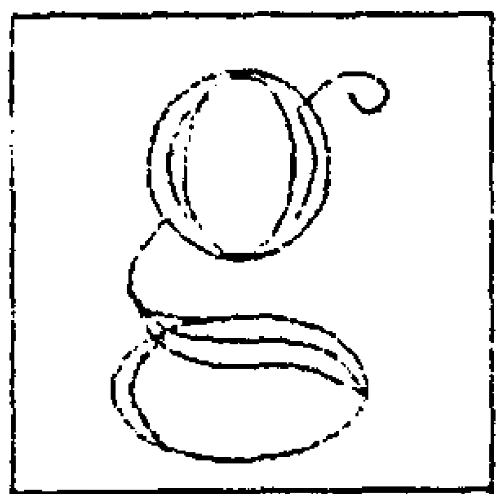
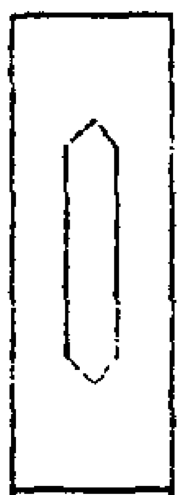
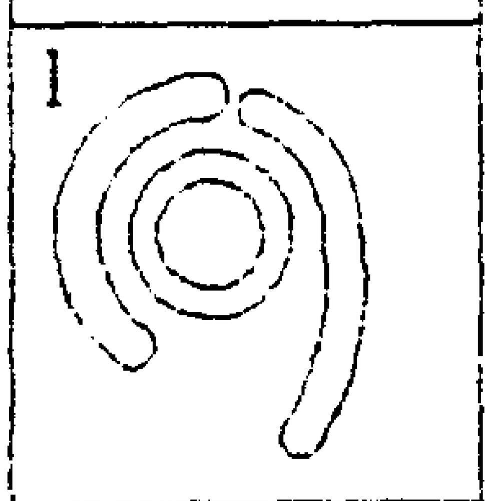
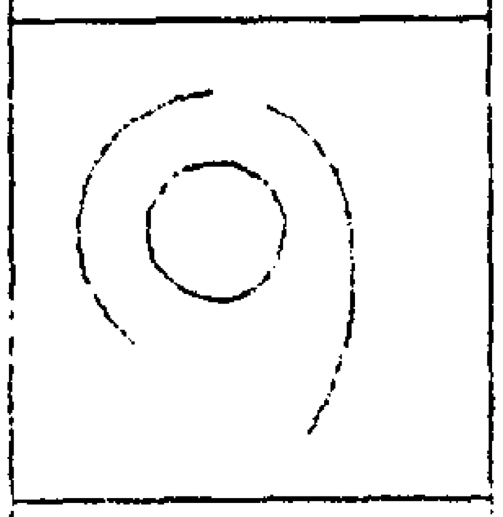
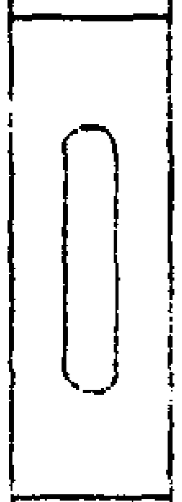
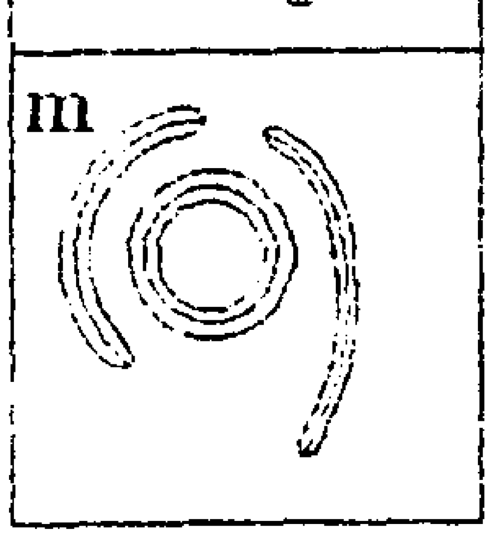
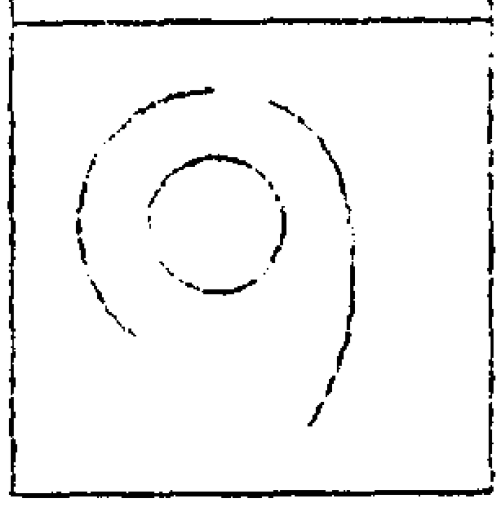
PANEL II CUT TYPE	CAD DRAWING	WHEEL TYPE	BASIC PROG	LAYER	DesignCAD FUNCTIONS USED
g 	 14 13		CRESCENT	13 14	Curve ArcV Join Combine
h i 			SEGMENTS	11	Curve ArcV Line Join Combine
j 	 18 19		MITRES	18	Curve ArcV Join Combine
k 			LINEWORK	UNSPECIFIED	Curve CircleV ElipseV ArcV Join Combine
l 			LINEWORK	UNSPECIFIED	
m 			LINEWORK	UNSPECIFIED	

Figure 31. Function icon overlay developed for the brilliant cutting CAD system.

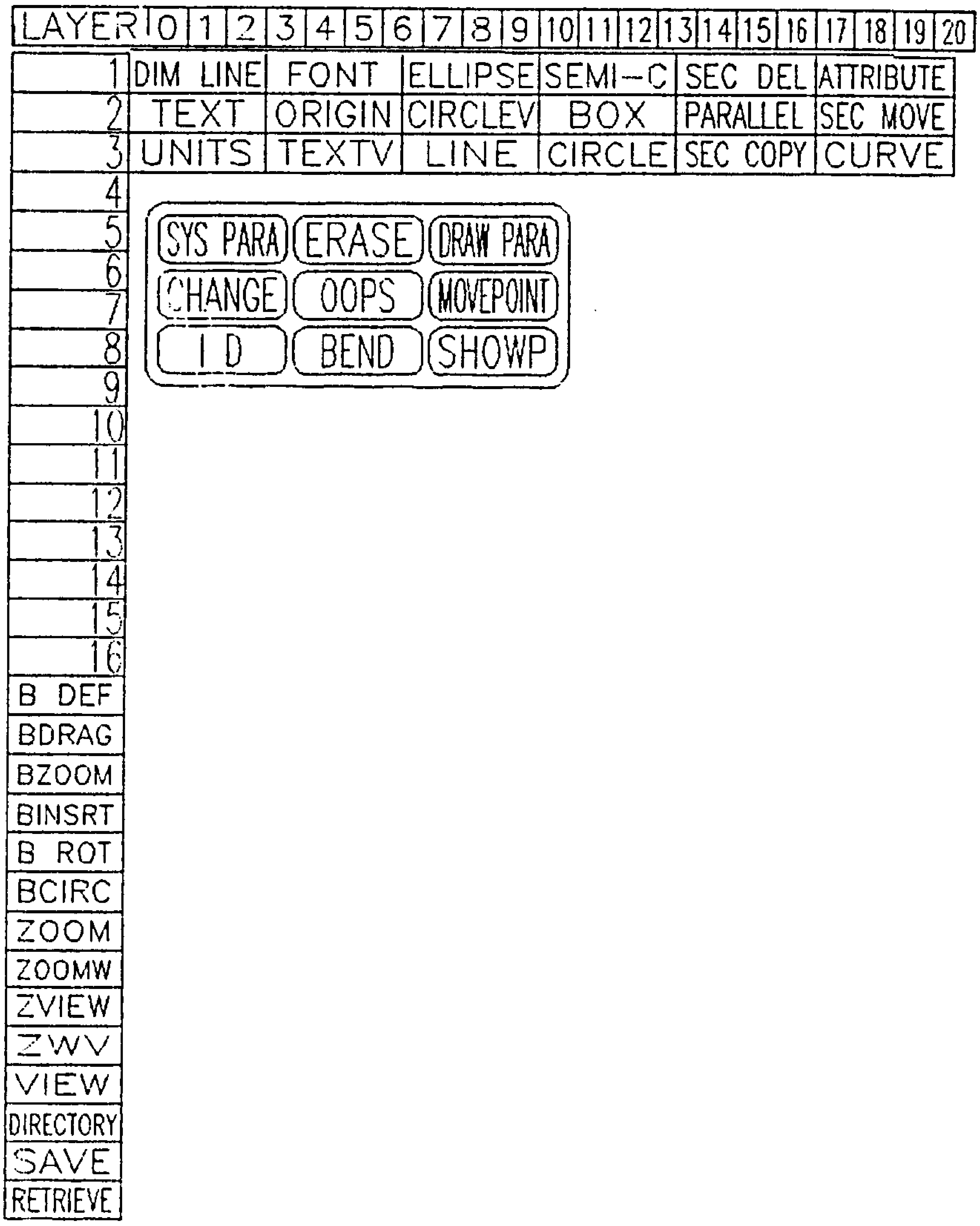


Figure 32. Graphs denoting the non-linear relationship between width and length for mitred and oval punts. Units are millimetres.

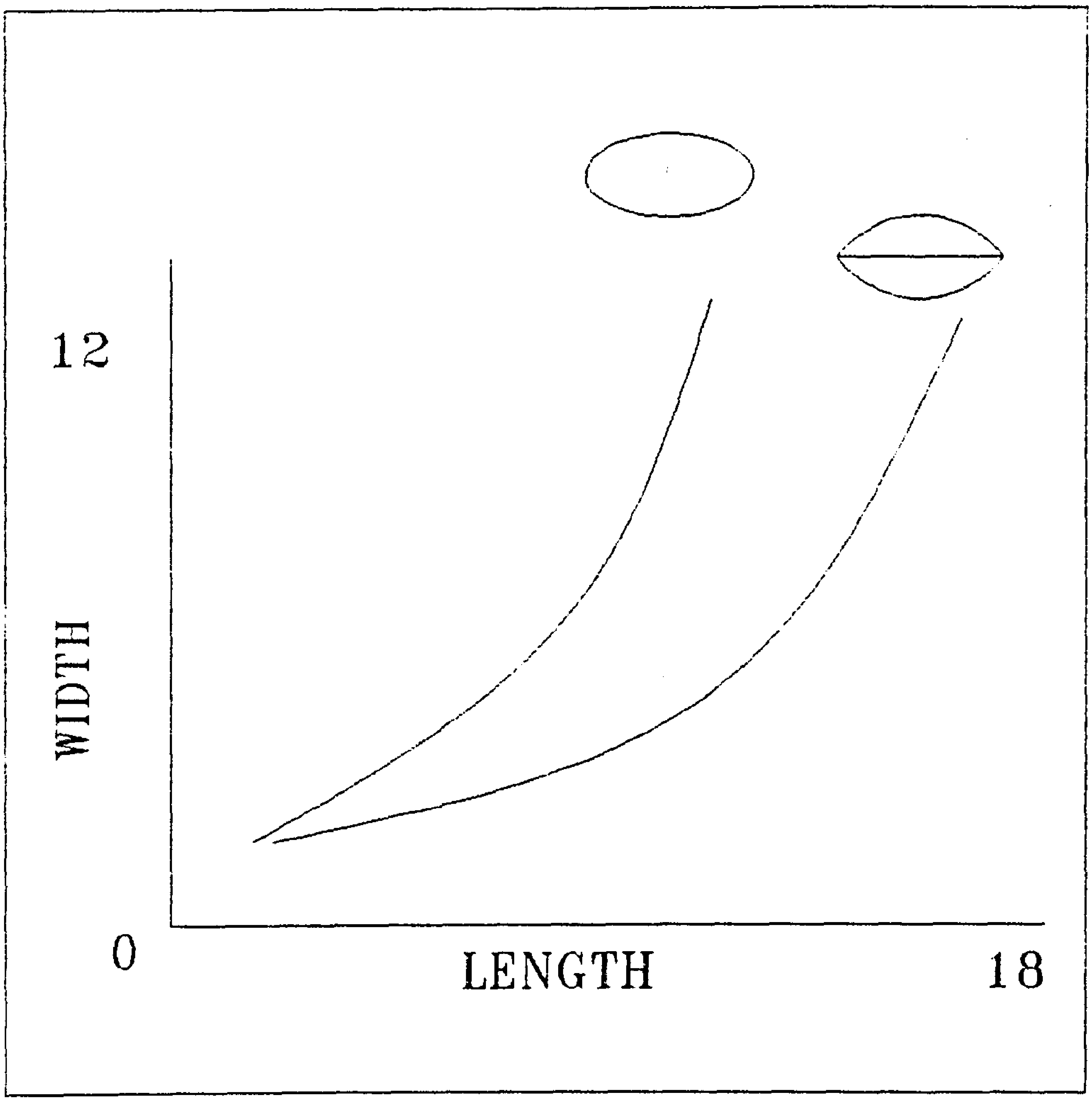


Figure 33. A modular gantry robot produced by Crocus Ltd. [ ].

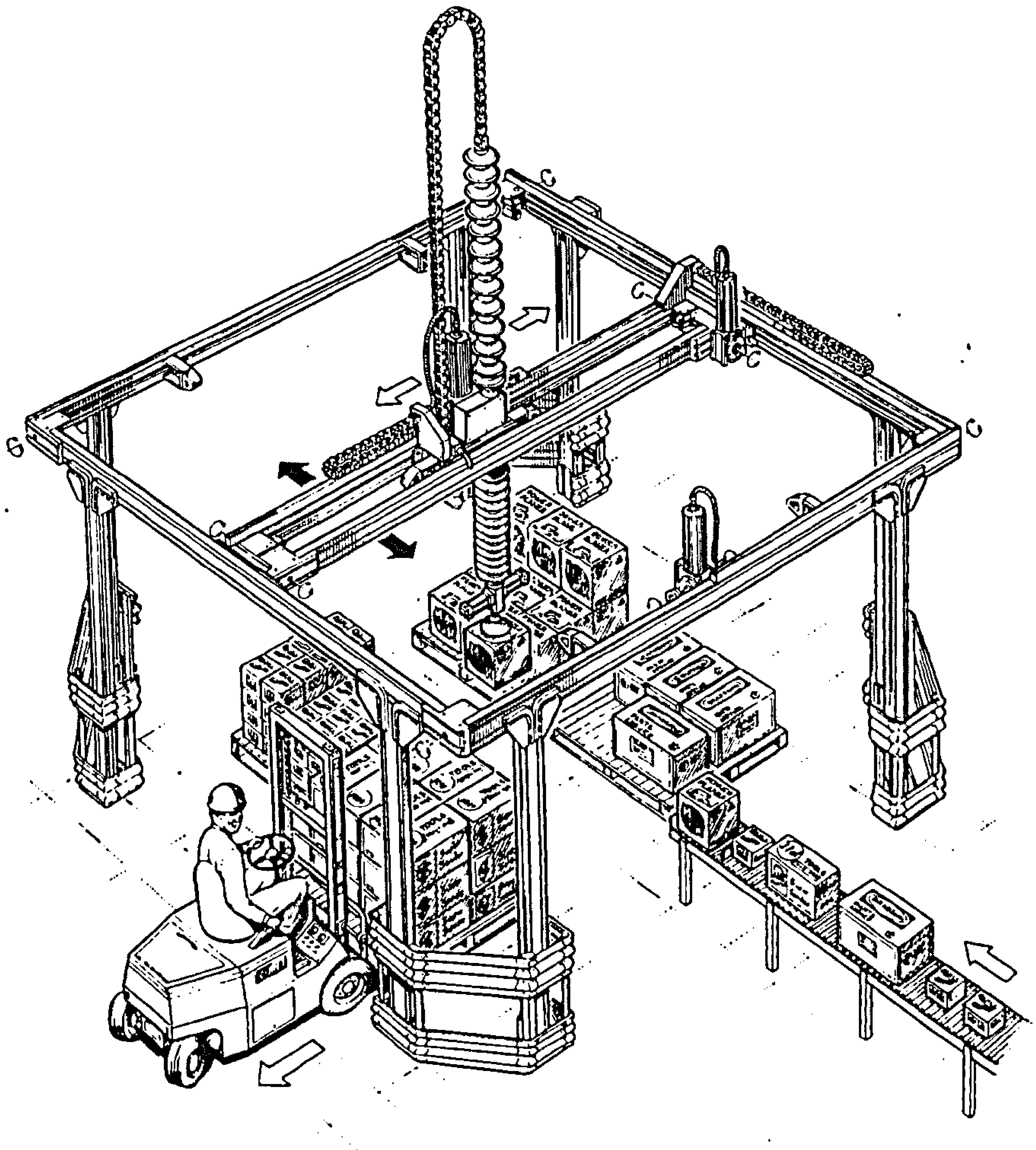


Figure 34. A further example of a modular robot produced by Tollo.

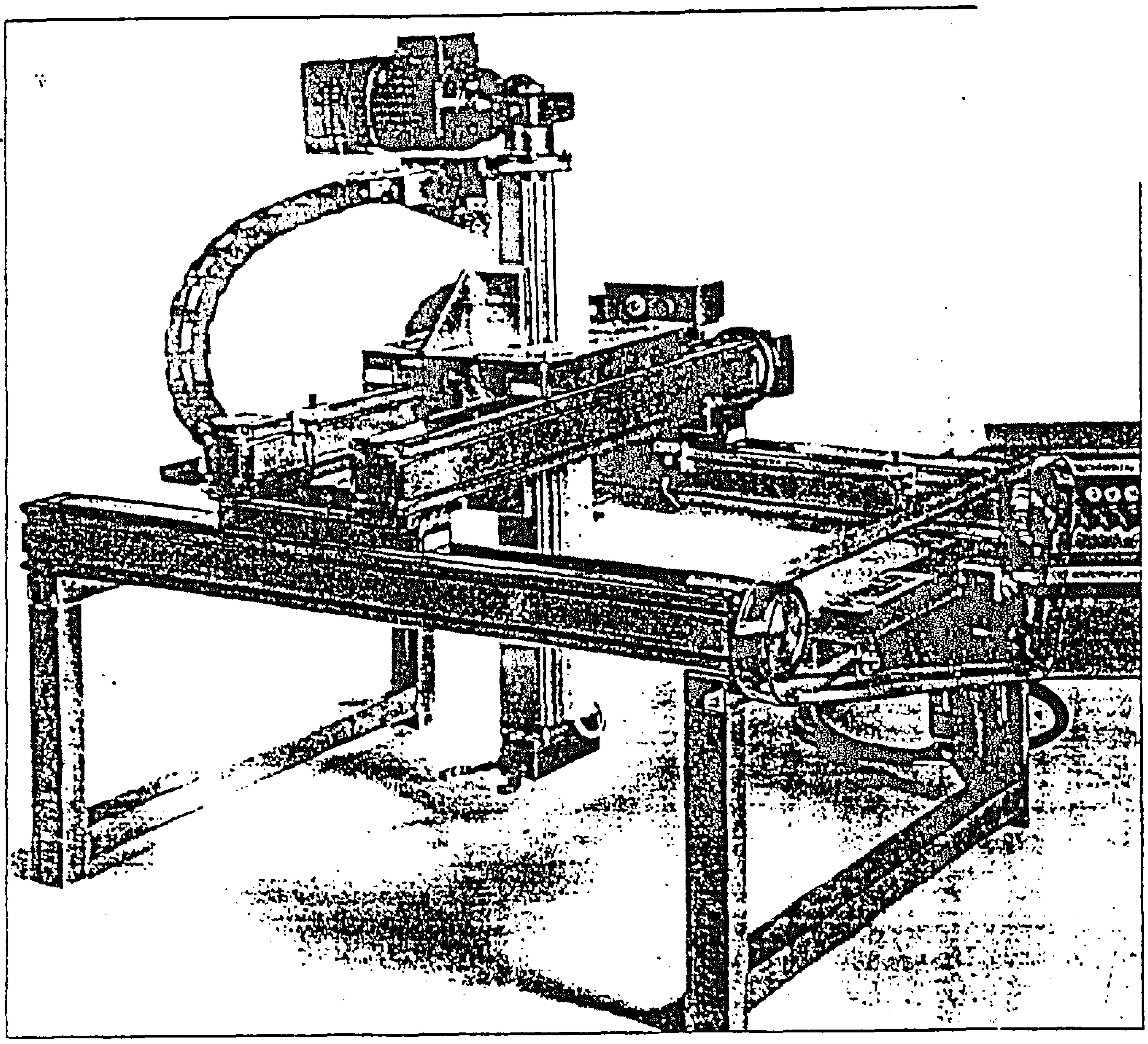


Figure 35. A design concept rendition of a gantry robot for a brilliant cutting machine. Original in colour.

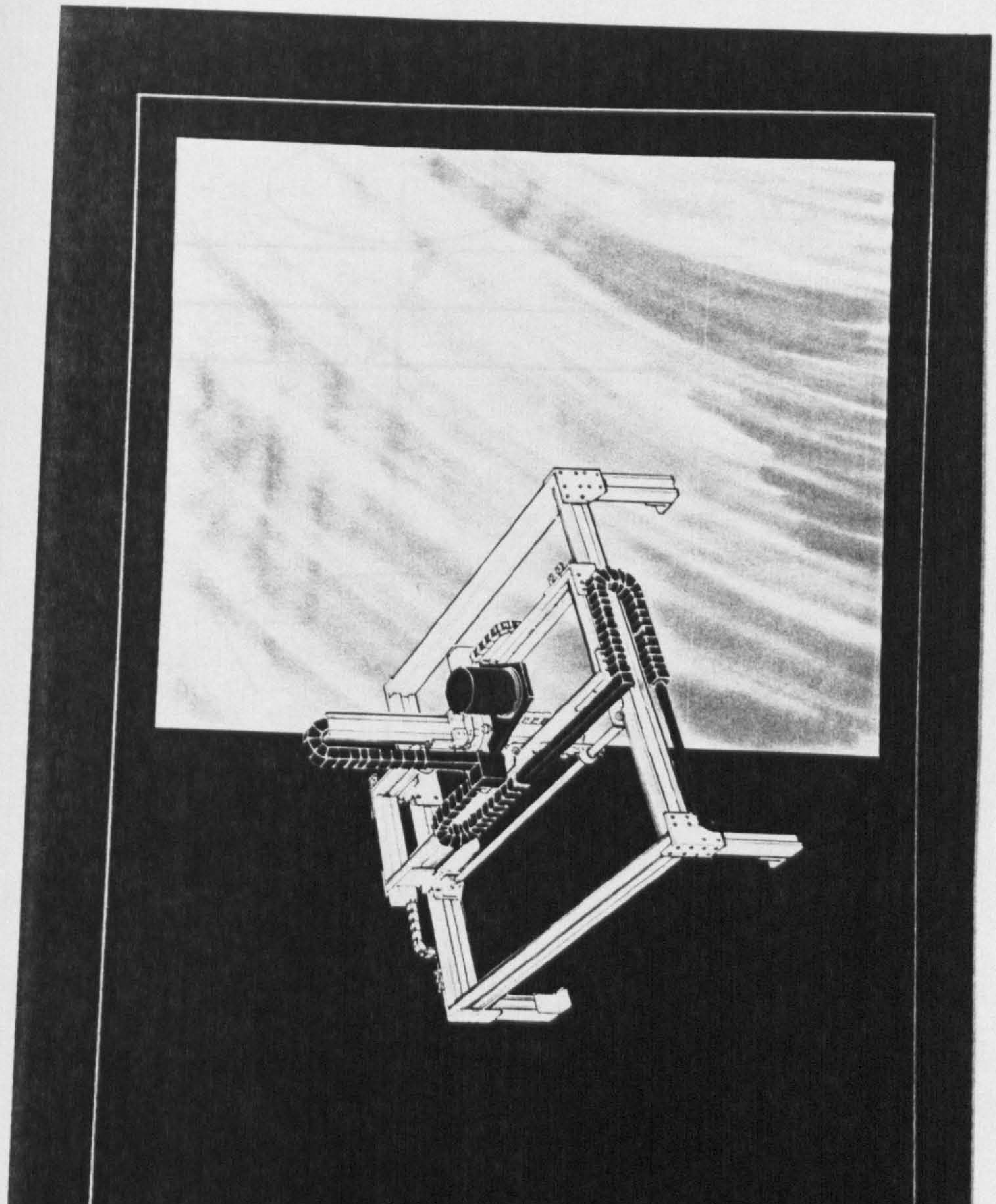


Figure 36. The five axes of the brilliant cutting machine.

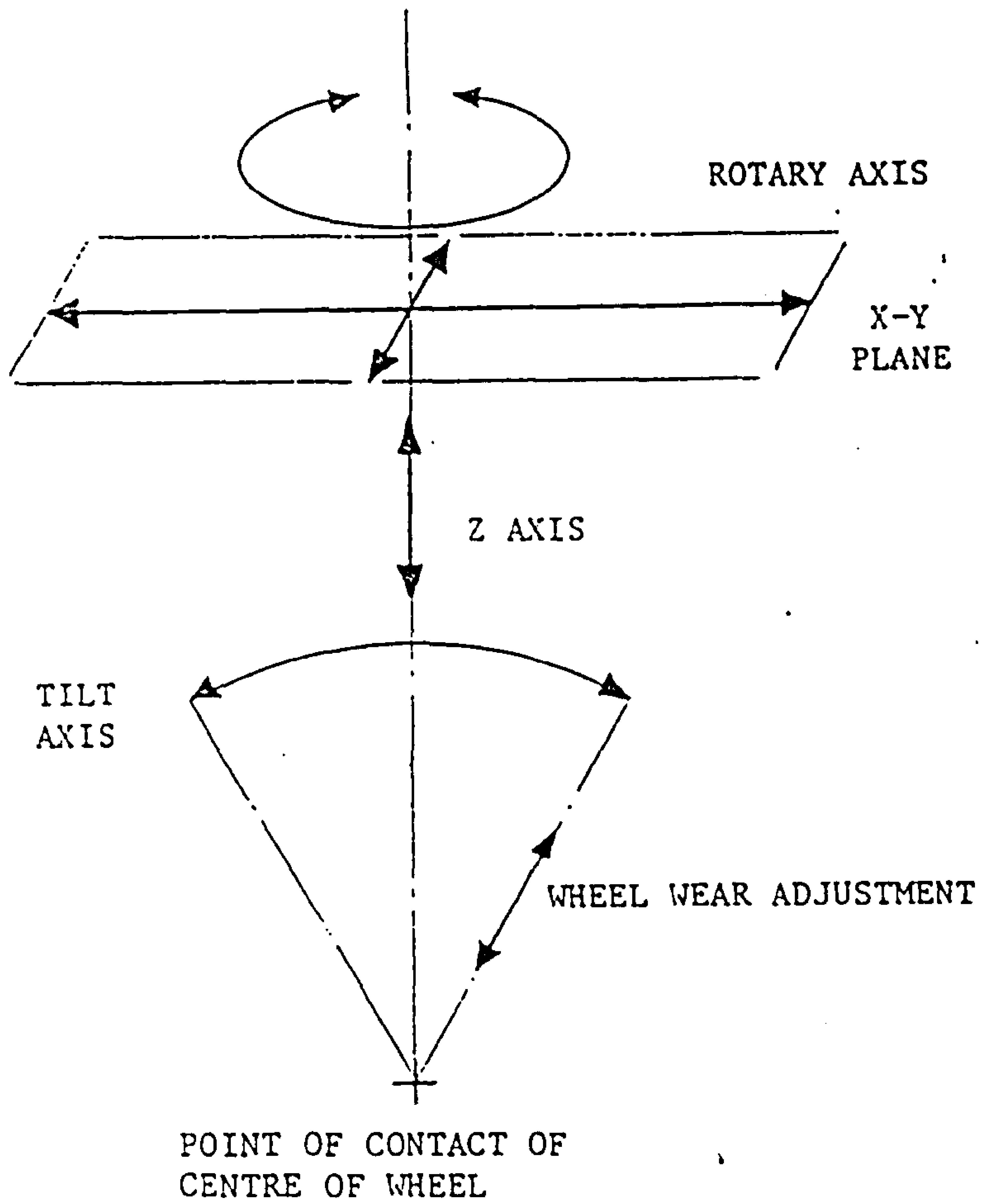


Figure 37. A design concept rendition for mounting the robot. Original in colour.

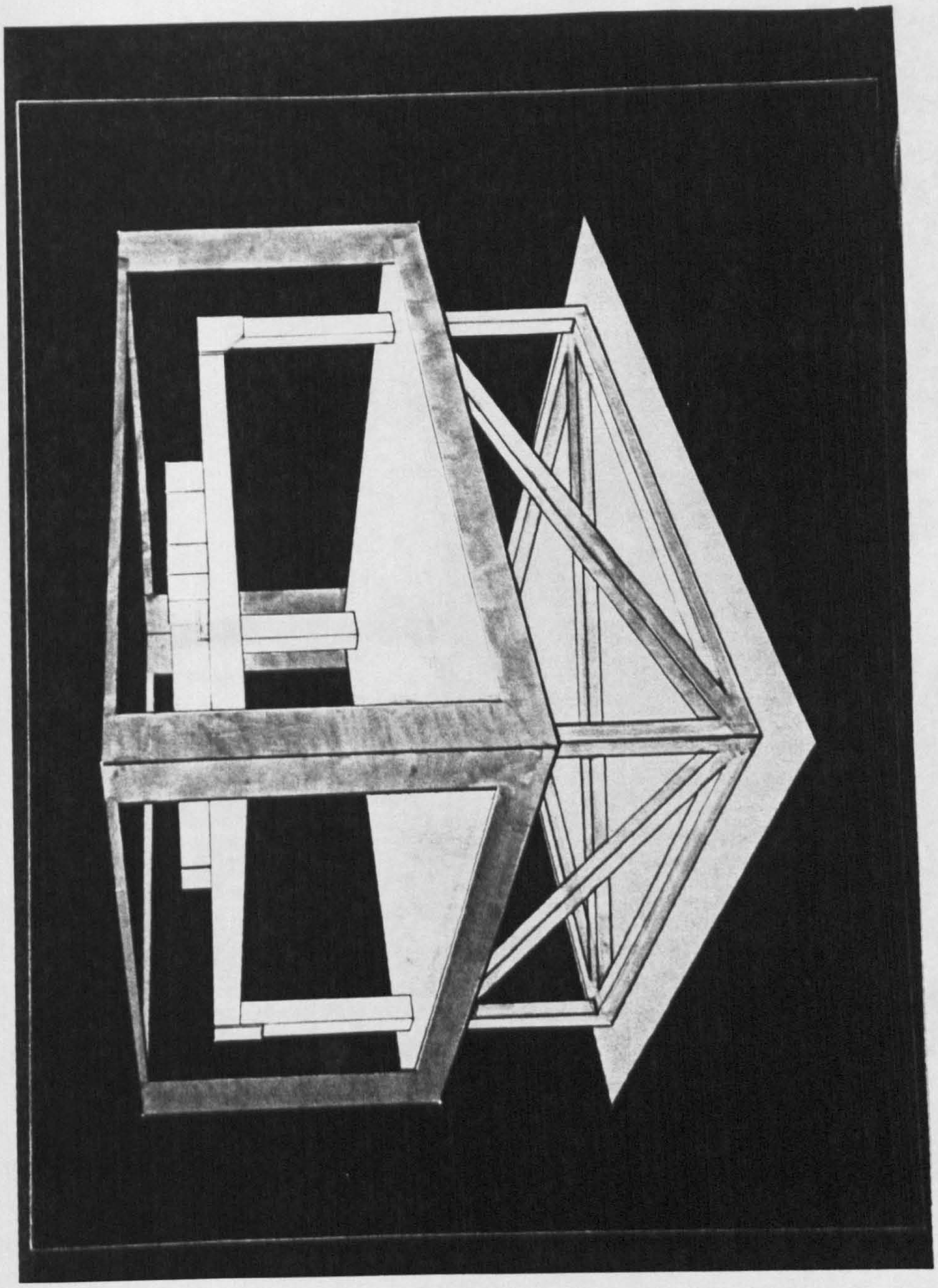


Figure 38. The gantry robot purchased for use as a brilliant cutting machine. Photograph by CAM Systems Ltd.

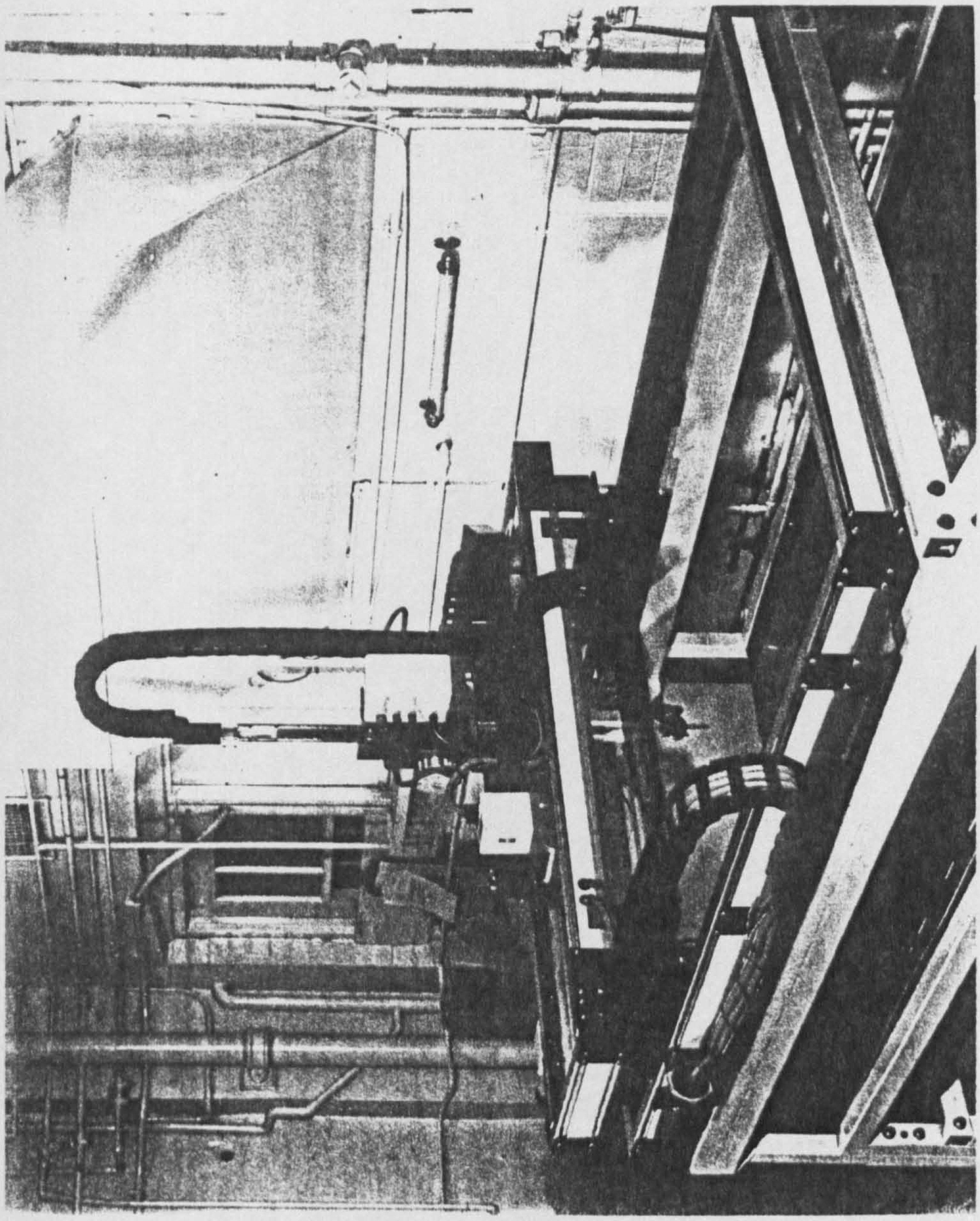


Figure 39. Two alternative concepts for the motion of the tilt- axis.

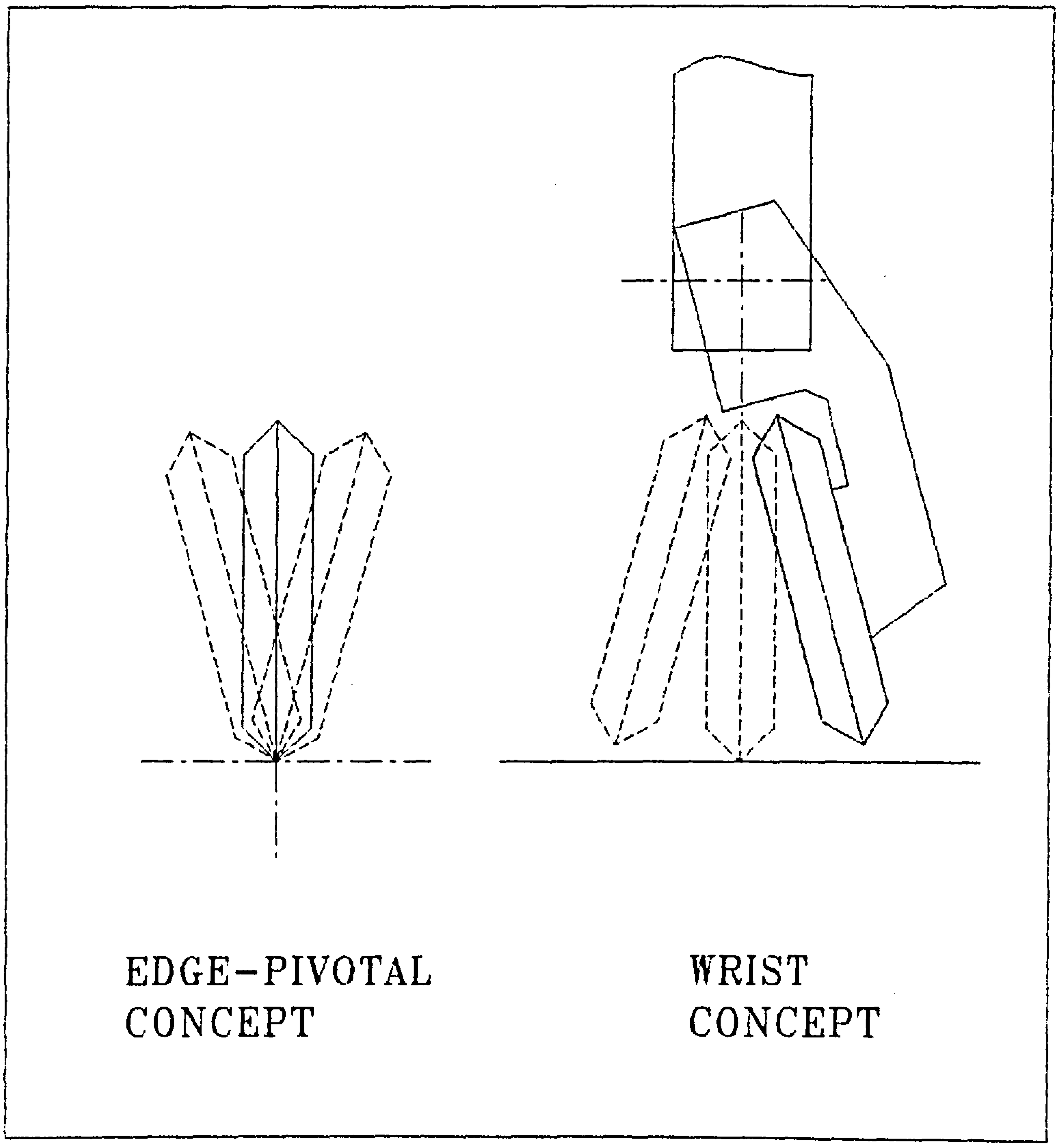


Figure 40. A design concept rendition of the grinding head assembly. Original in colour.

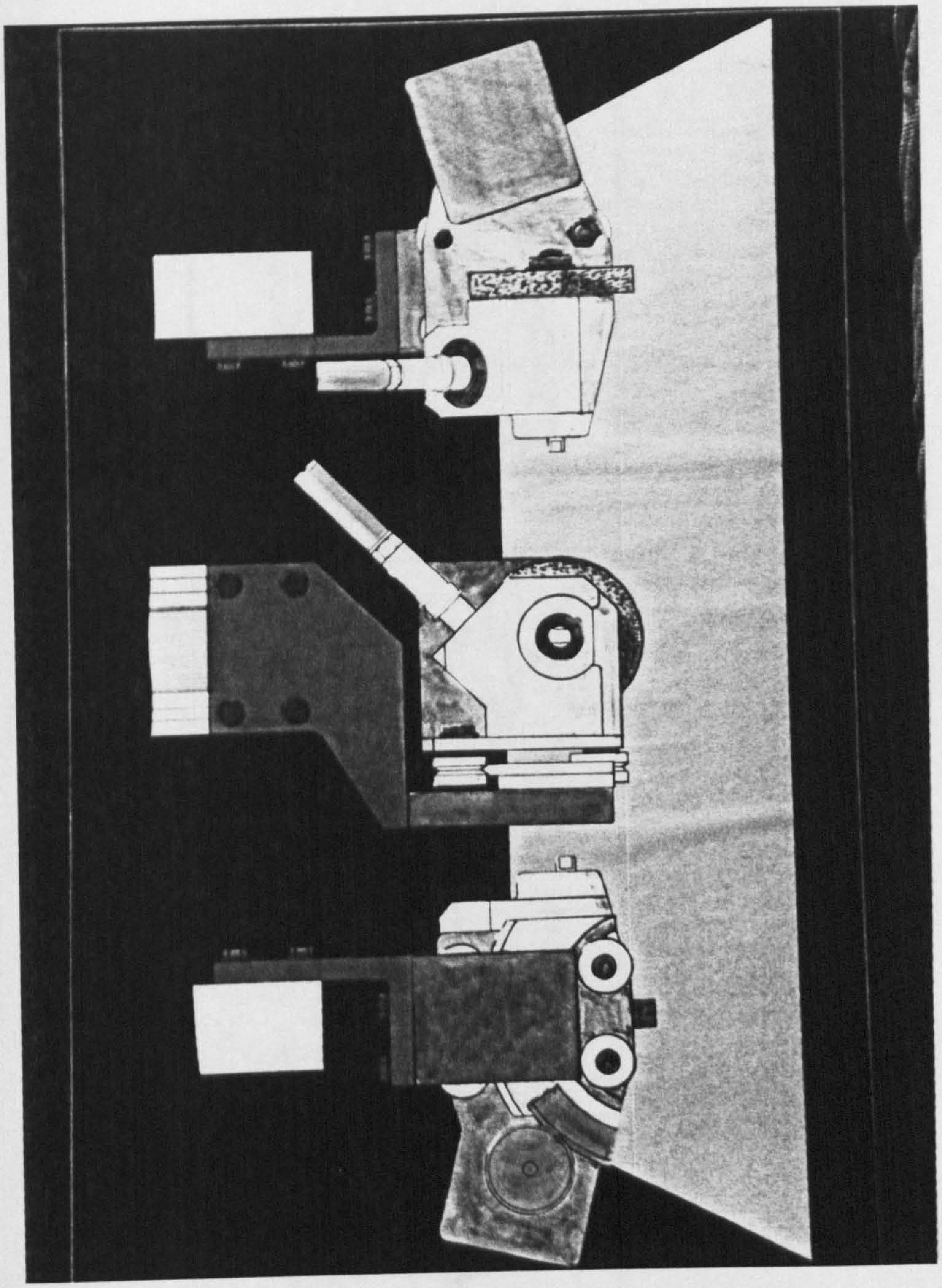


Figure 41. How the curved rail is used to guide the tilt-axis.

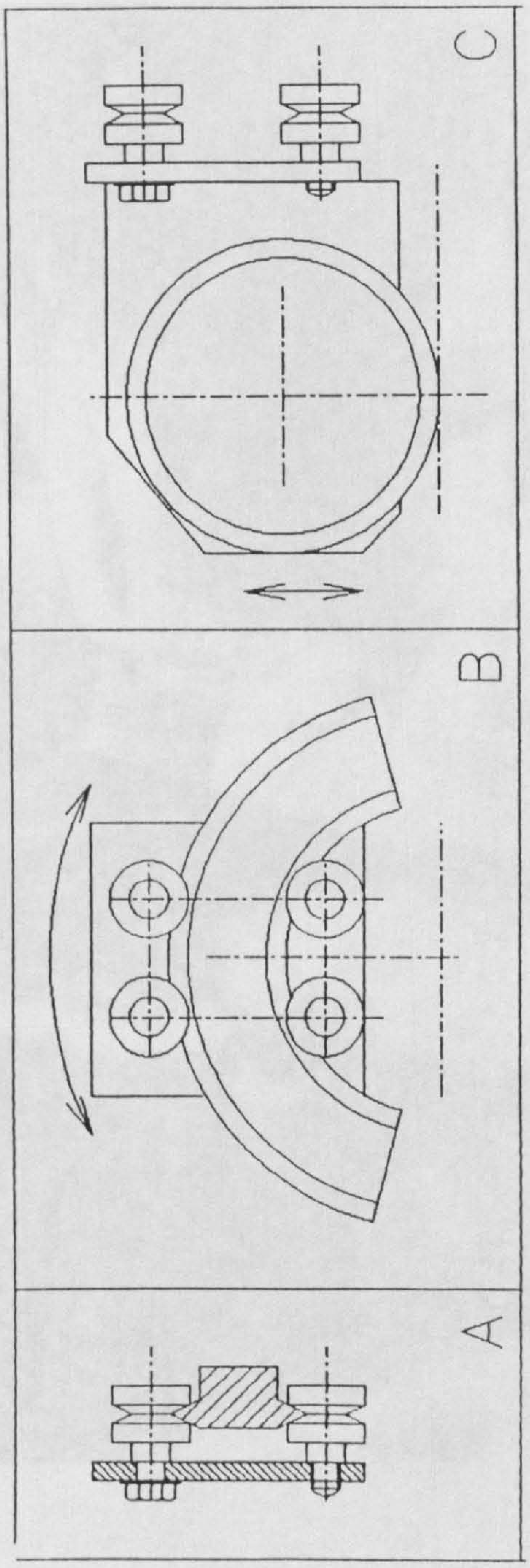


Figure 42. The grinding head assembly from the supported side, showing the curved rail and quadrant gear. Photograph by R.C.J. Best.

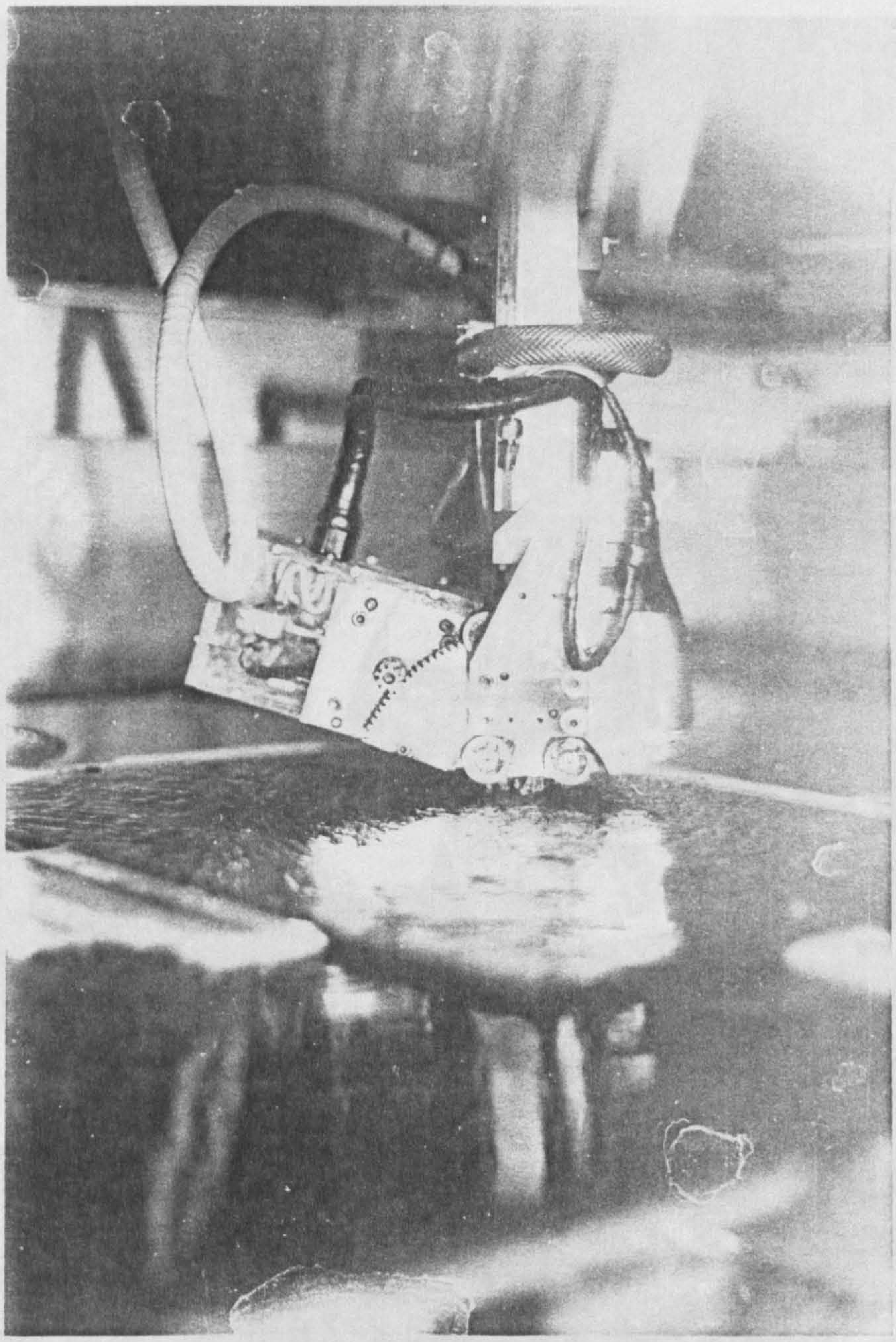


Figure 43. The grinding head assembly from the unsupported side. Photograph by the De Montfort University photographic department. Original in colour.

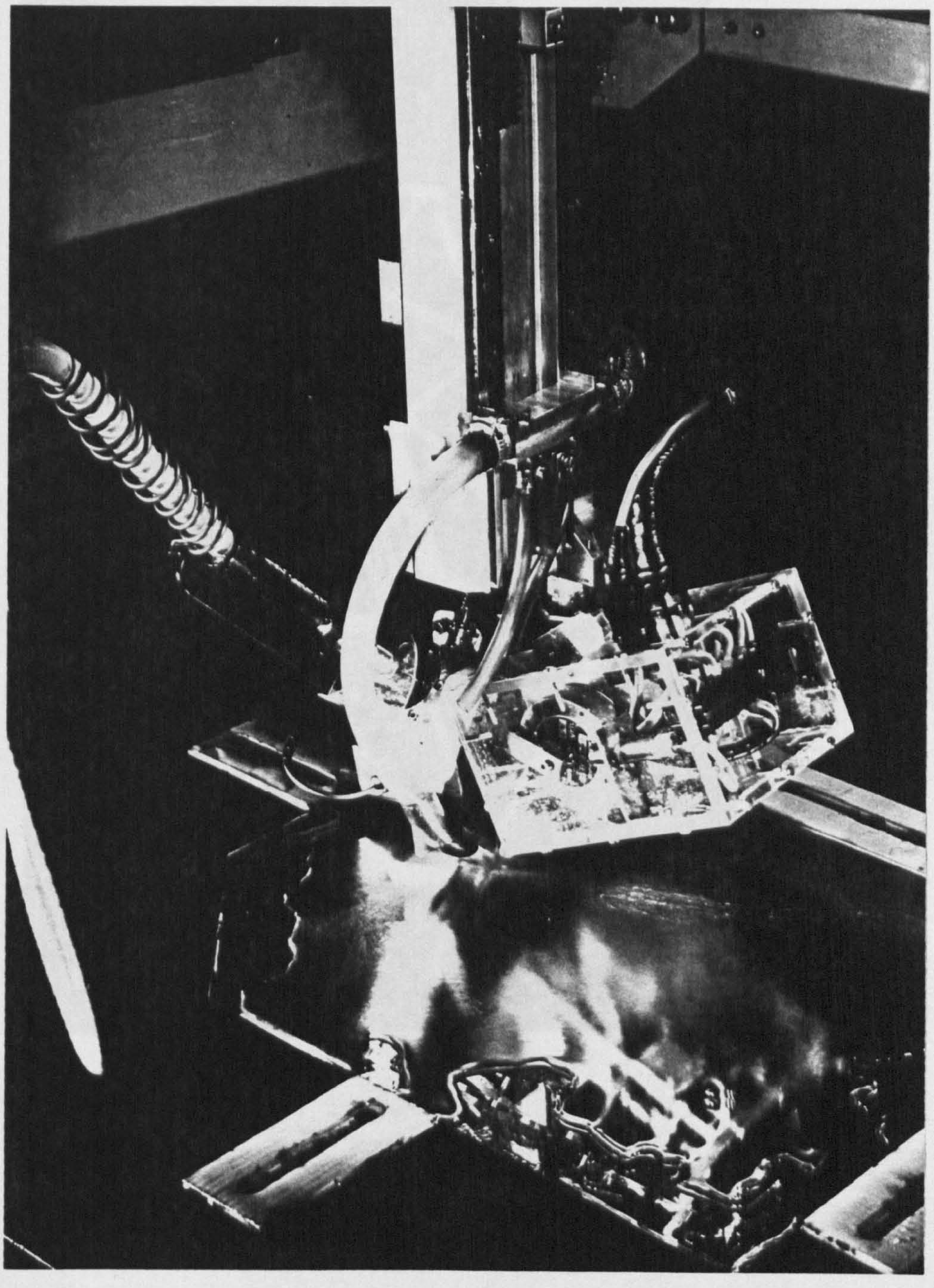


Figure 44. A development model of the machine supporting structure.

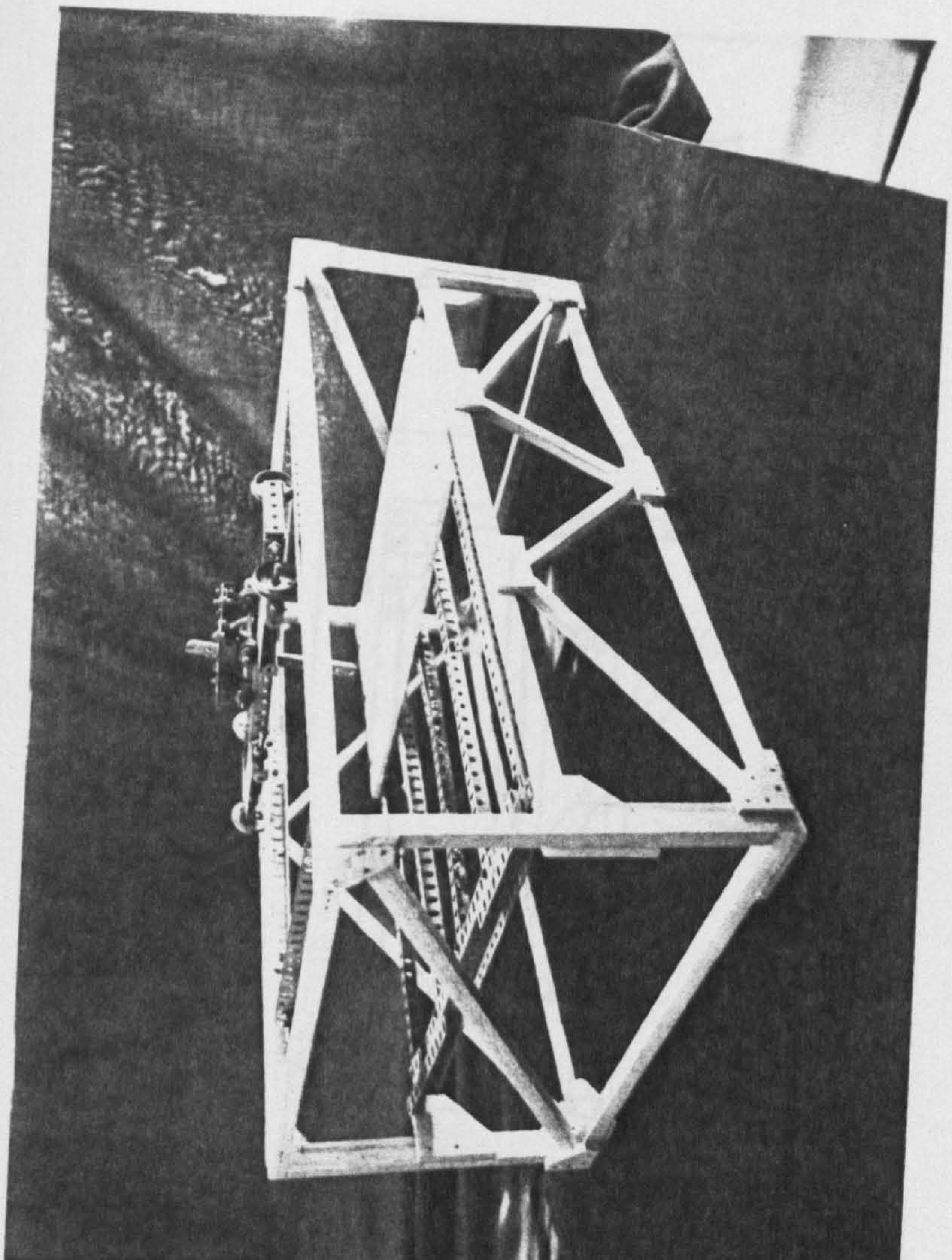


Figure 45. The position and details of the adjustment bolt assemblies of the machine supporting structure.

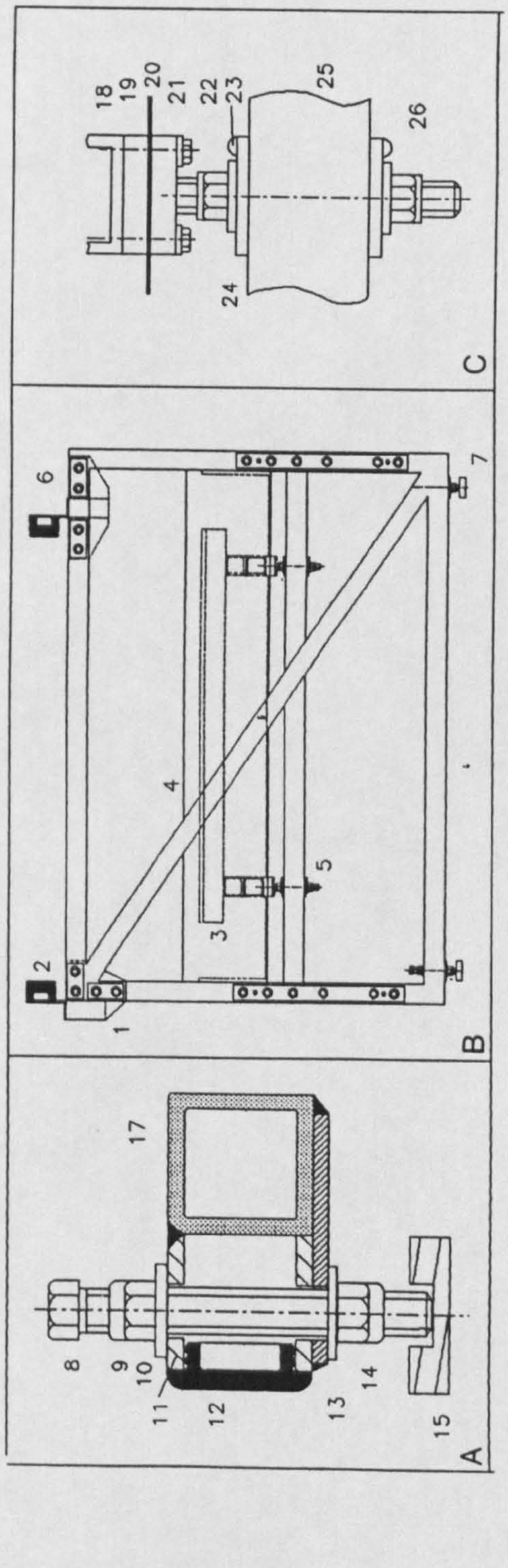


Figure 46. The coolant system.

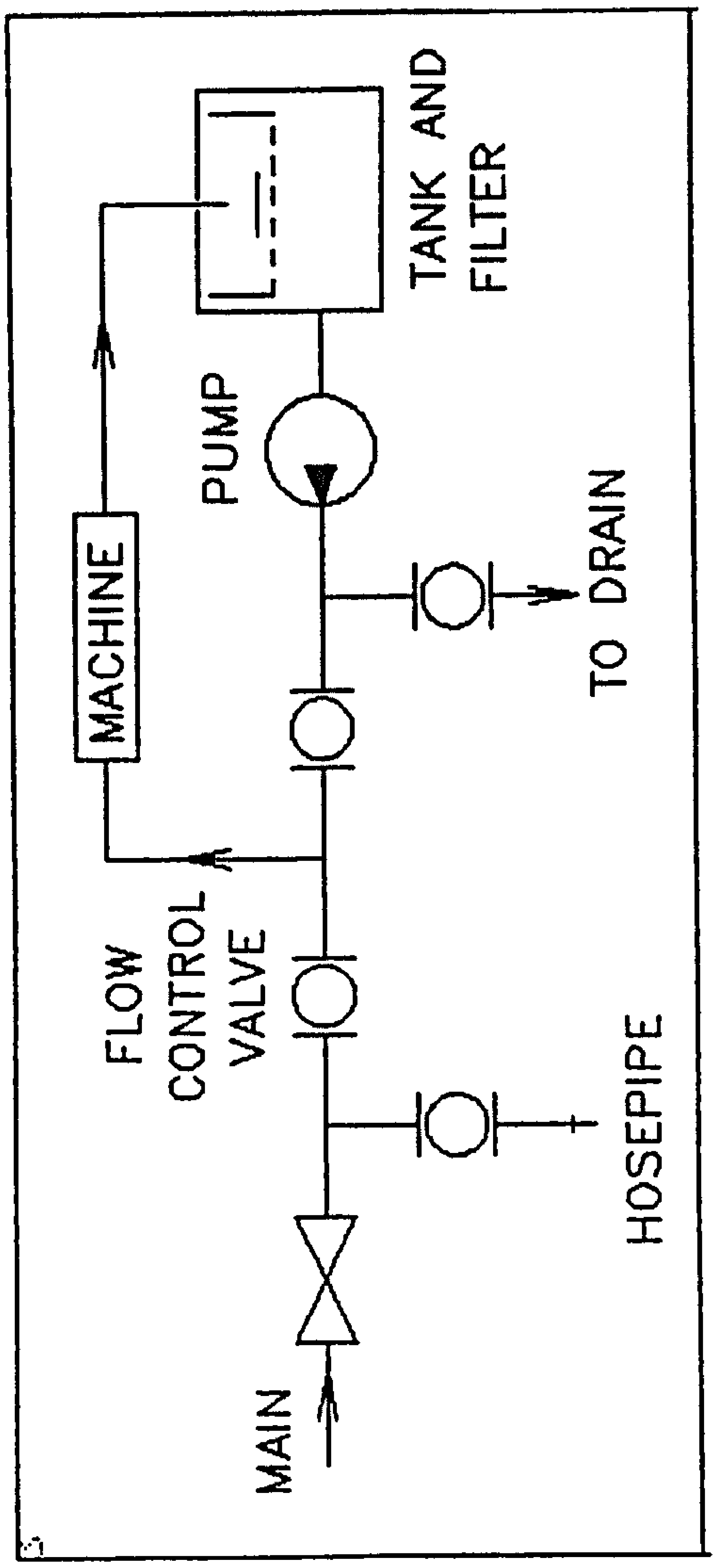


Figure 47. The brilliant cutting machine as built. Note that the machine is fully guarded. Original in colour.

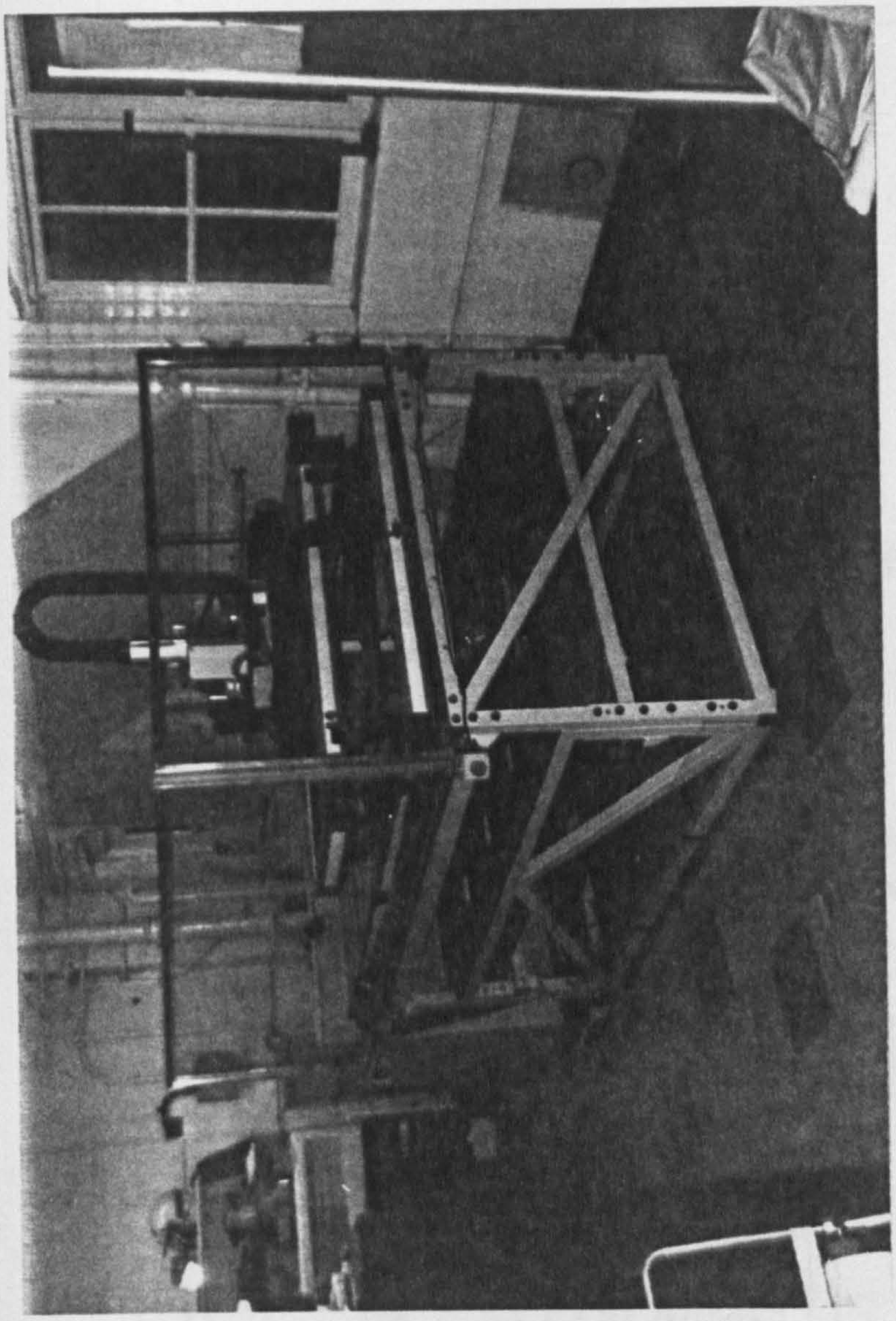


Figure 48. Circuit diagram of the low voltage safety circuit and ancillary control systems.

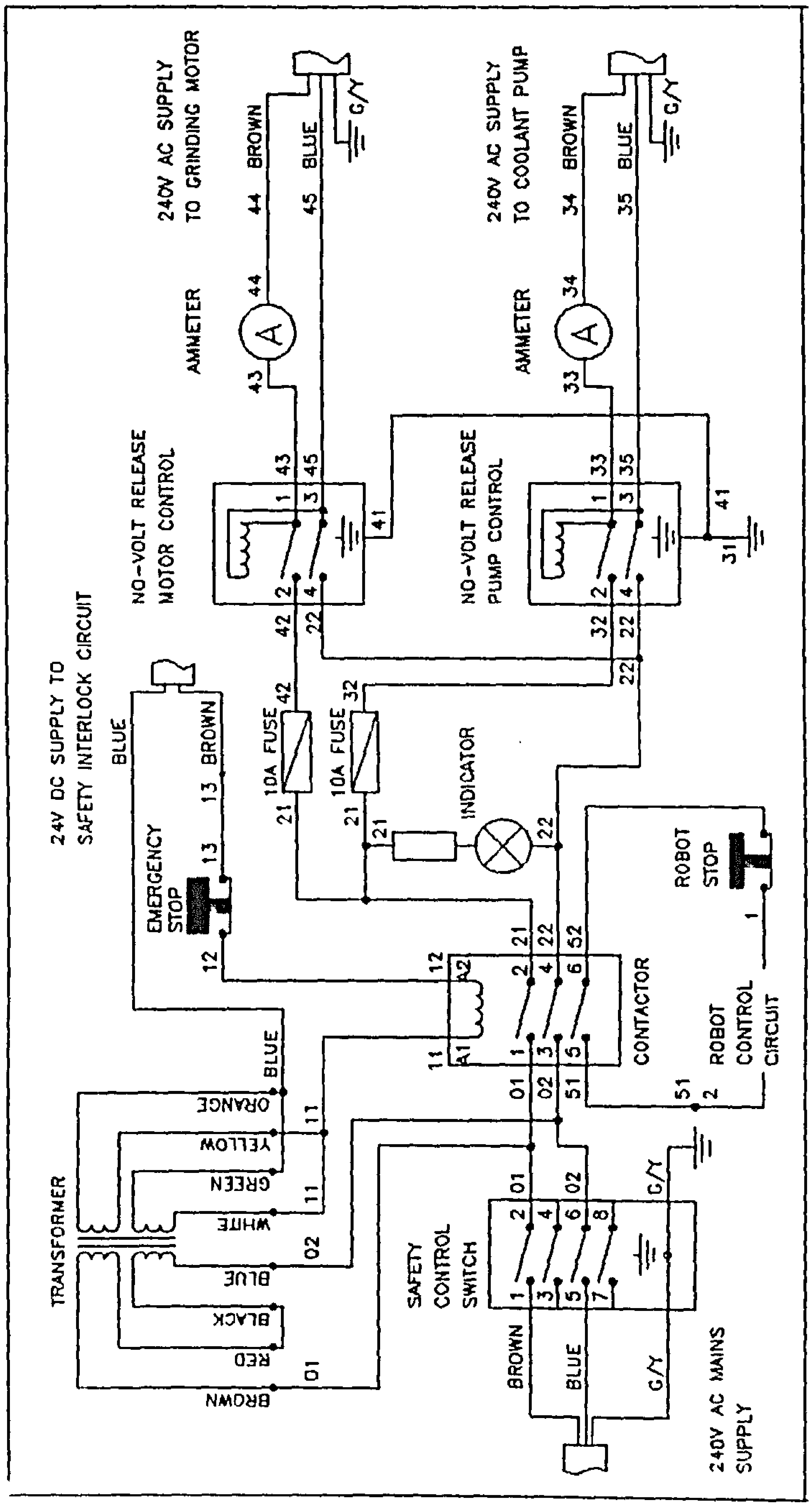


Figure 49. The machine operator position, showing the guarding and control switches on the main electrical cabinet. Photograph by R.C.J. Best.

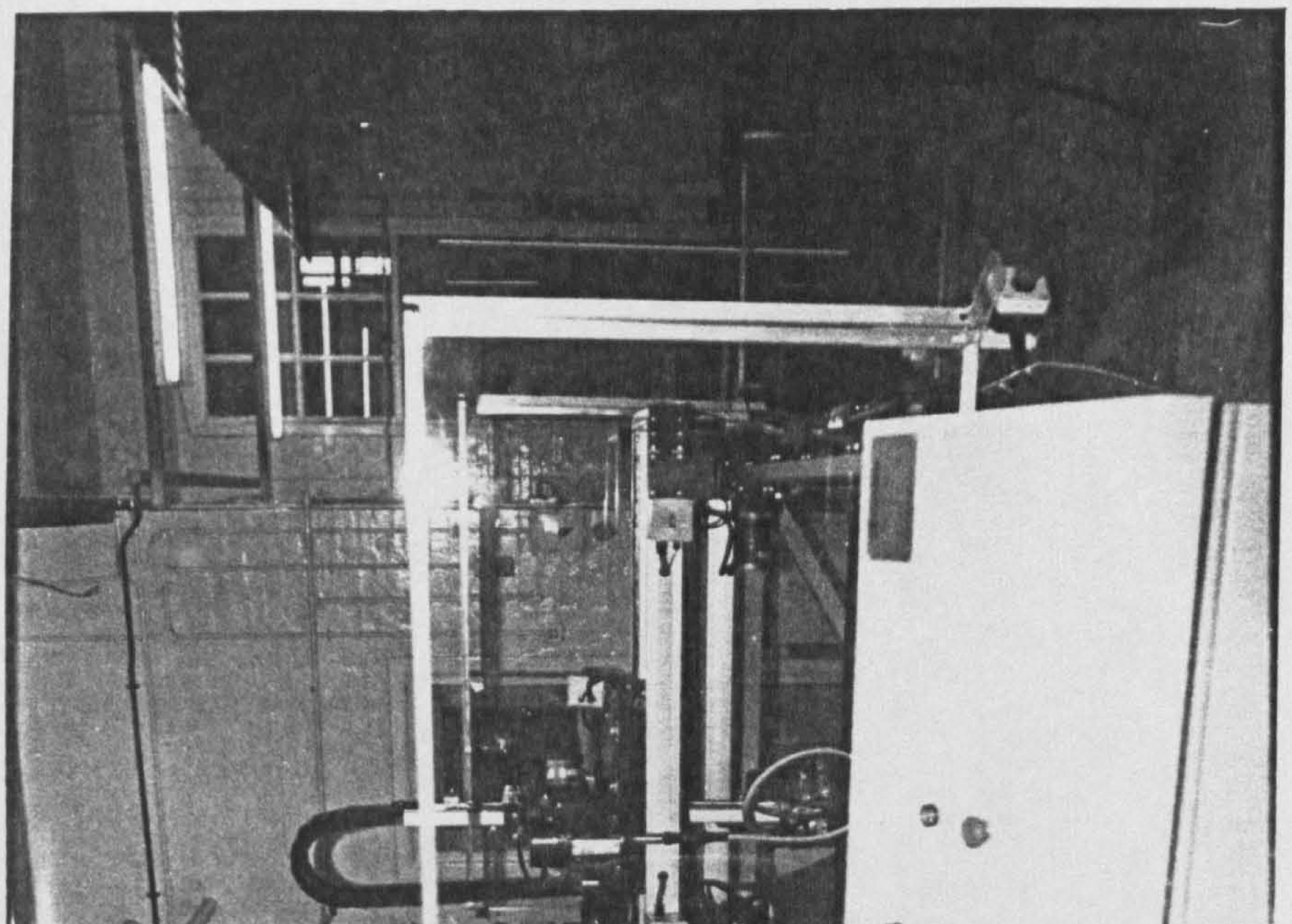


Figure 50. Plots generated by the brilliant cutting machine demonstrating circular interpolation.

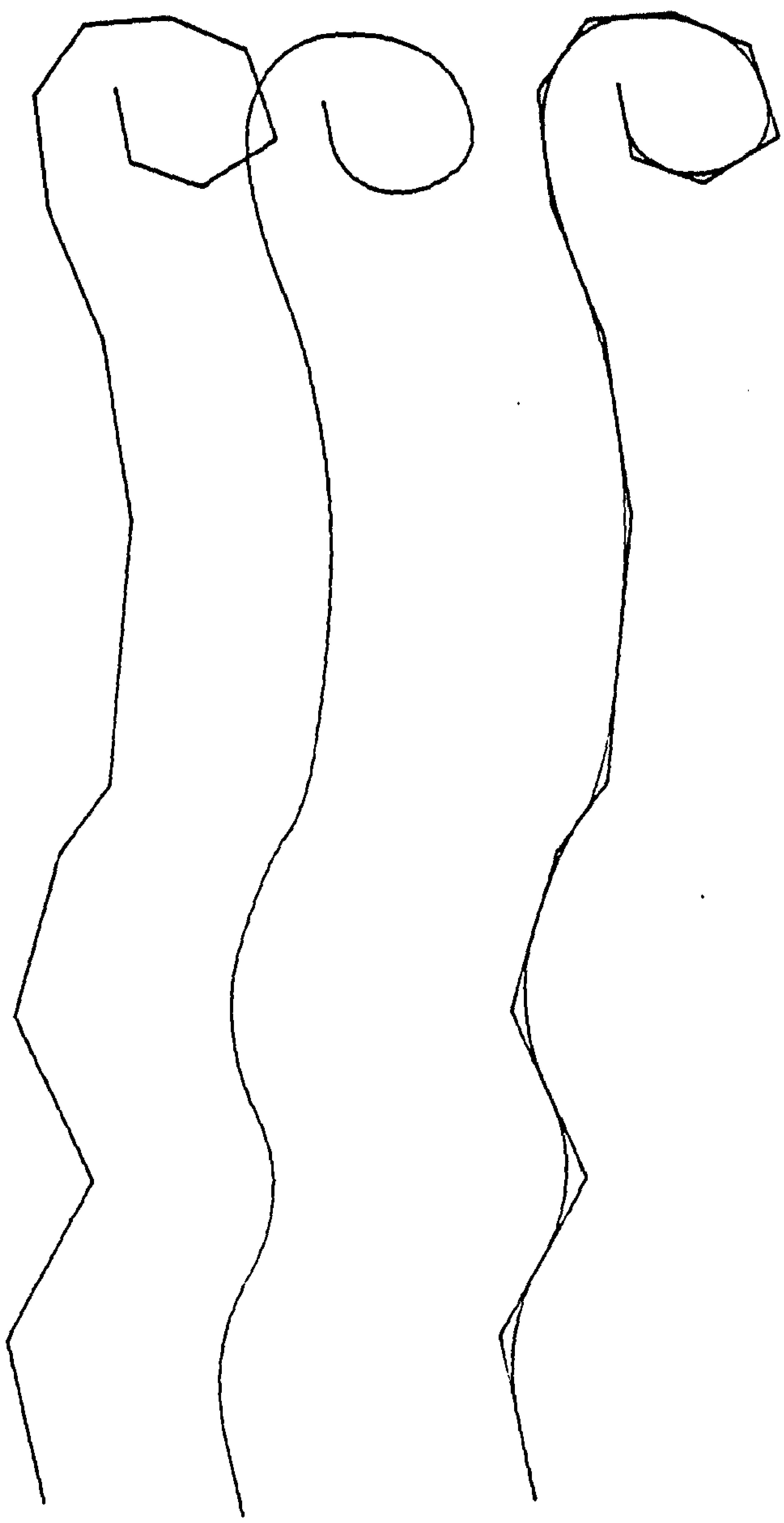


Figure 51. Plot illustrating points 20mm apart.

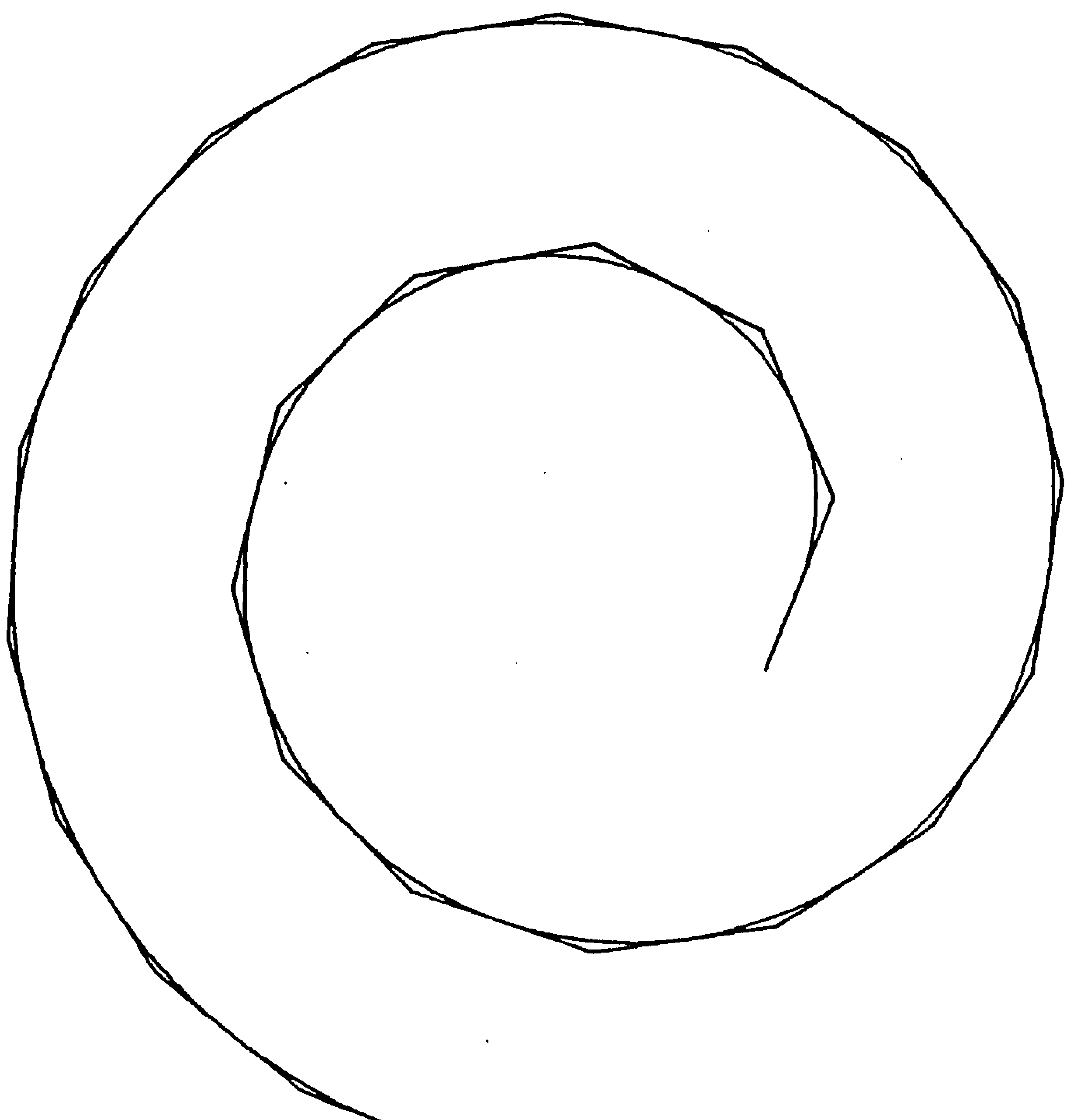


Figure 52. Plot illustrating points 3mm apart.

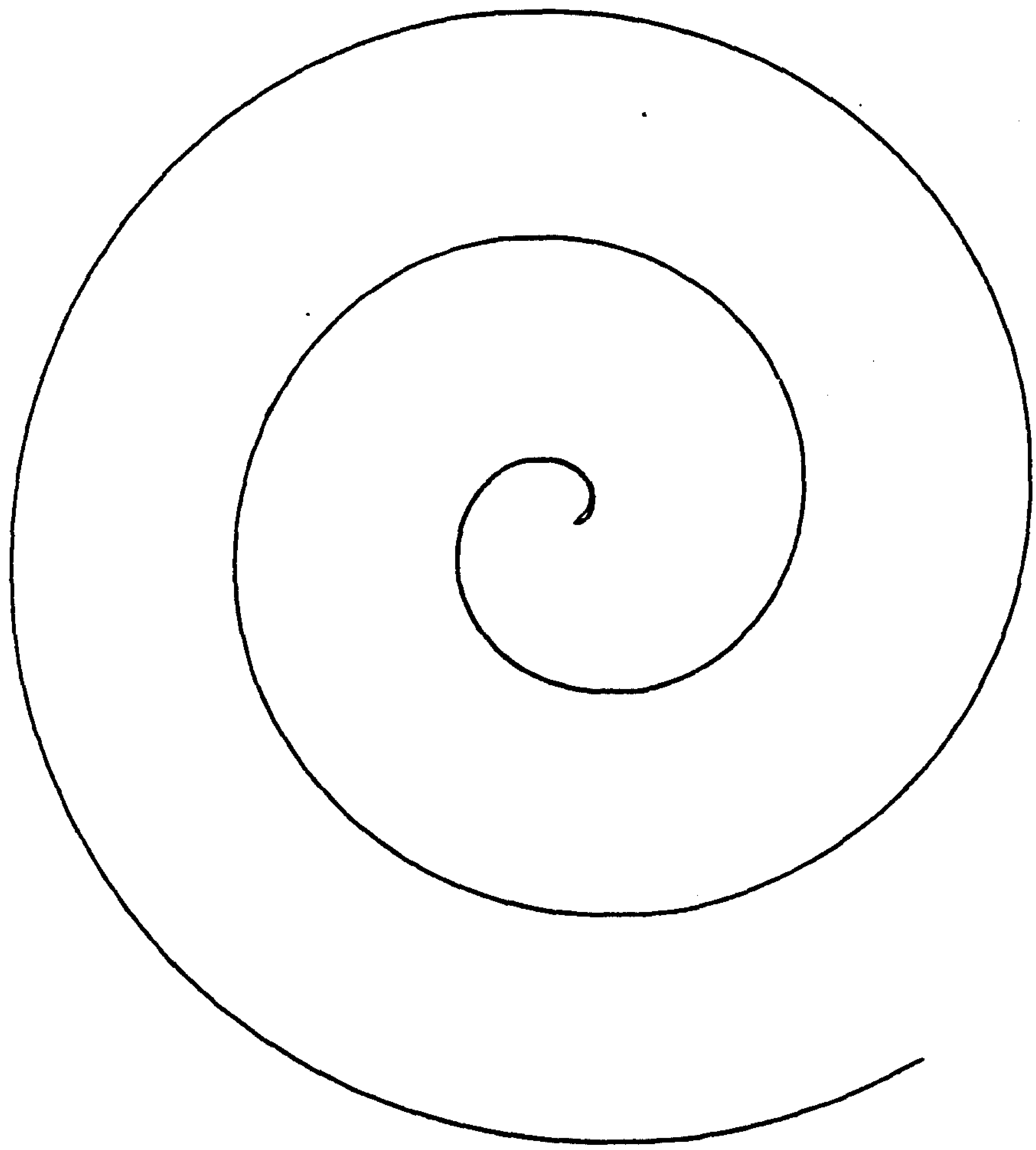
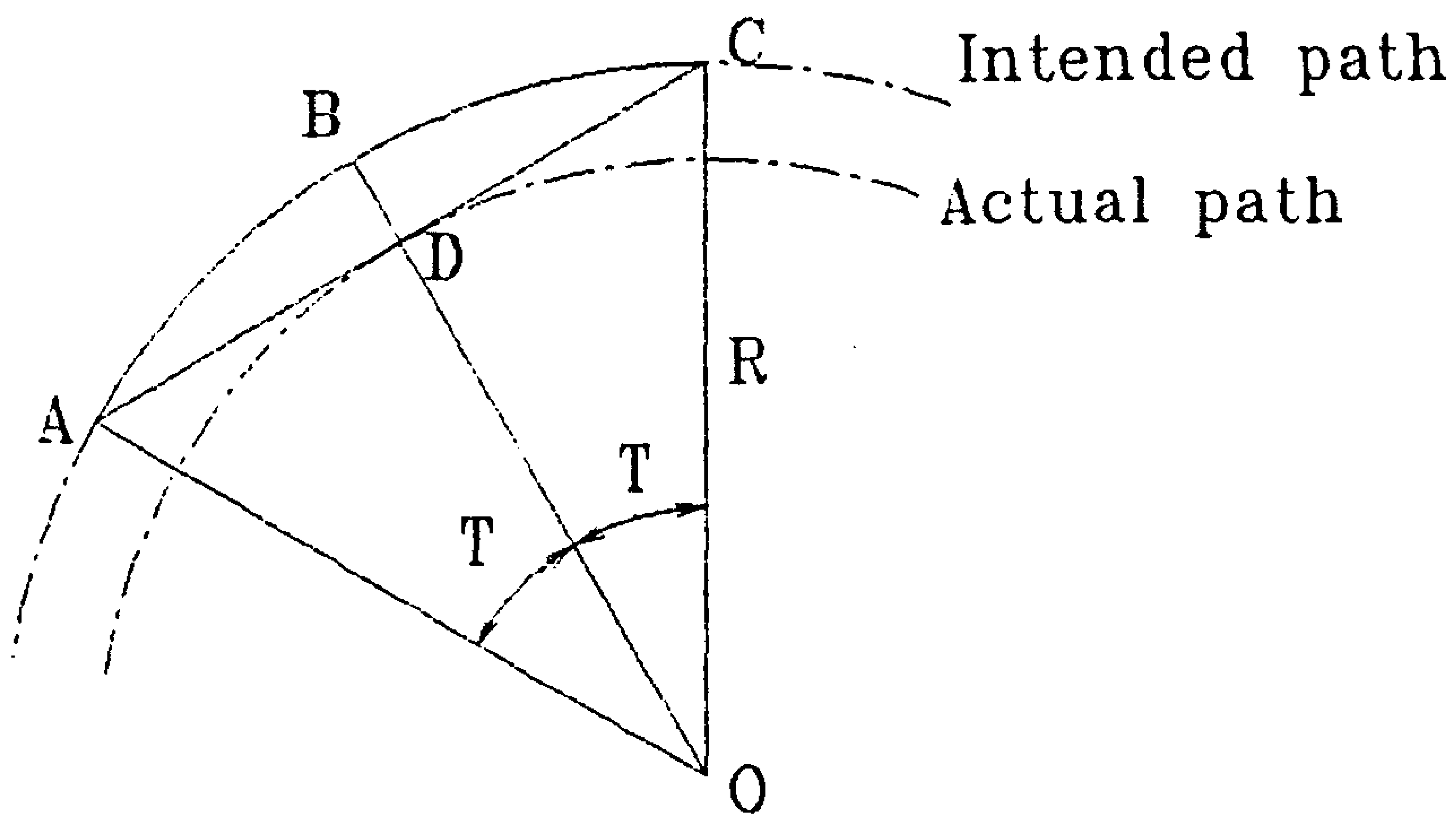
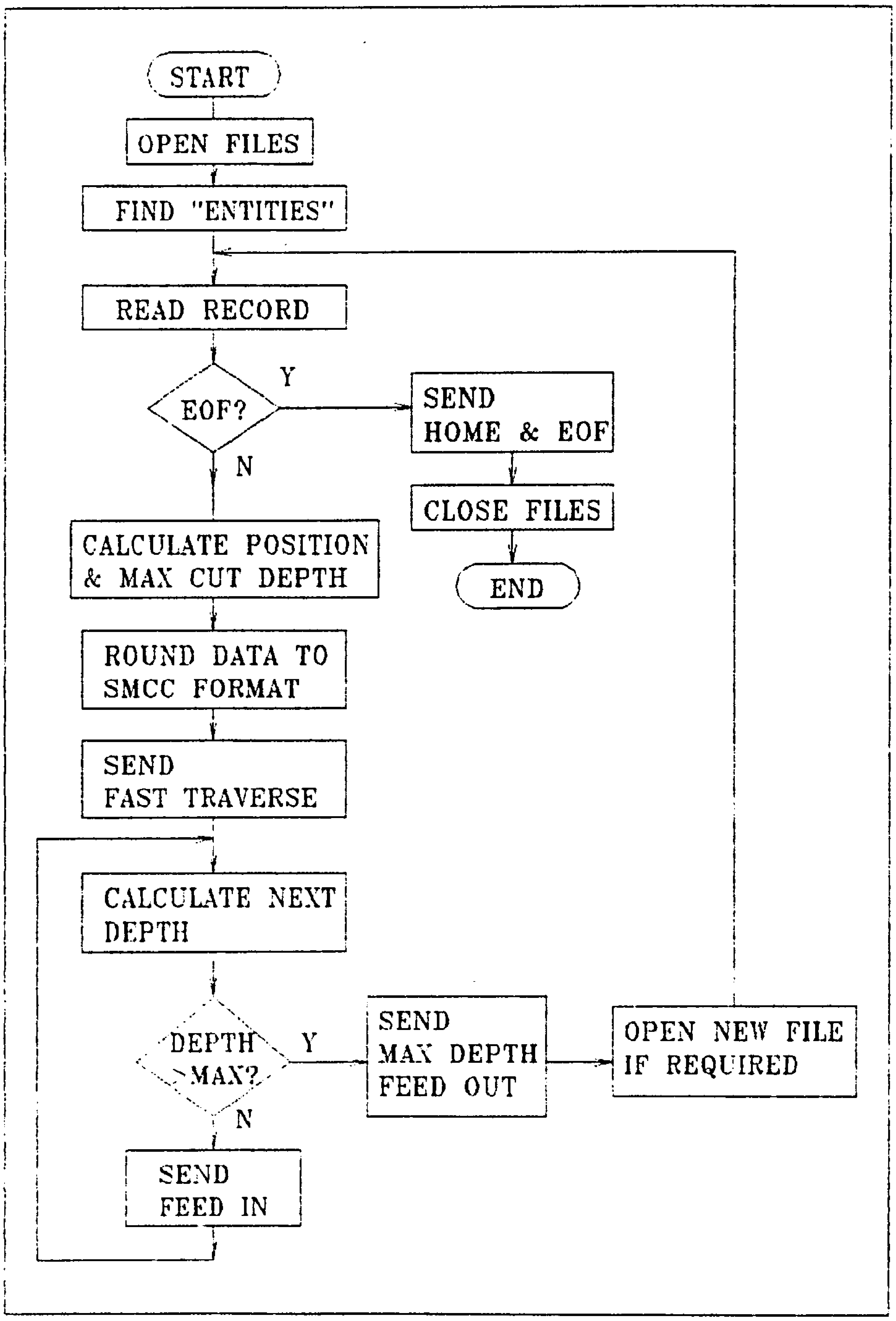


Figure 53. Calculating the positional error when following a circular interpolated path generated by the SMCC.



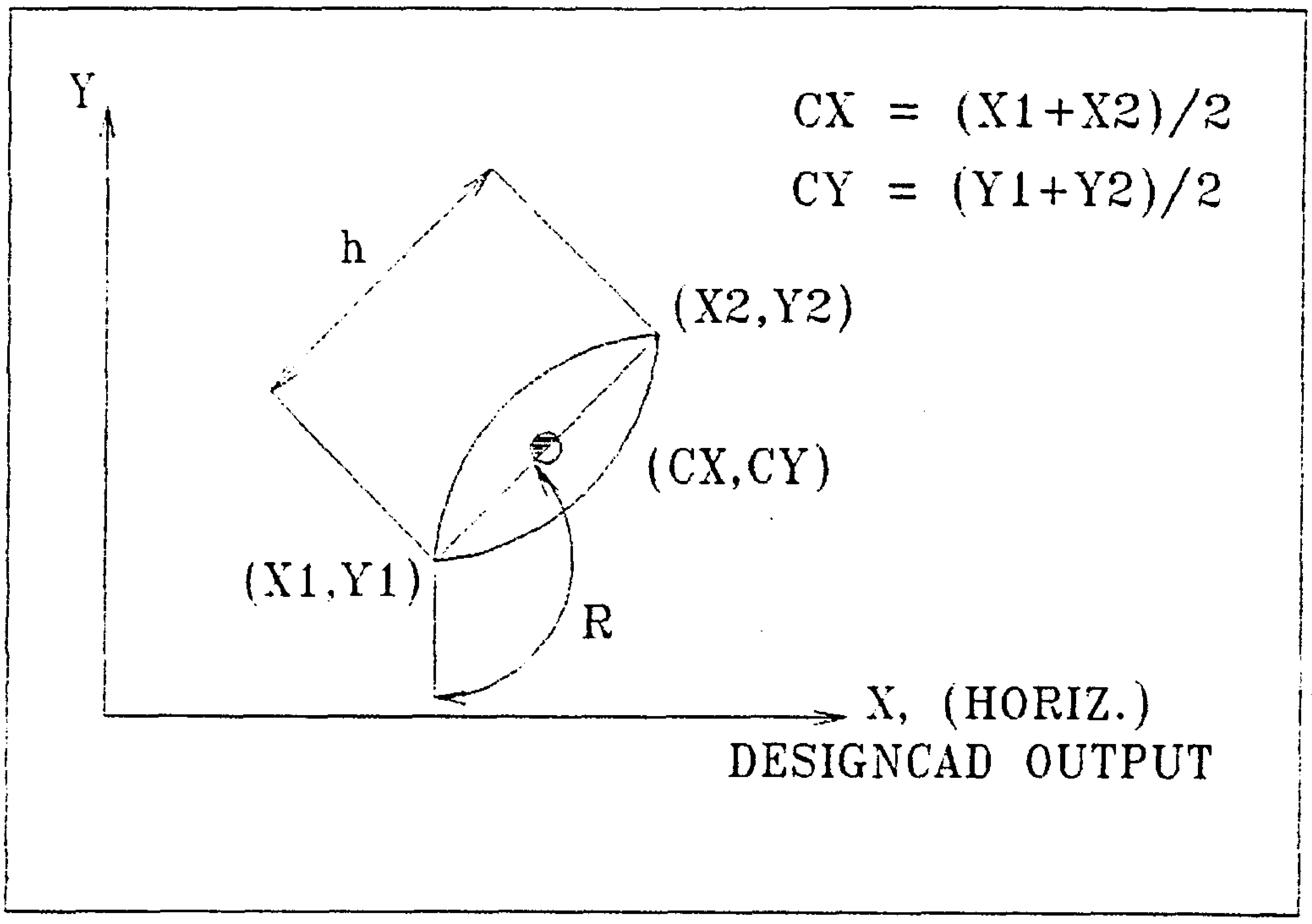
DC=AC/2
T=Arcsin(DC/R)
DO=R.CosT
BD=R−DO
for R=37mm and AC=3mm
BD is approx. 0.03mm

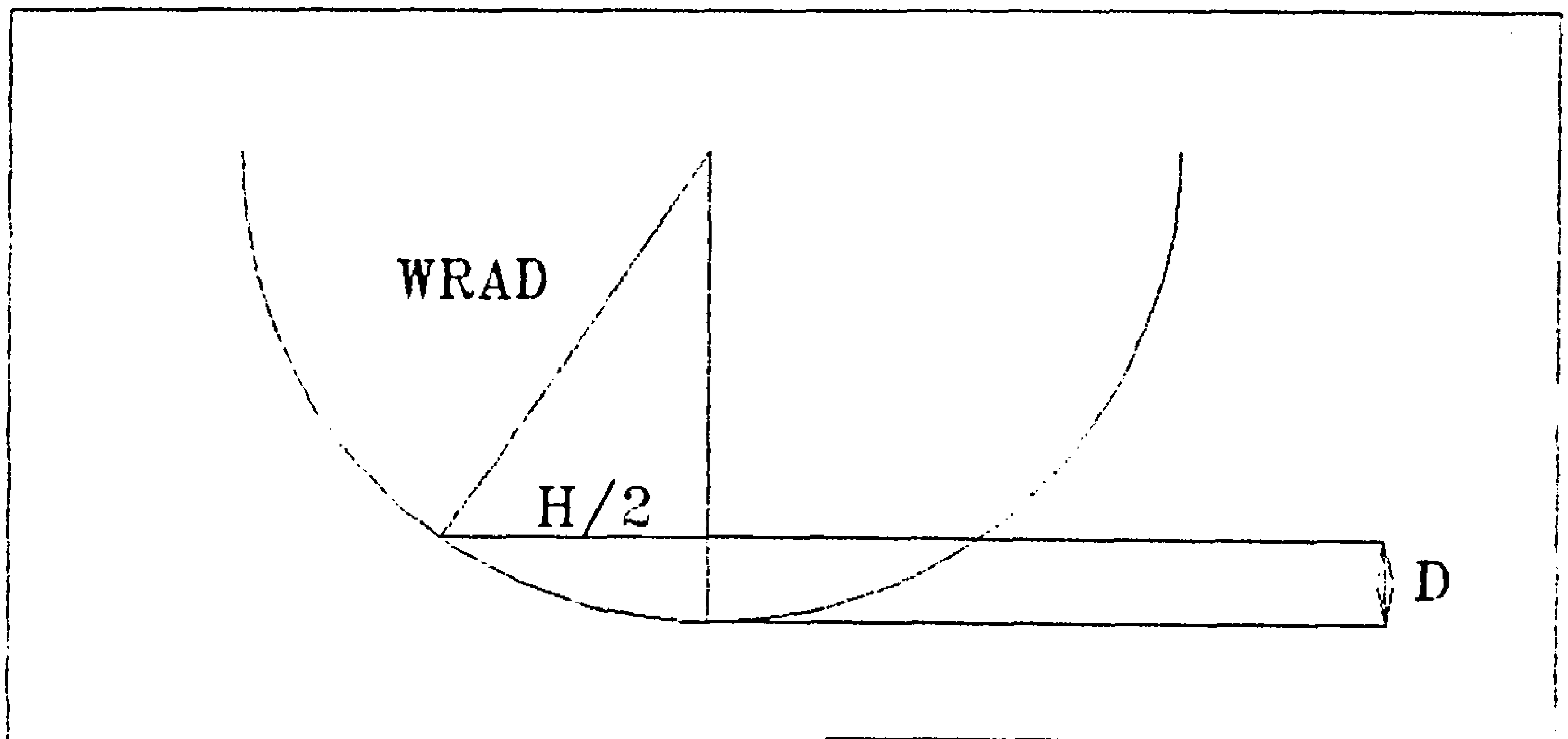
Figure 54. Programme flowchart for mitred punts module.



Above: Figure 55. Calculating the centre of a mitred punt.

Below: Figure 56. Calculating the depth of cut from the length of the punt





$$D = WRAD - \sqrt{WRAD^2 - \frac{H^2}{4}}$$

Figure 57. An example of a brilliant cut design employing deep mitred punts.

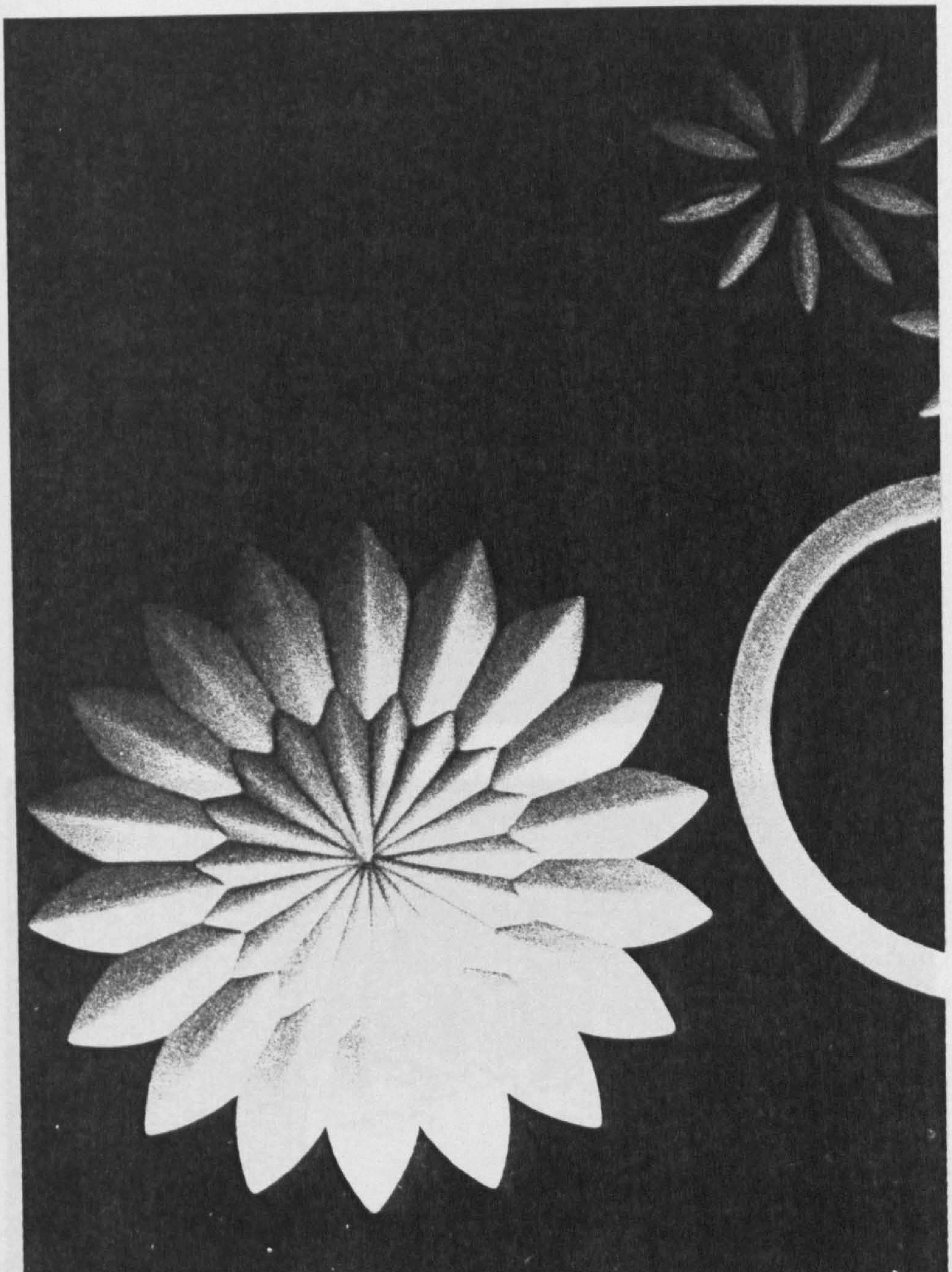
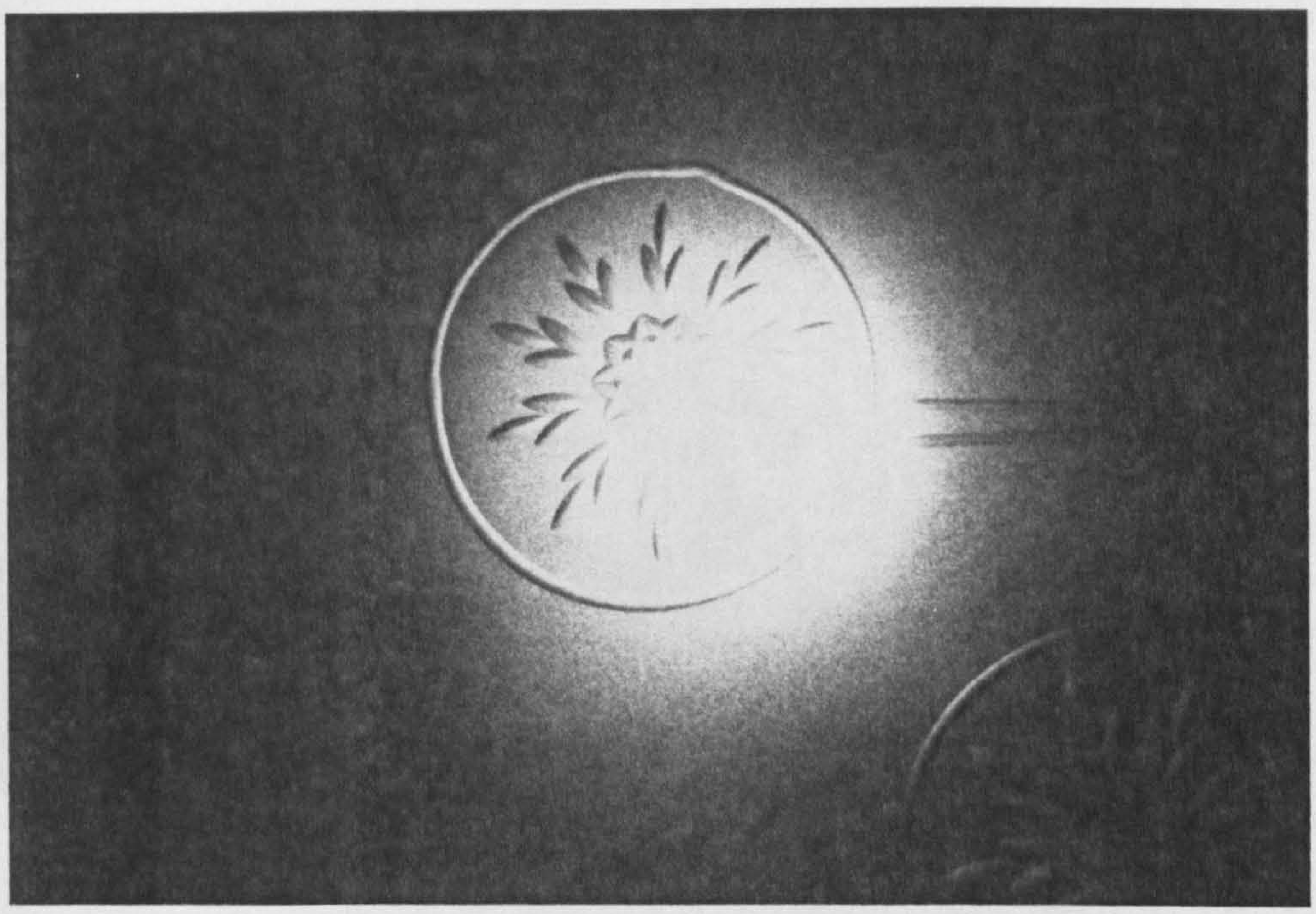


Figure 58. Examples of brilliant cut designs employing shallow mitred cuts on a hand ground field. The CAD drawing used for these designs is shown in figure 61.



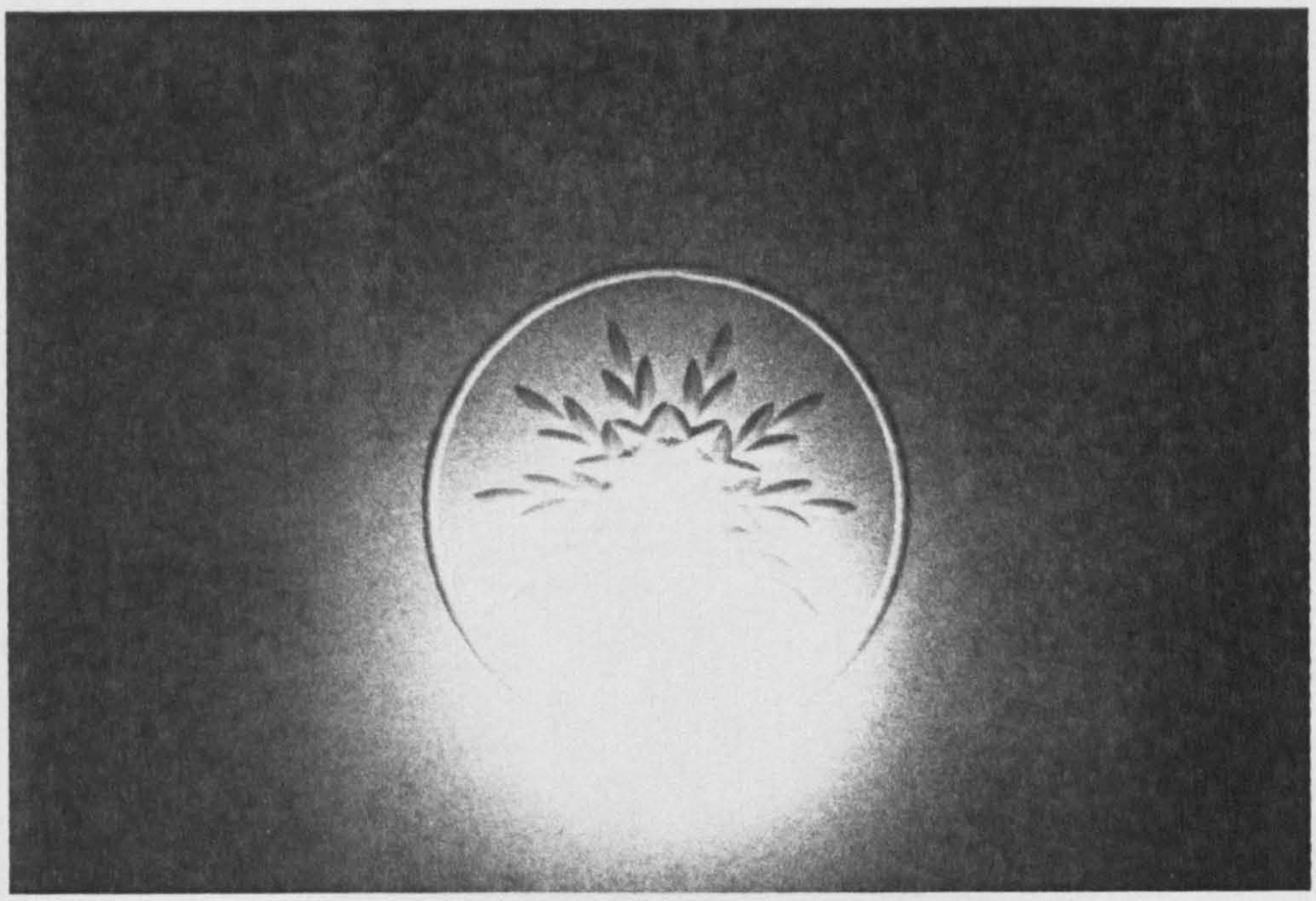


Figure 59. Oval Punts.

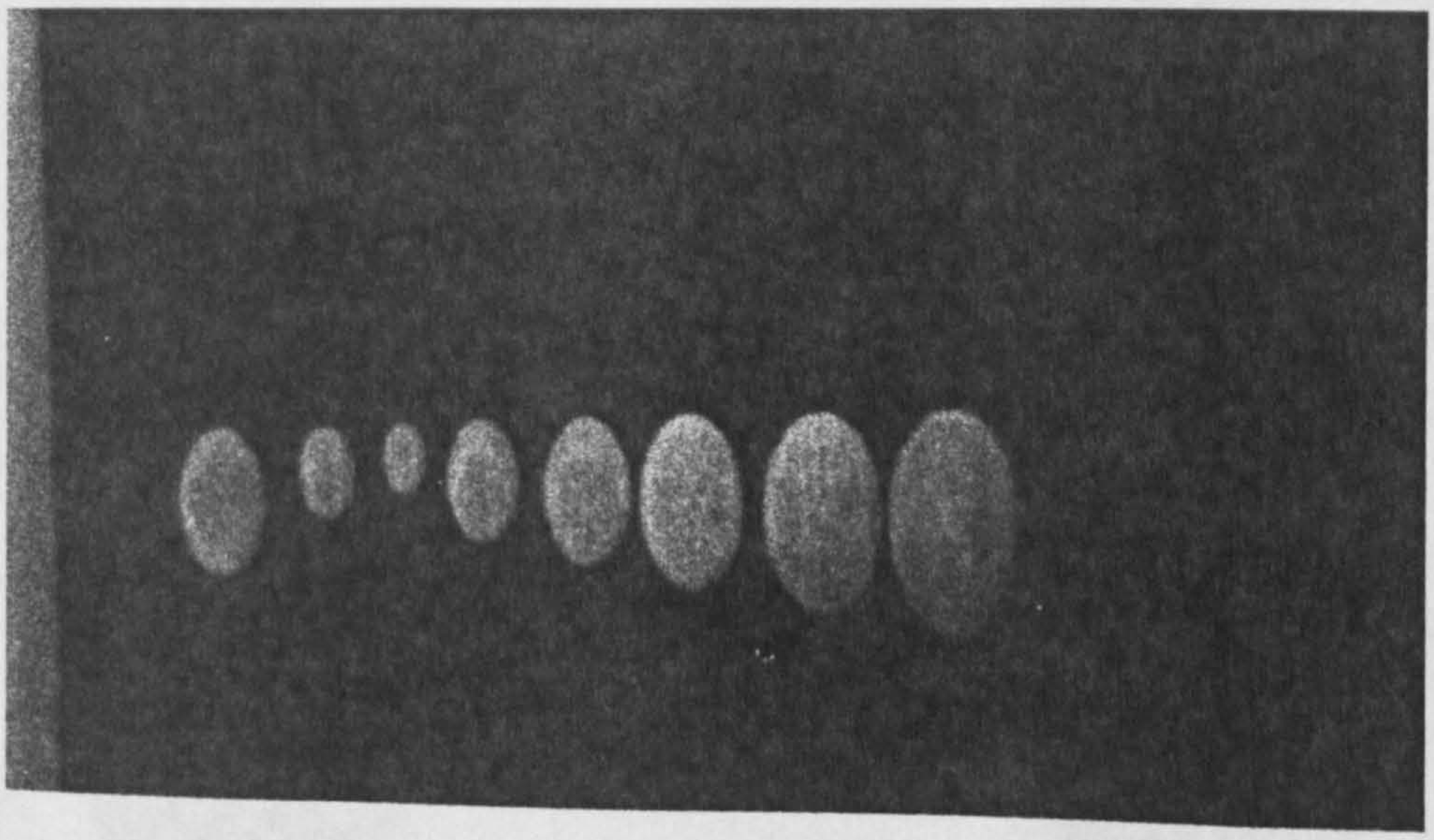
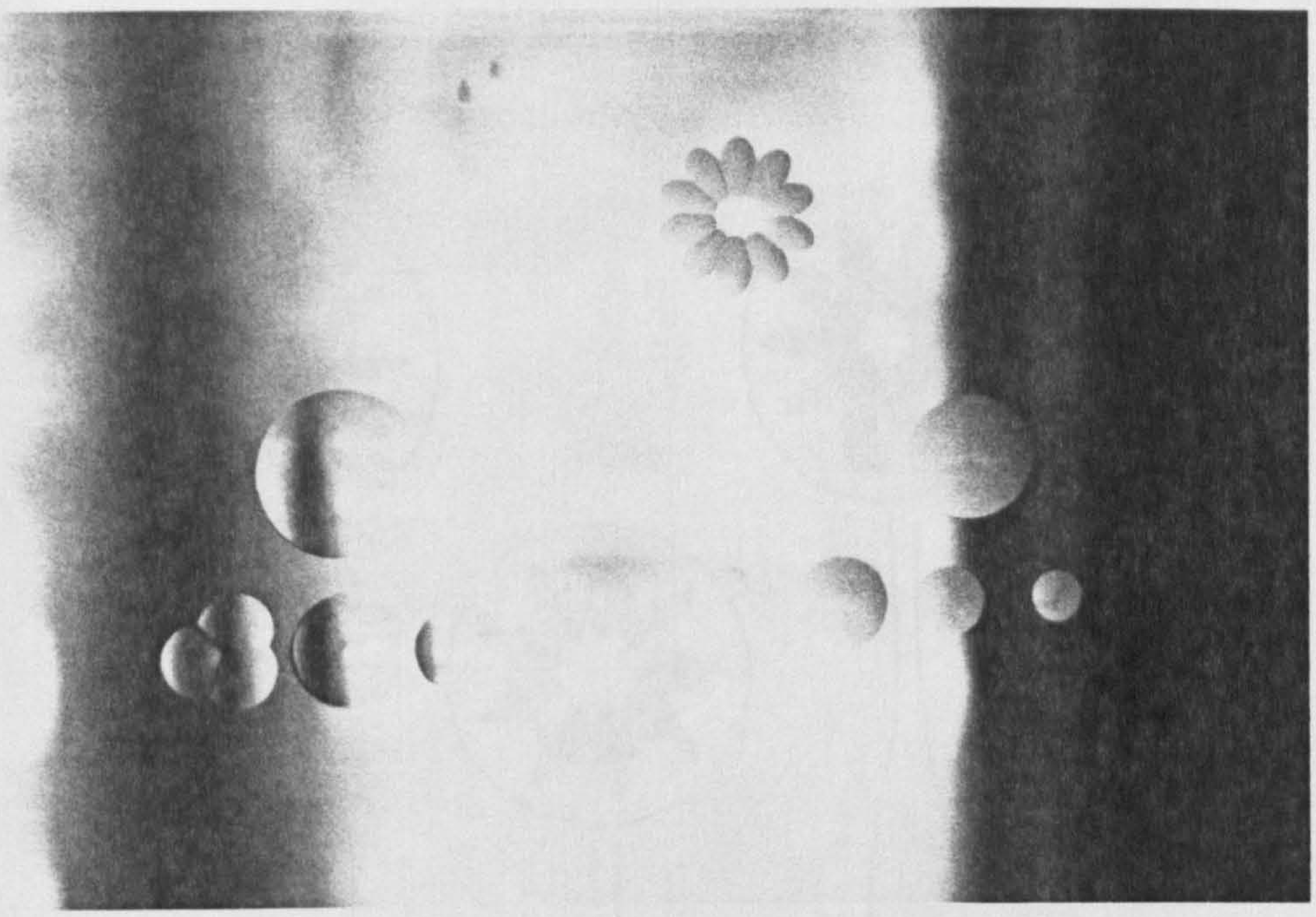


Figure 60. Brilliant cut features employing polished and unpolished round punts.



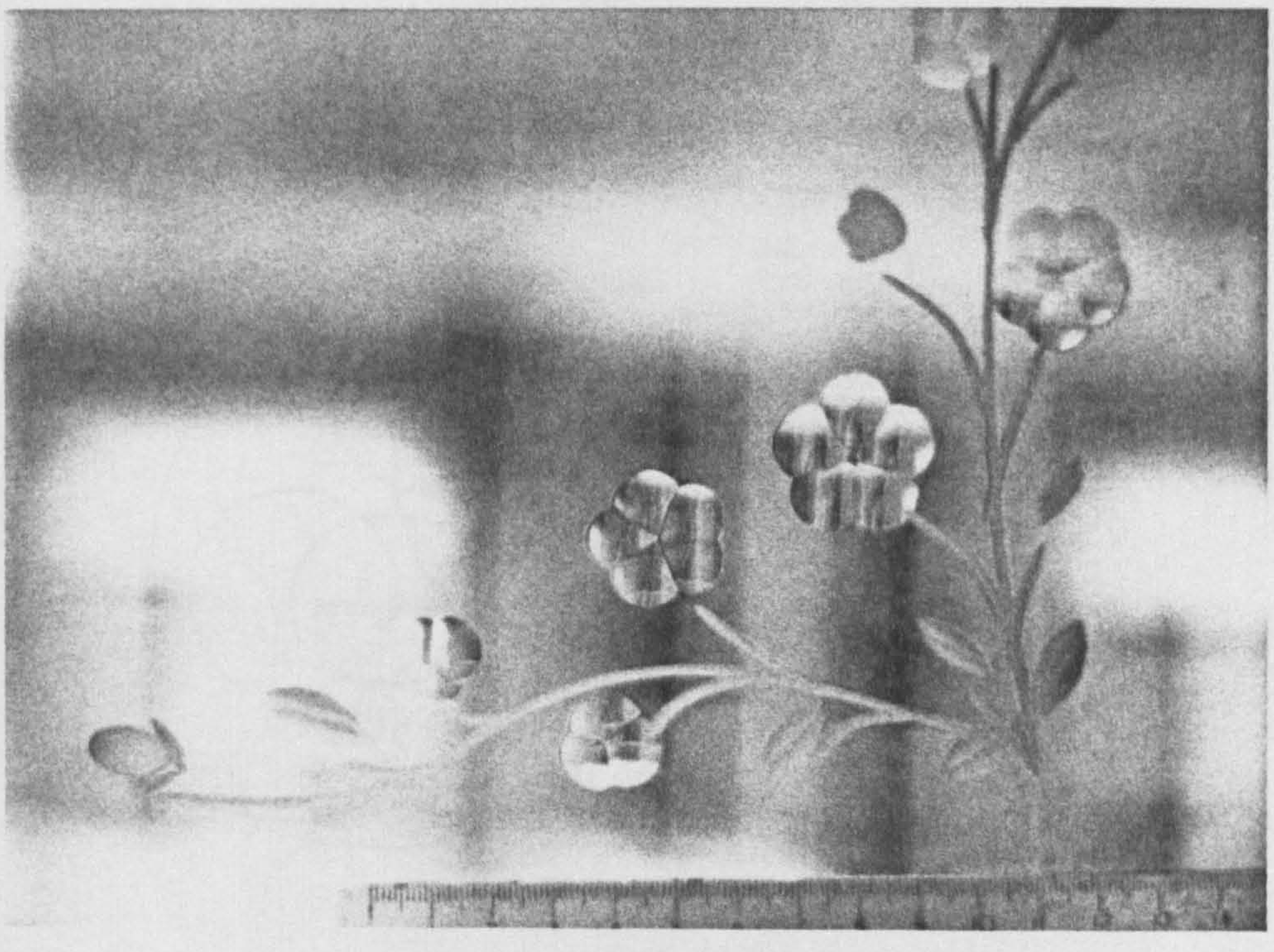


Figure 61. An example of a design using a large amount of line work, (500 x 380mm).

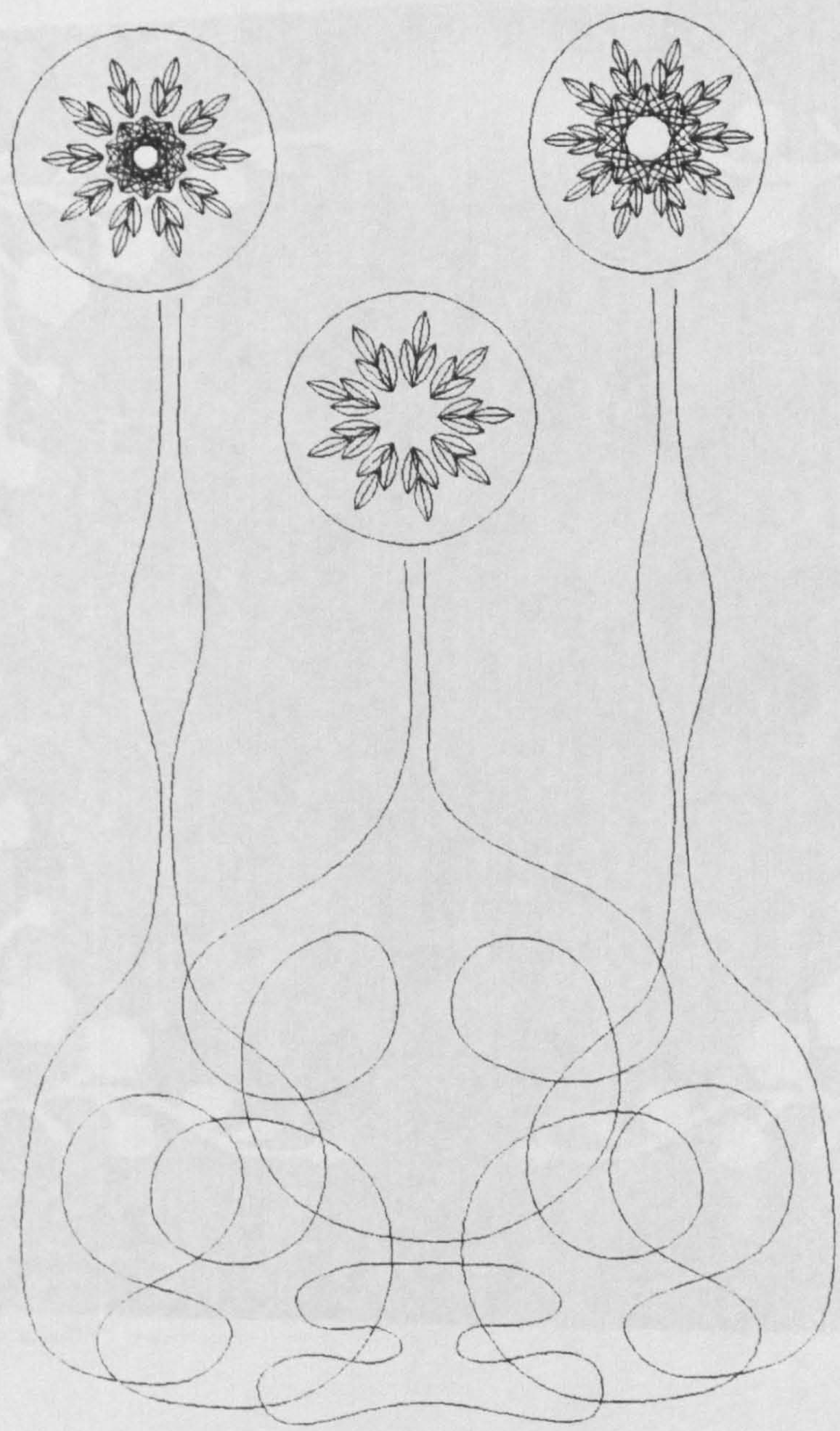


Figure 62. A silvered mirror, 500 x 500mm, containing 208 separate brilliant cut features. The mirror is silvered on the engraved side, the ground finished features being highlighted as a bright frosted silver colour.

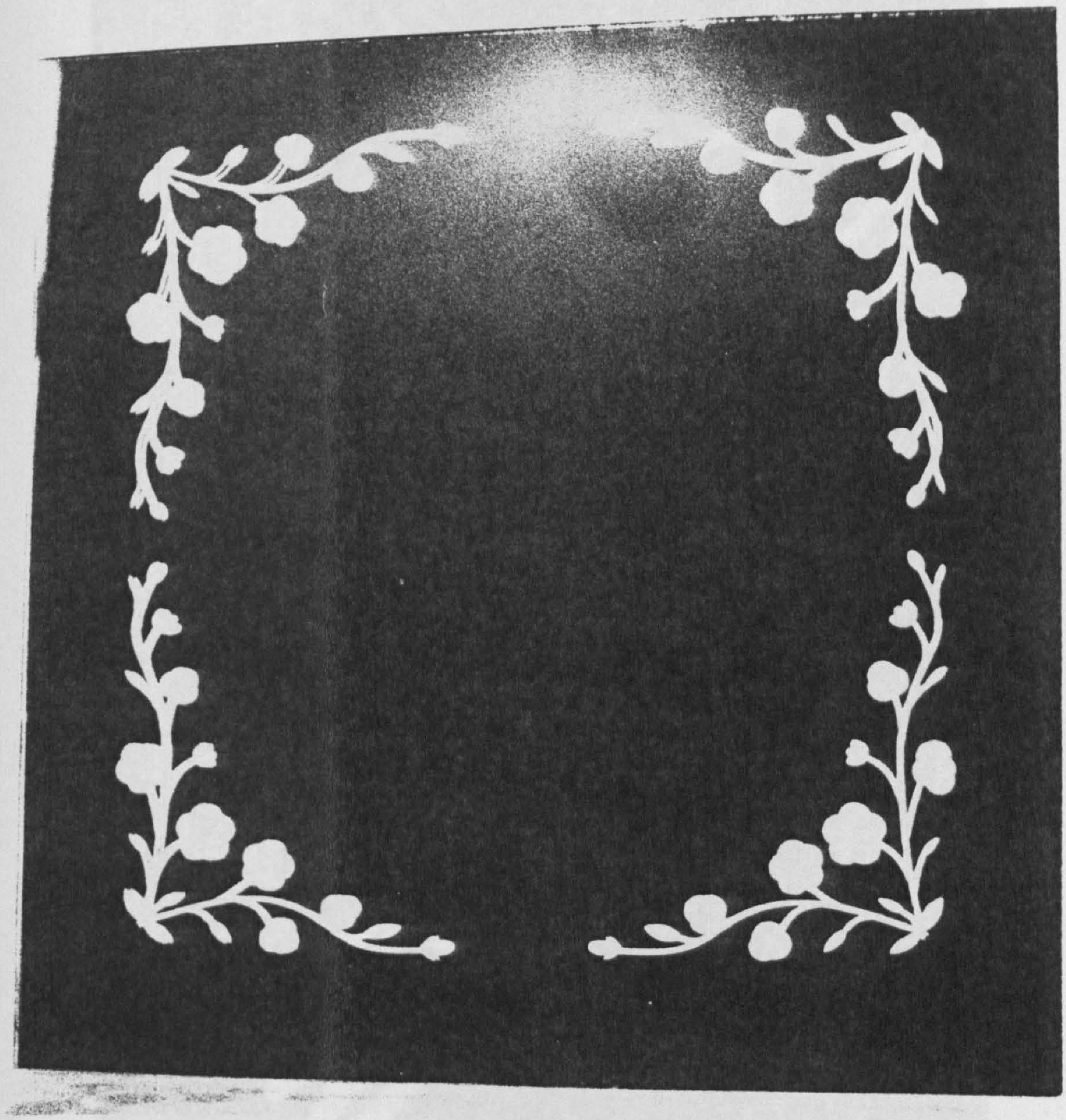


Figure 63. A brilliant cut motif containing approximate 92 separate features, illustrated approximately 0.8 scale. The fish scales are overlapping round punts, the eye and bubbles are polished. The panel is silvered, the dark background being a reflection of the black board reflected in the eye.

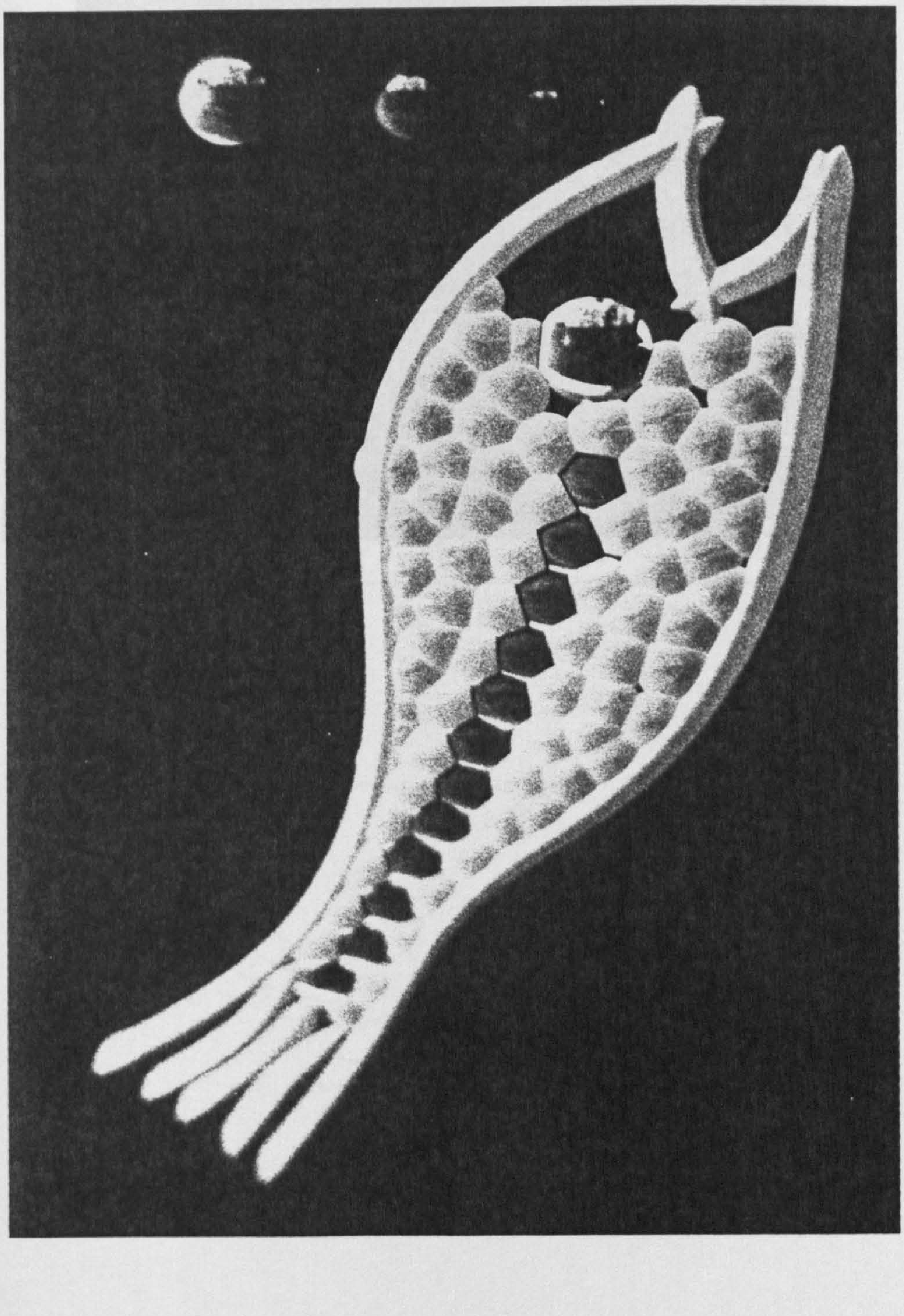


Figure 64. A bevelled mirror of the sort of simple design commercially available but accentuated by the use of five axis cutting.

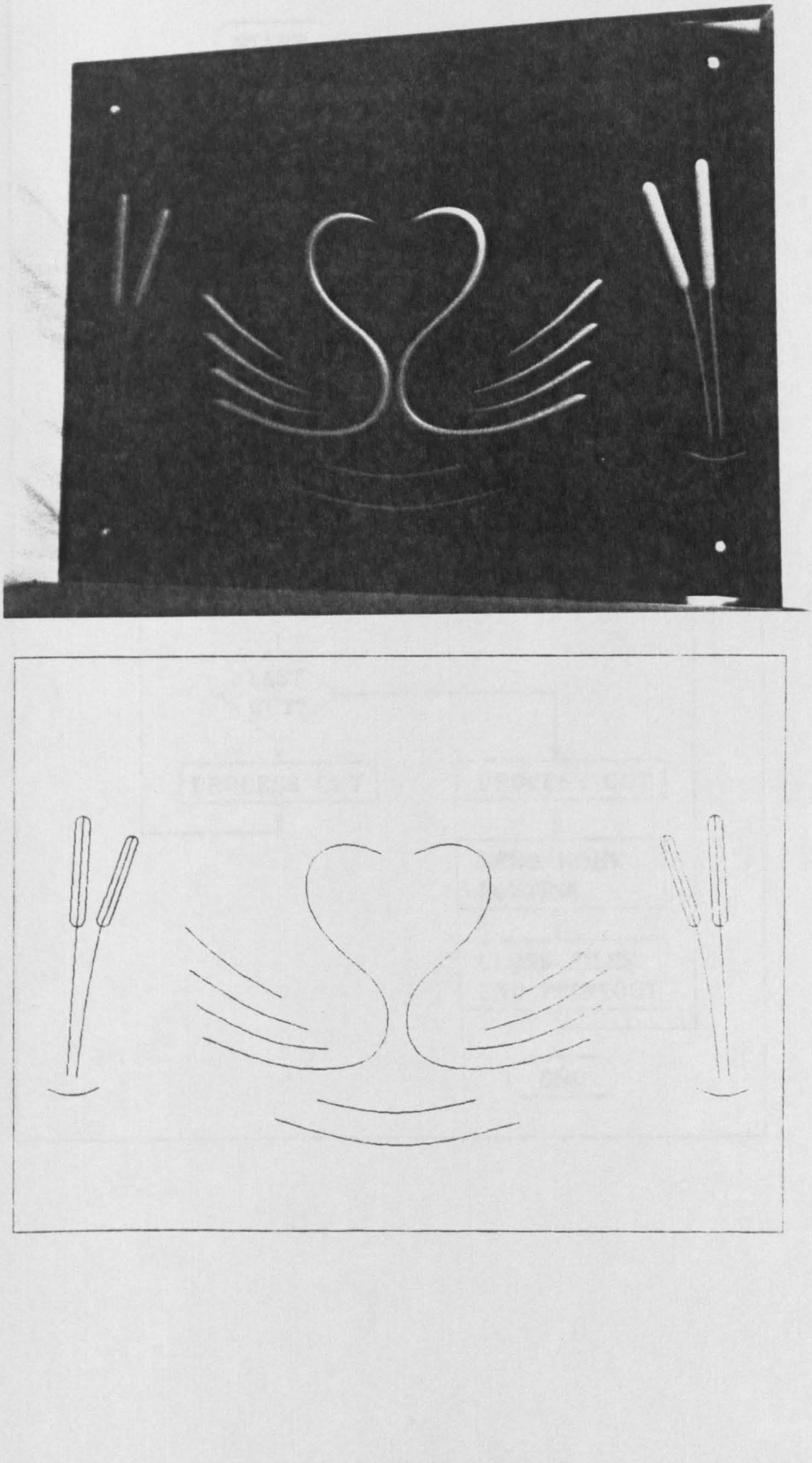


Figure 65. Programme flowchart for curved linework module.

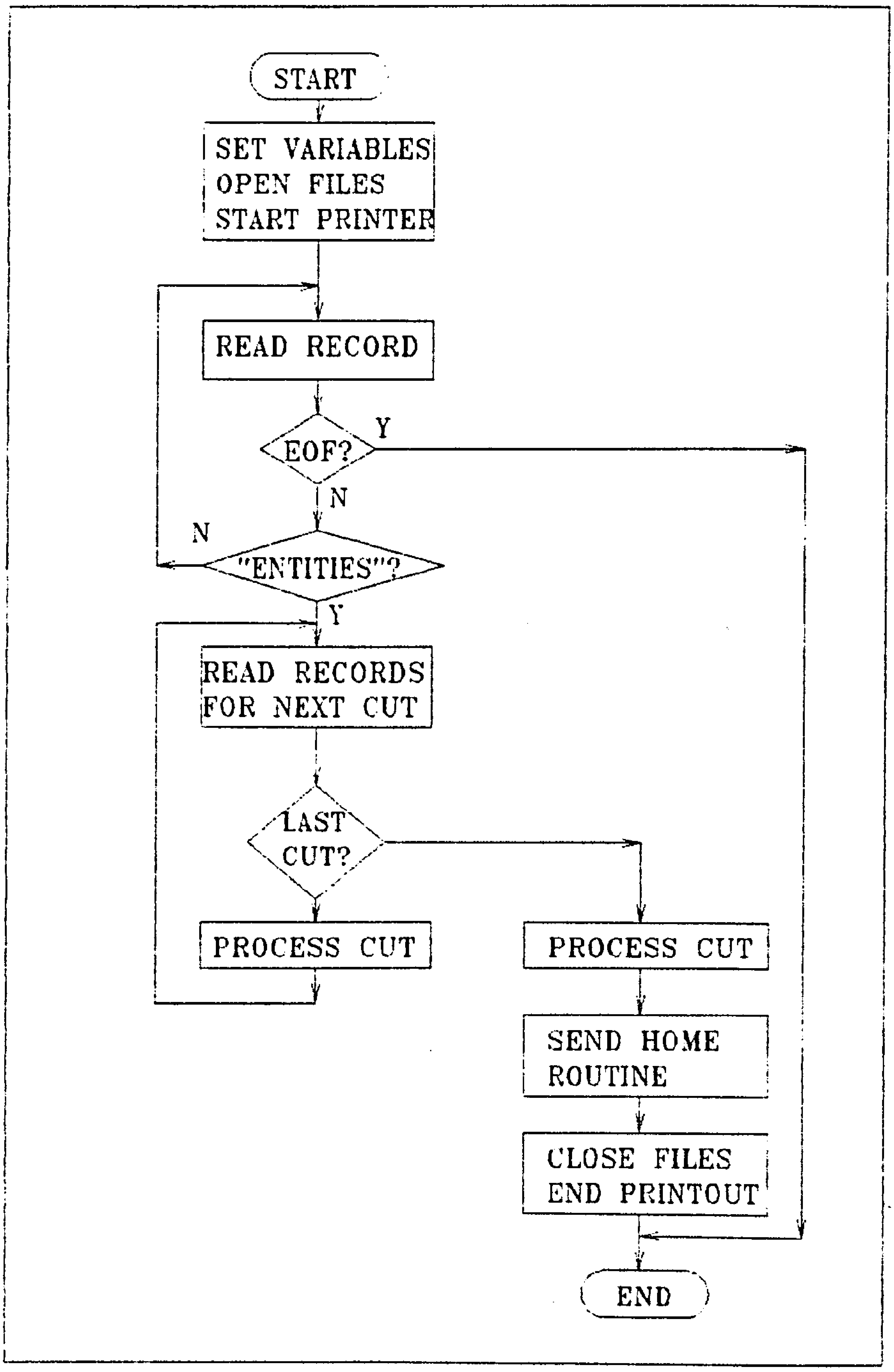


Figure 66. Programme flowchart for the "Process cut" routine of the curved linework module.

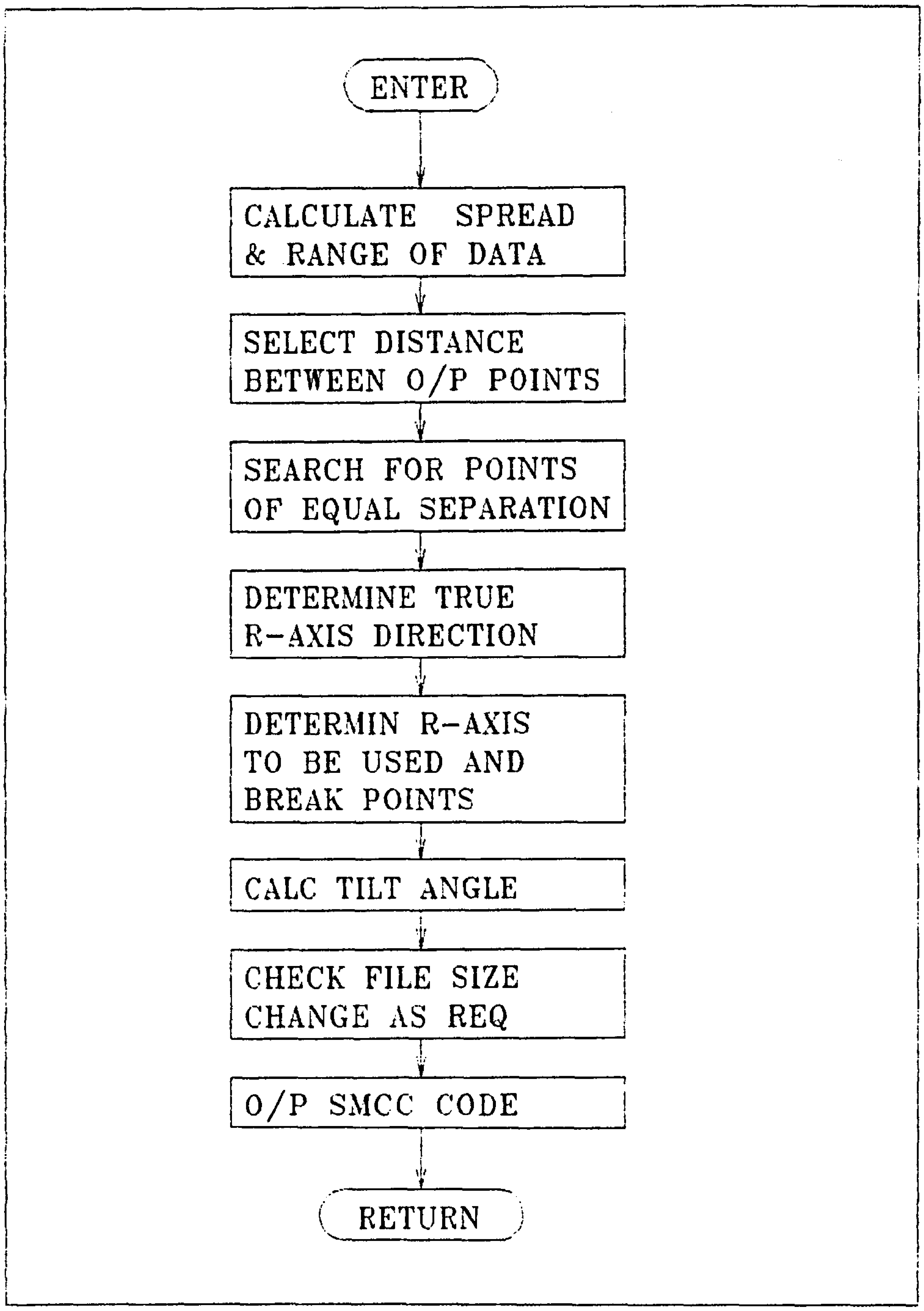


Figure 67. The path of the TCP during a change in grinding mode.

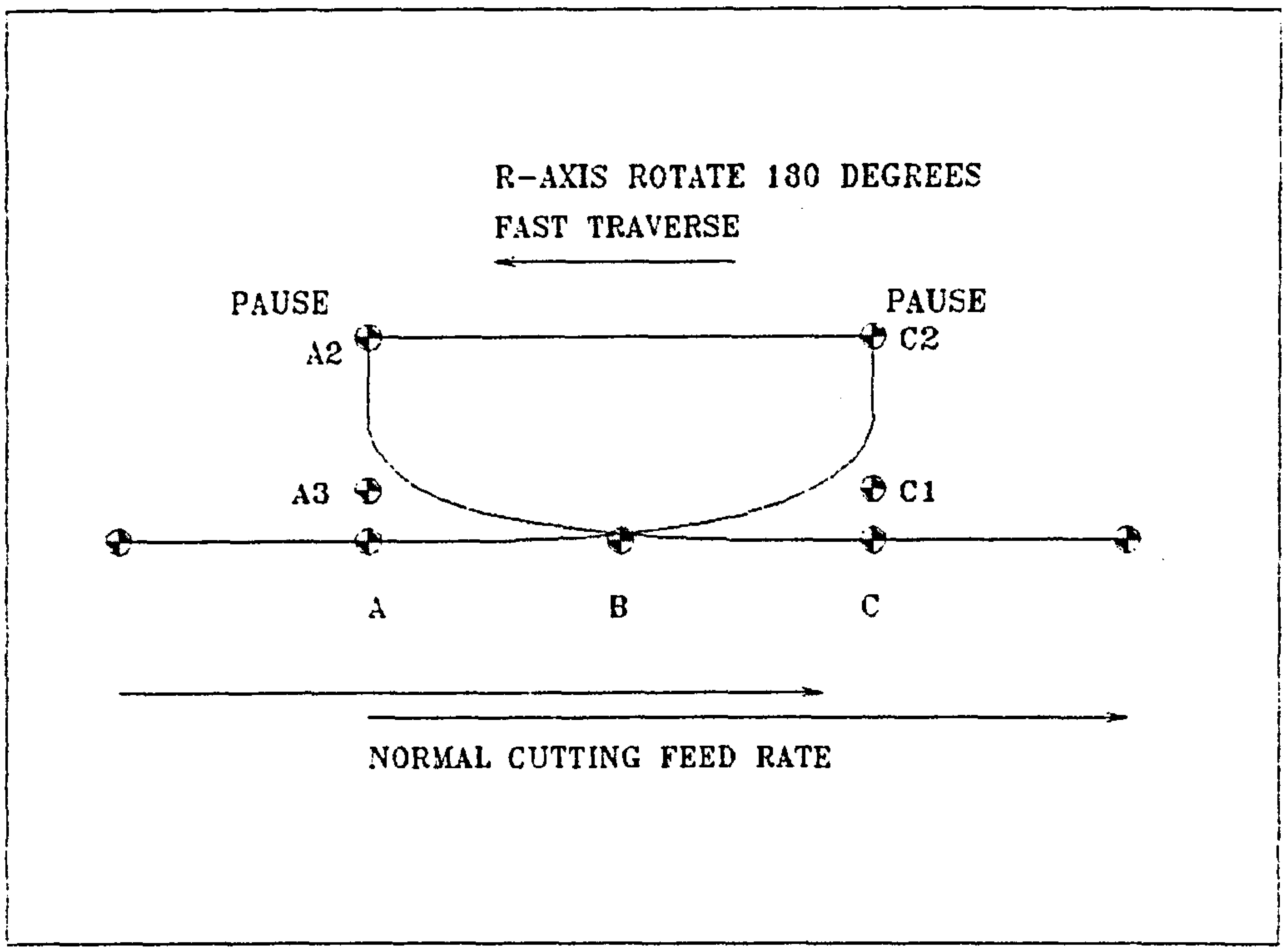


Figure 68. The directions in which brilliant cut segments must be drawn using CAD.

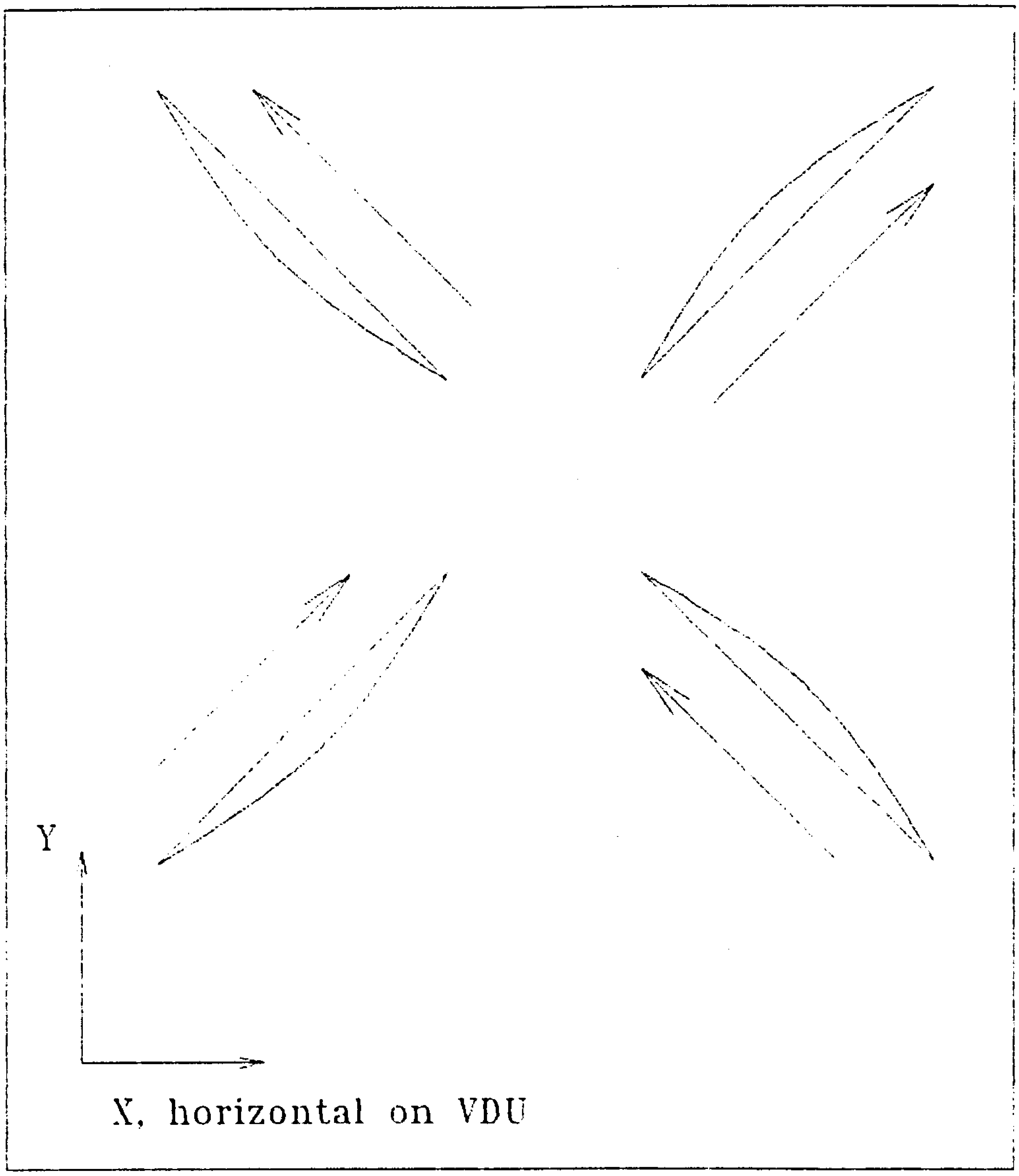


Figure 69. Programme flowchart for Segments module.

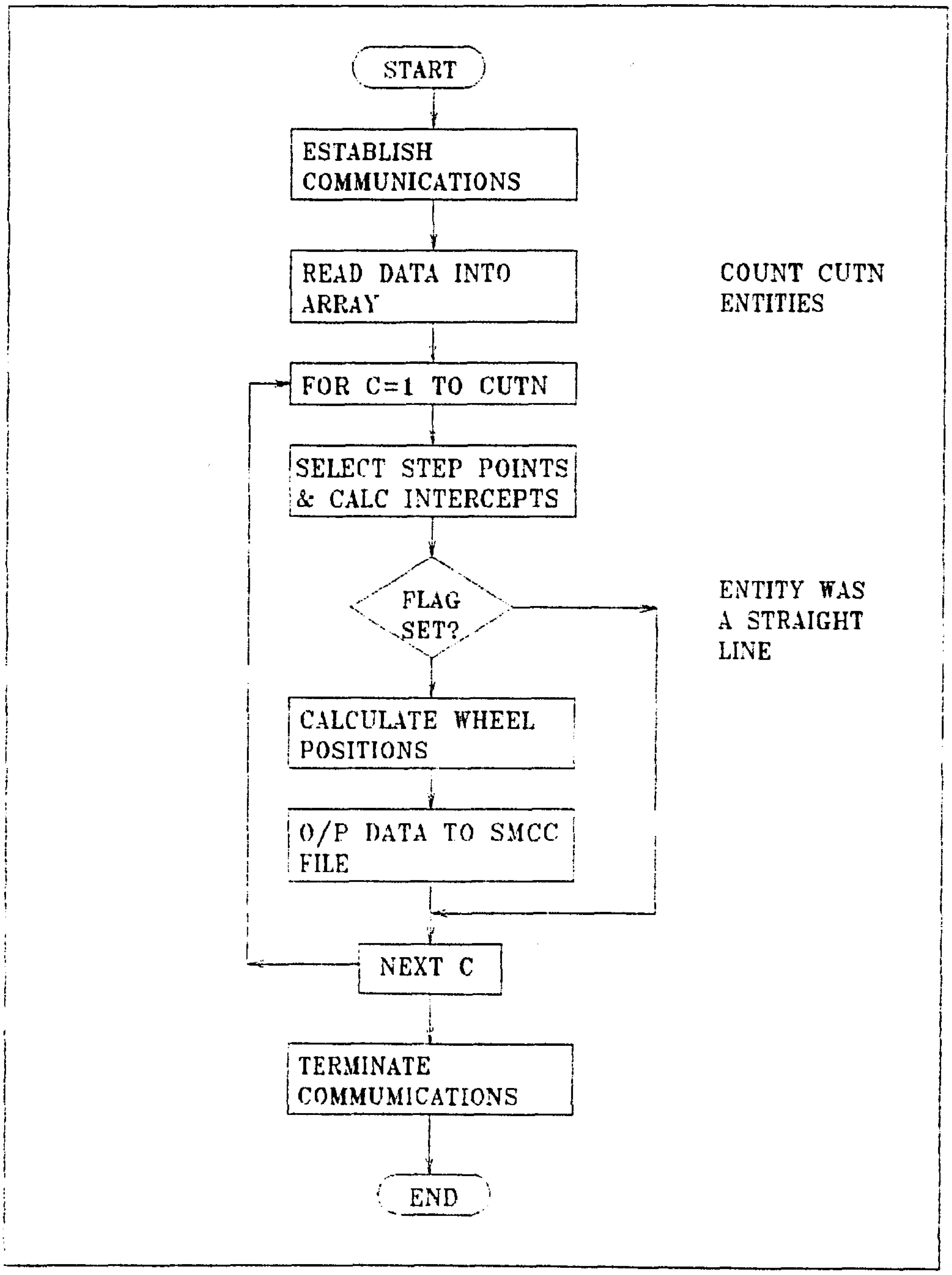


Figure 70. Calculating the cross-section of a Segment cut.

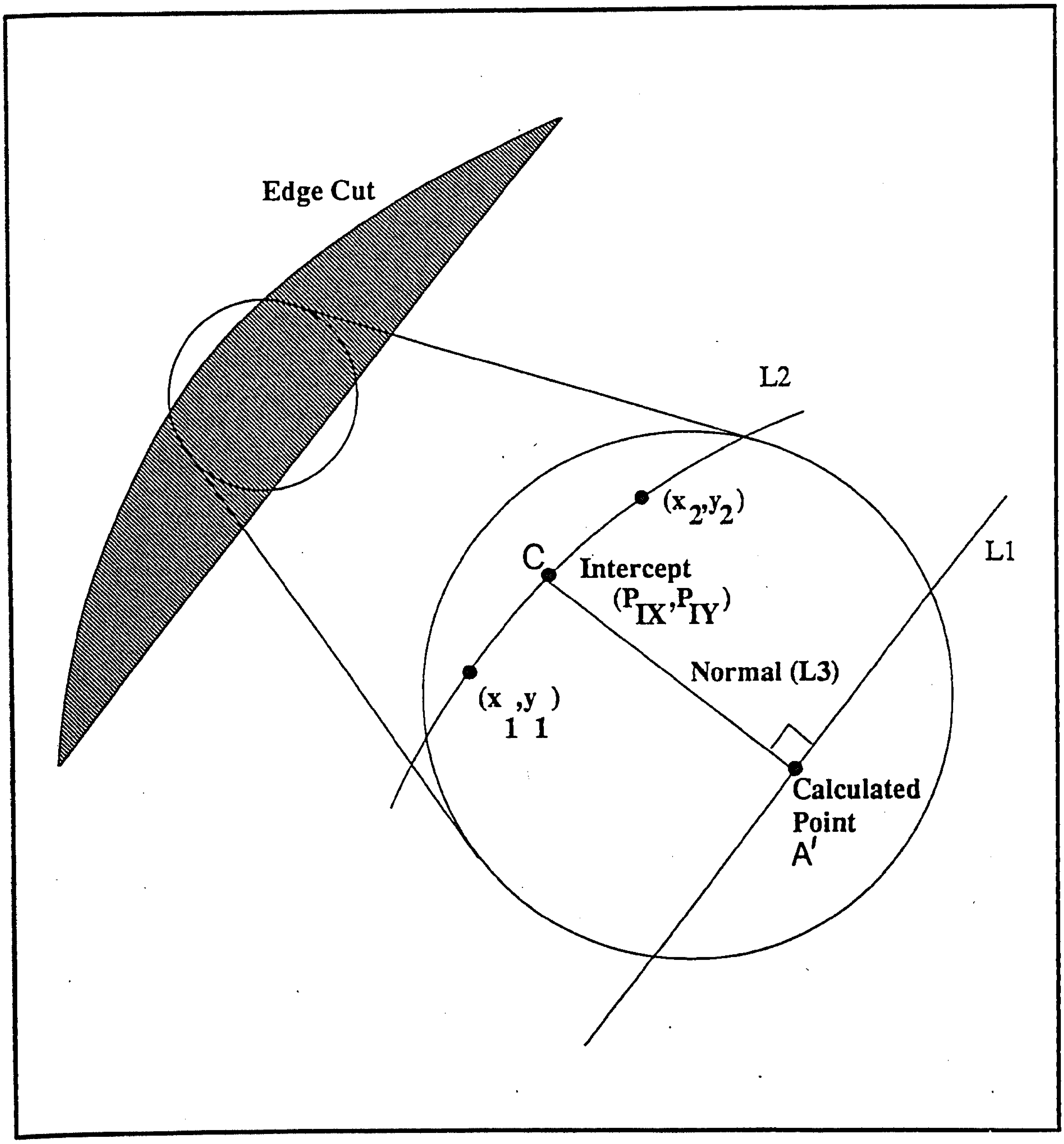


Figure 71. A cross section of an edge cut.

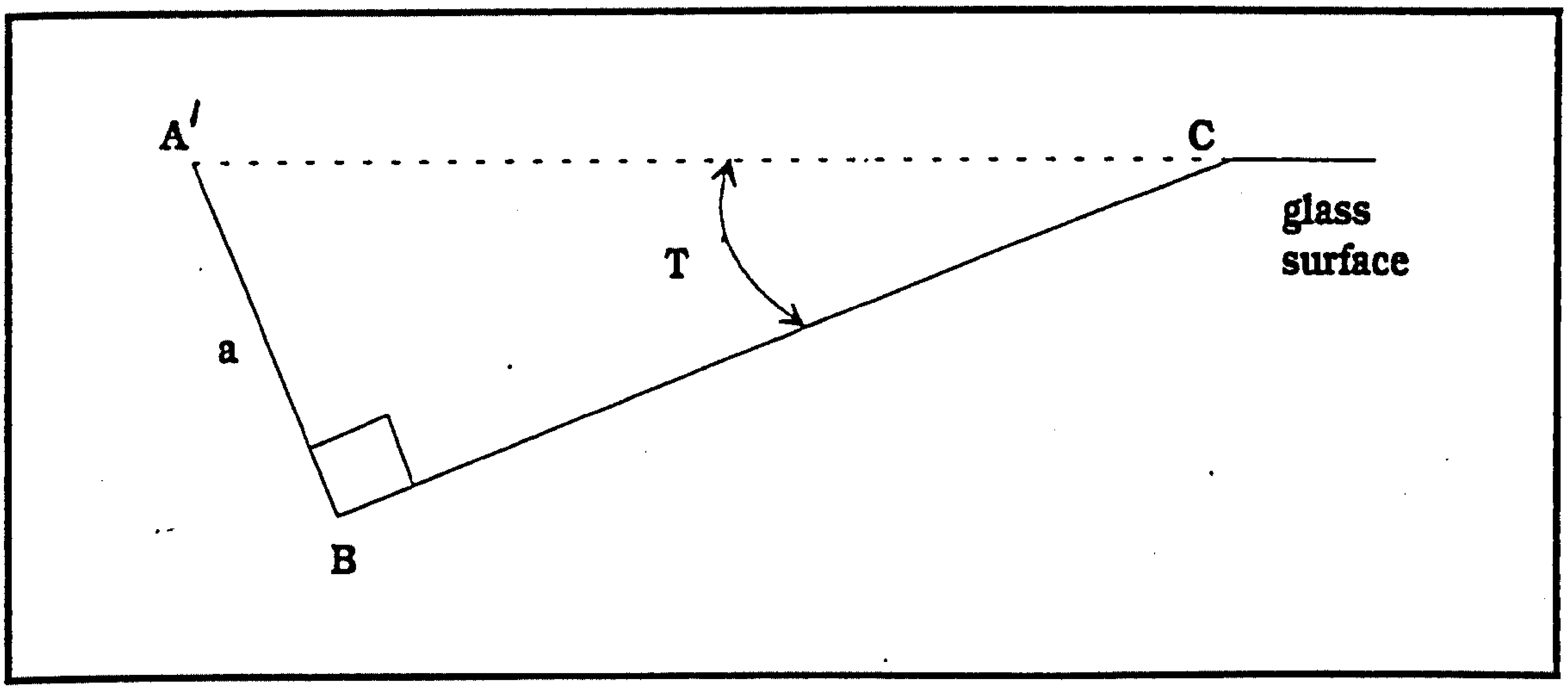


Figure 72. Location of the tool centre point, (TCP).

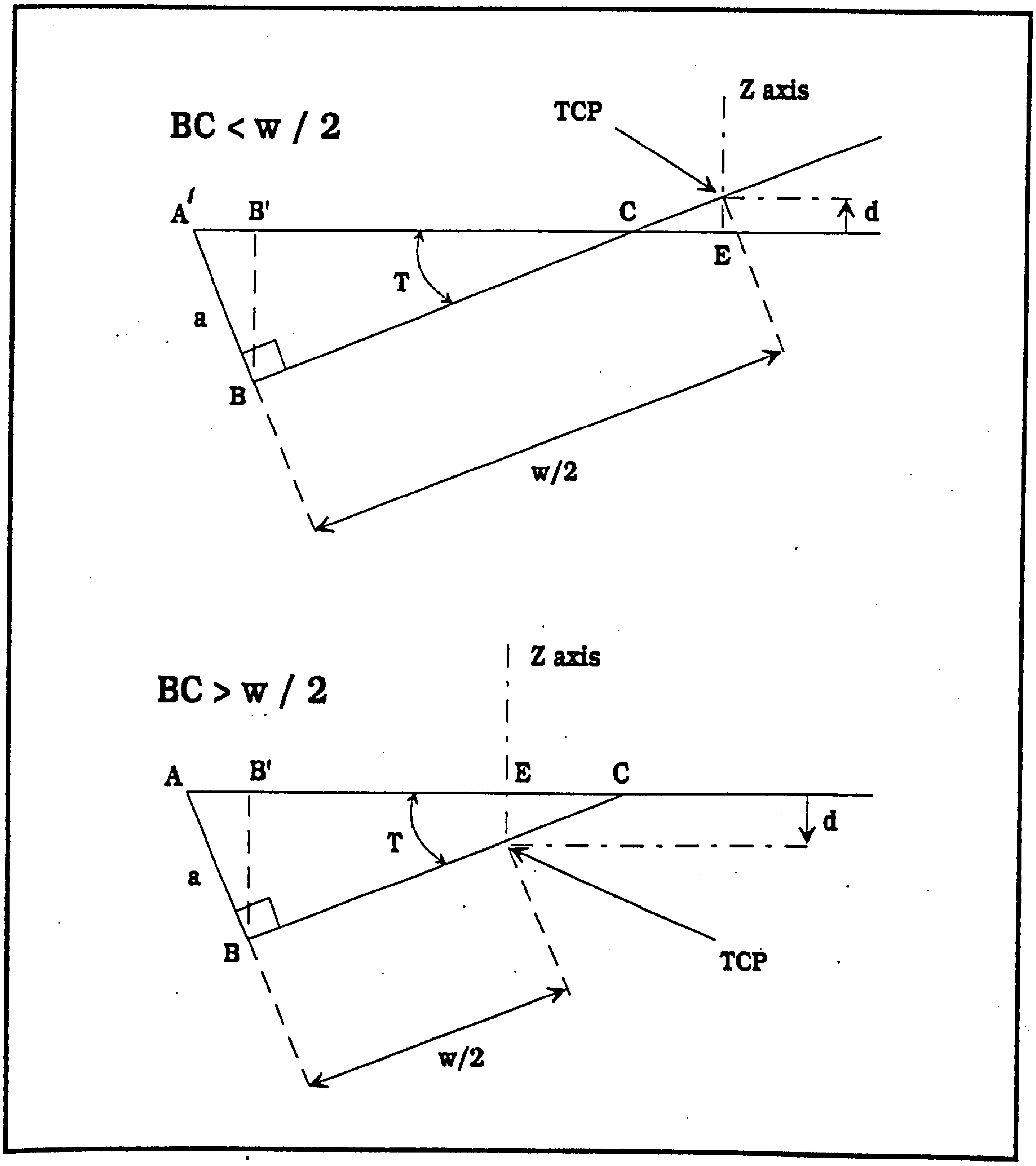


Figure 73. Data used to test the Segments module. Dimensioning and origin where added for comparison with the cut panel below.

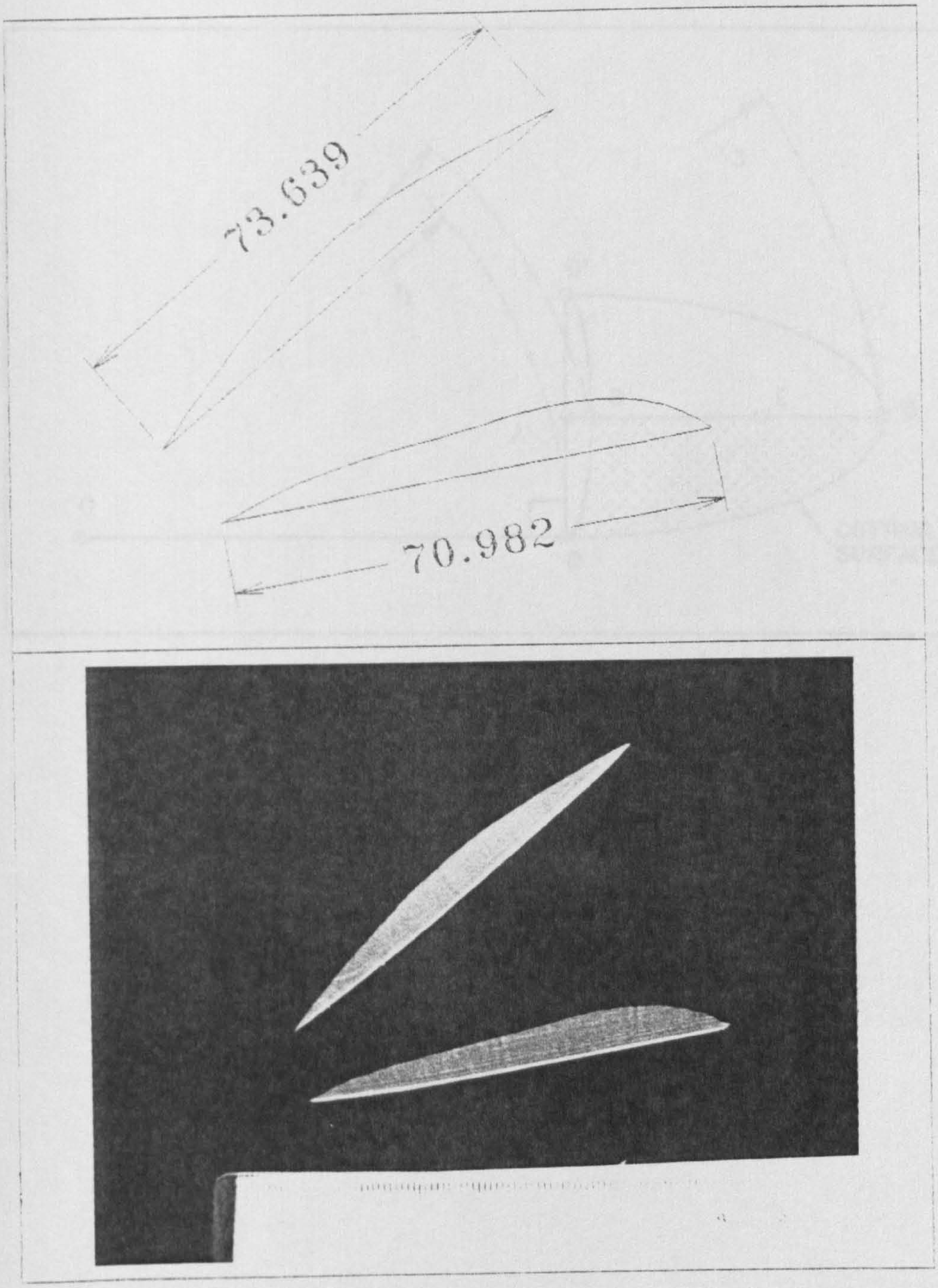


Figure 74. The imprint of the grinding wheel through the surface of the glass for an arc shaped edge cut.

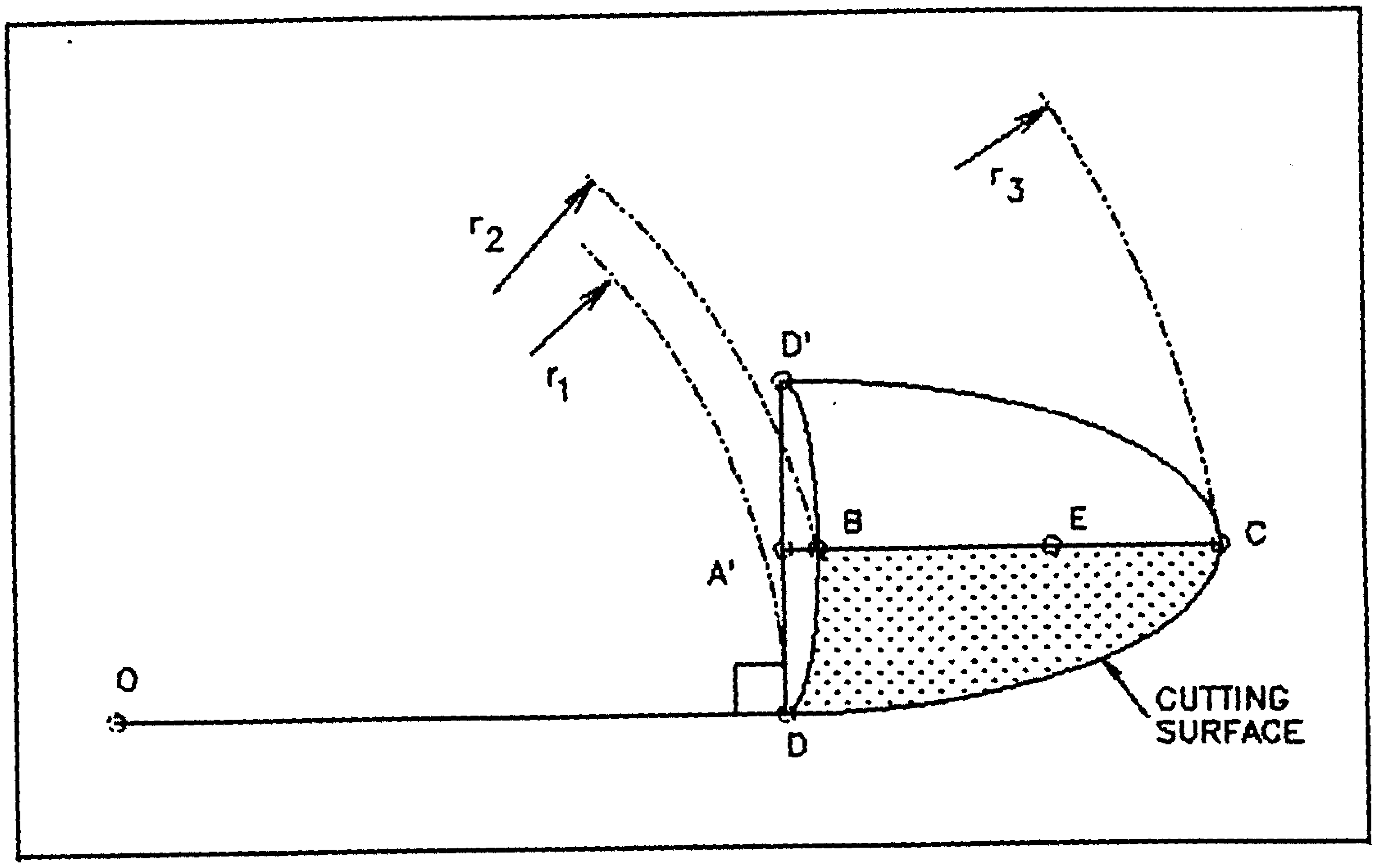


Figure 75. Examples of arc shaped edge cuts.

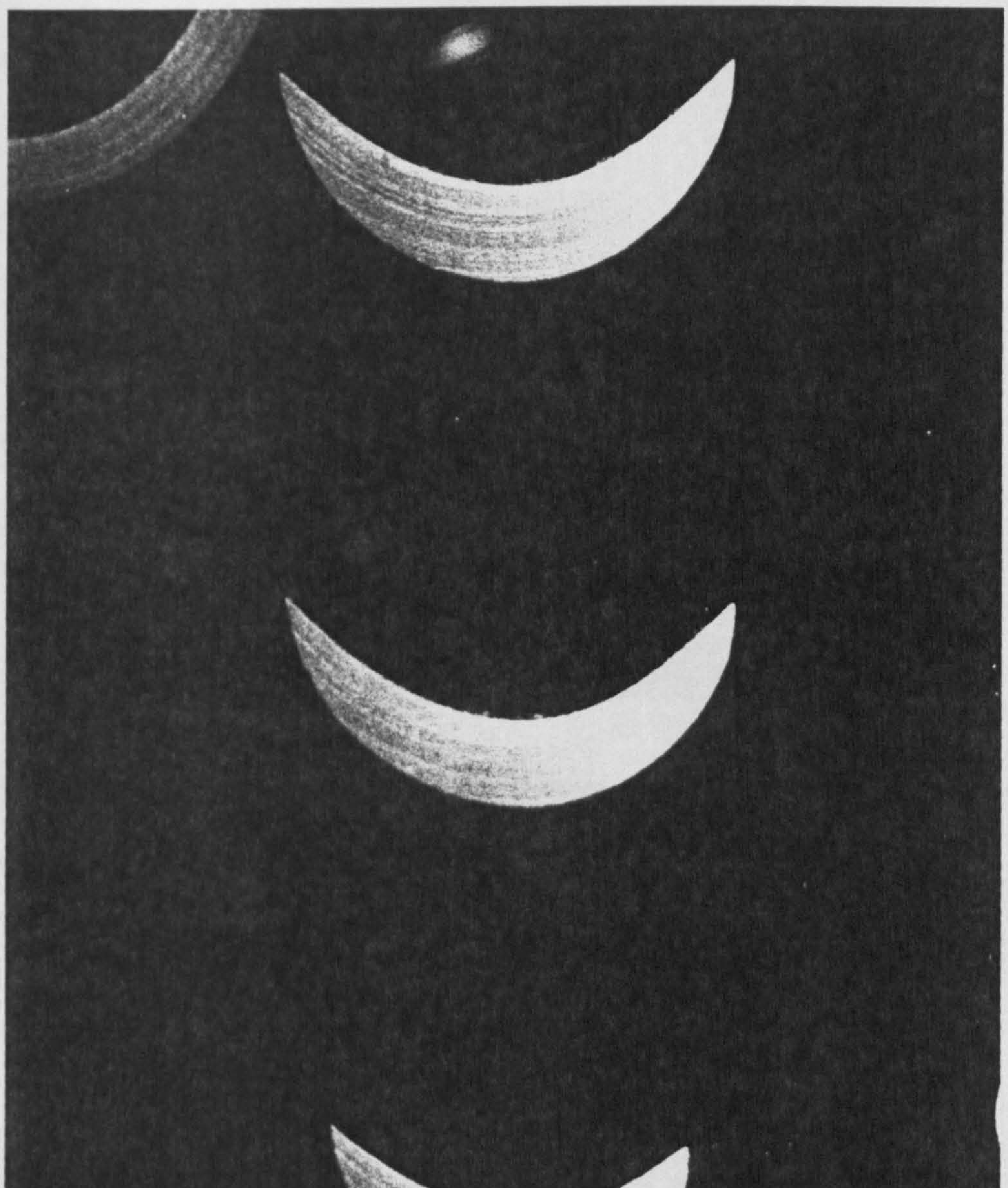


Figure 76. Cross-section of a curved edge cut.

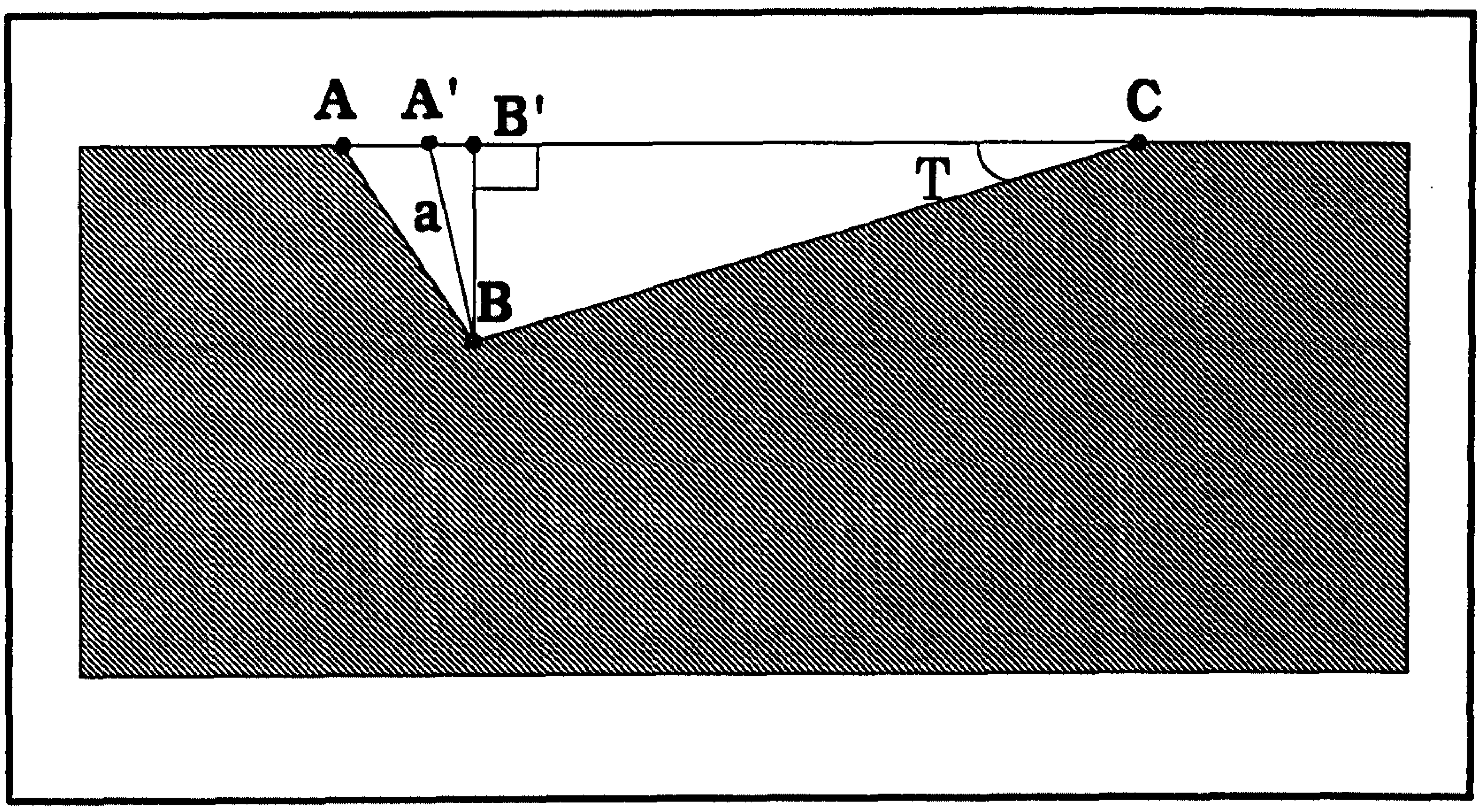


Figure 77. Calculation of A'D.

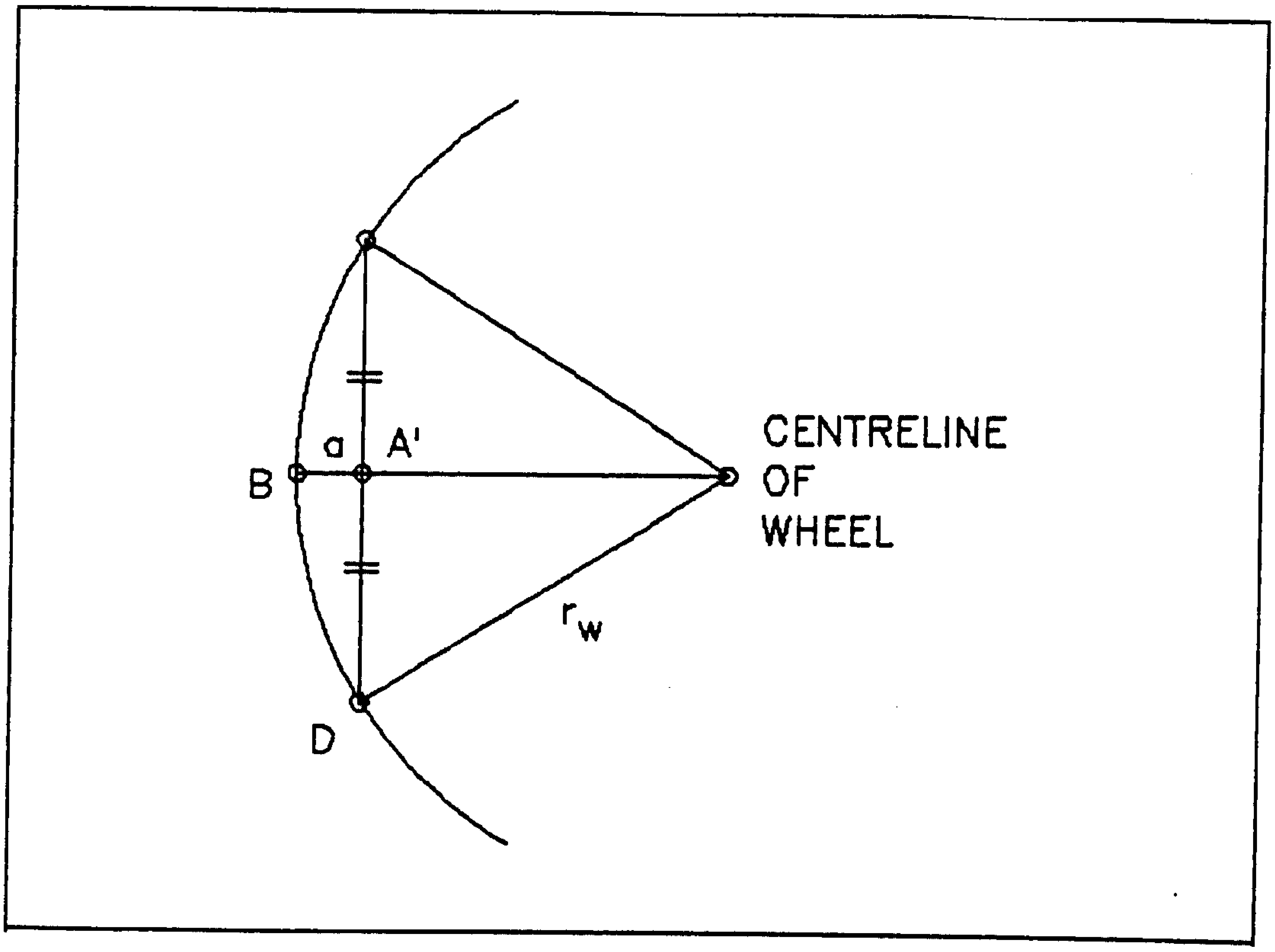


Figure 78. Horizontal plane.

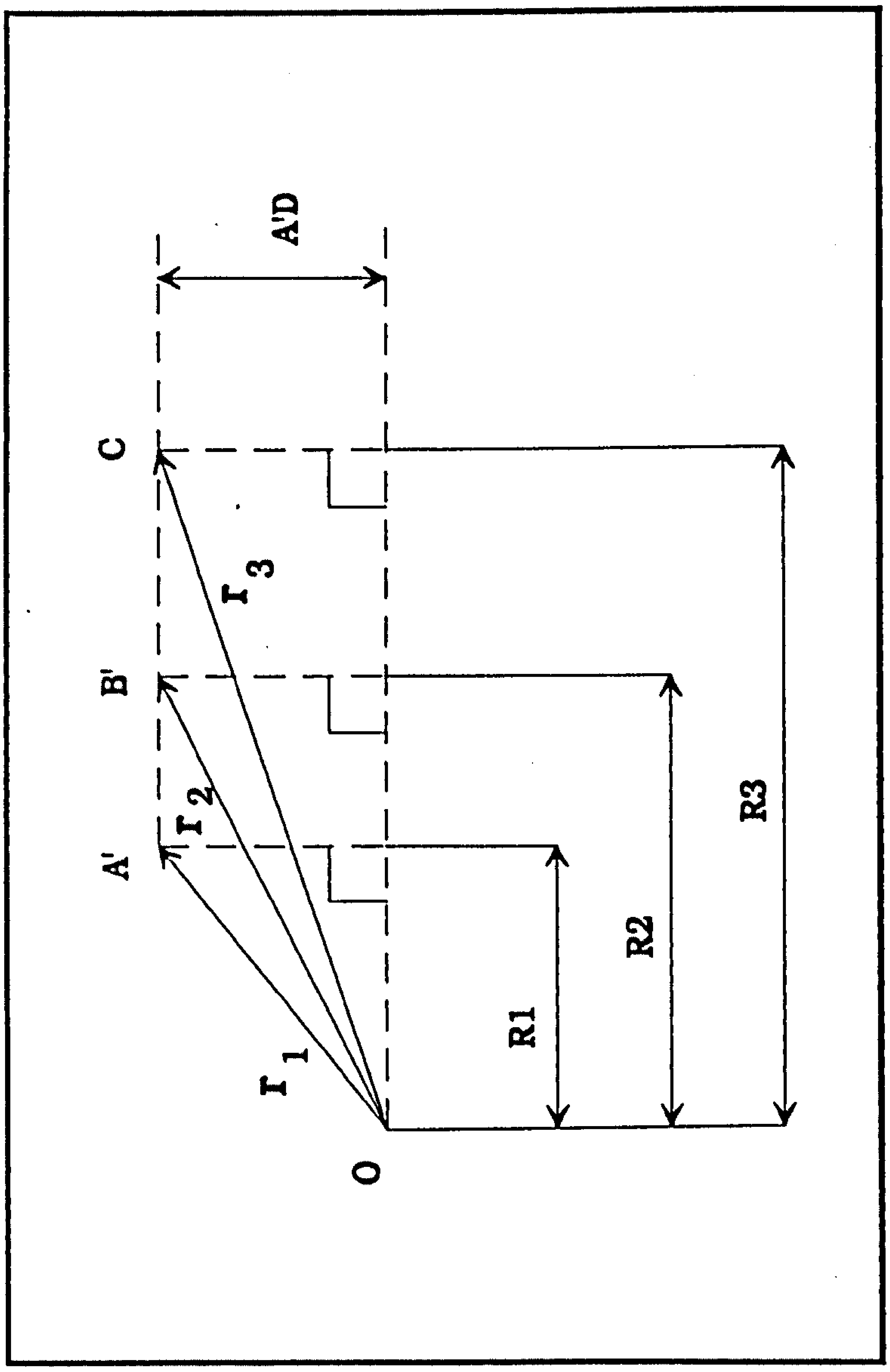


Figure 79. Calculation of rE.

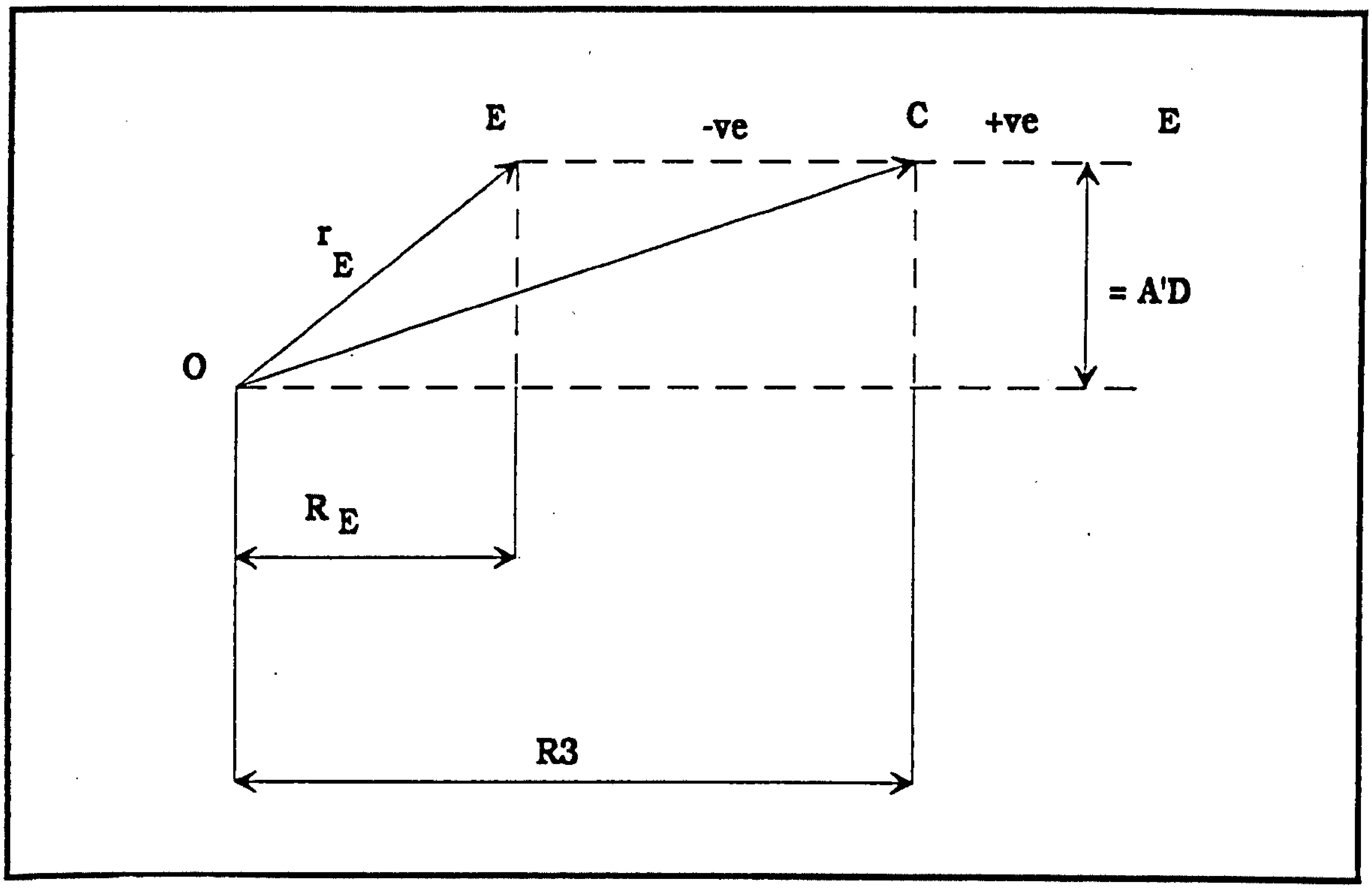


Figure 80. The required directions for drawing crescent shaped edge cuts.

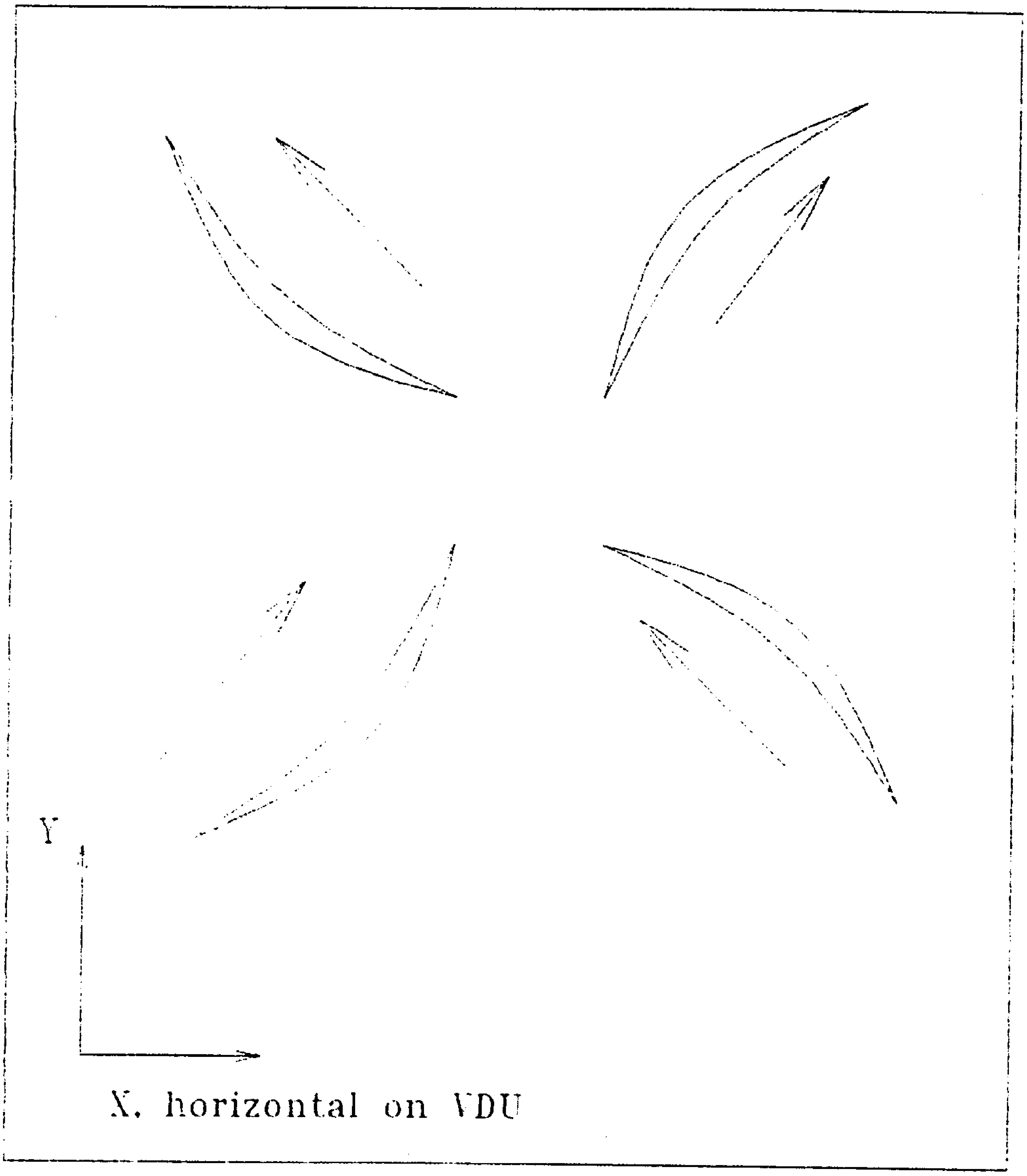


Figure 81. Programme flowchart for the crescent module.

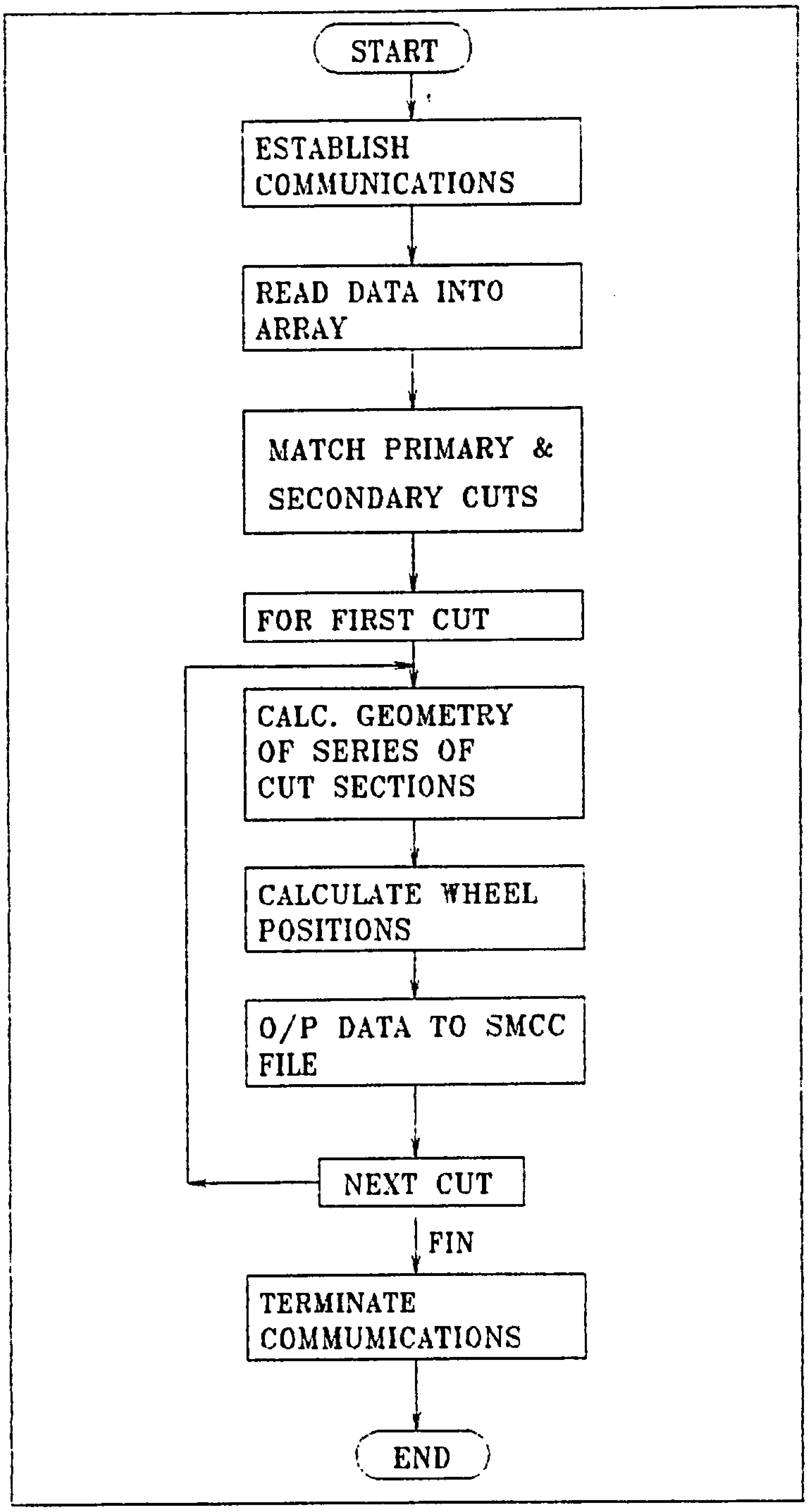


Figure 82. Geometry of a crescent edge cut.

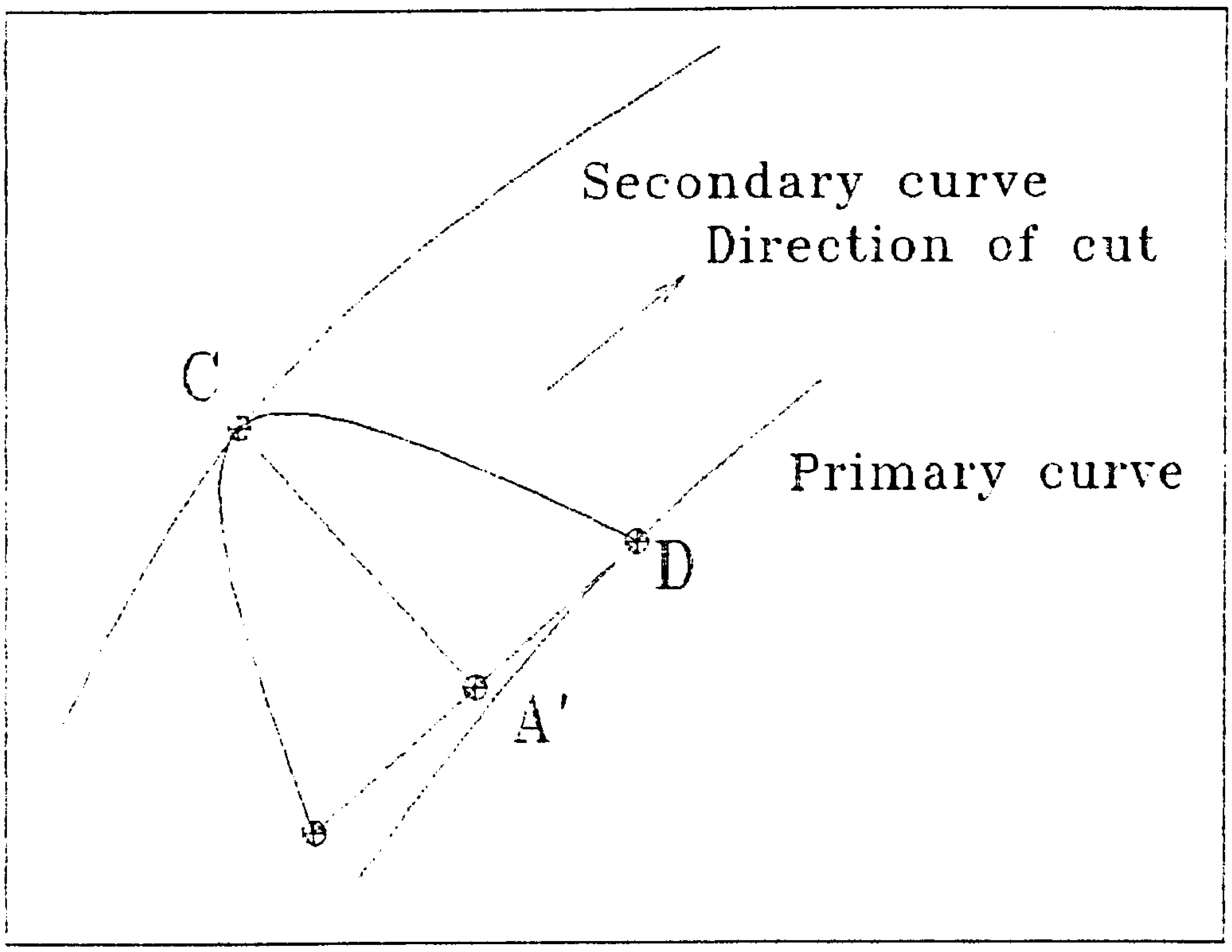


Figure 83. Data curves used to test the CRESCENT module. Dimensions where added for comparison with the cut panel below.

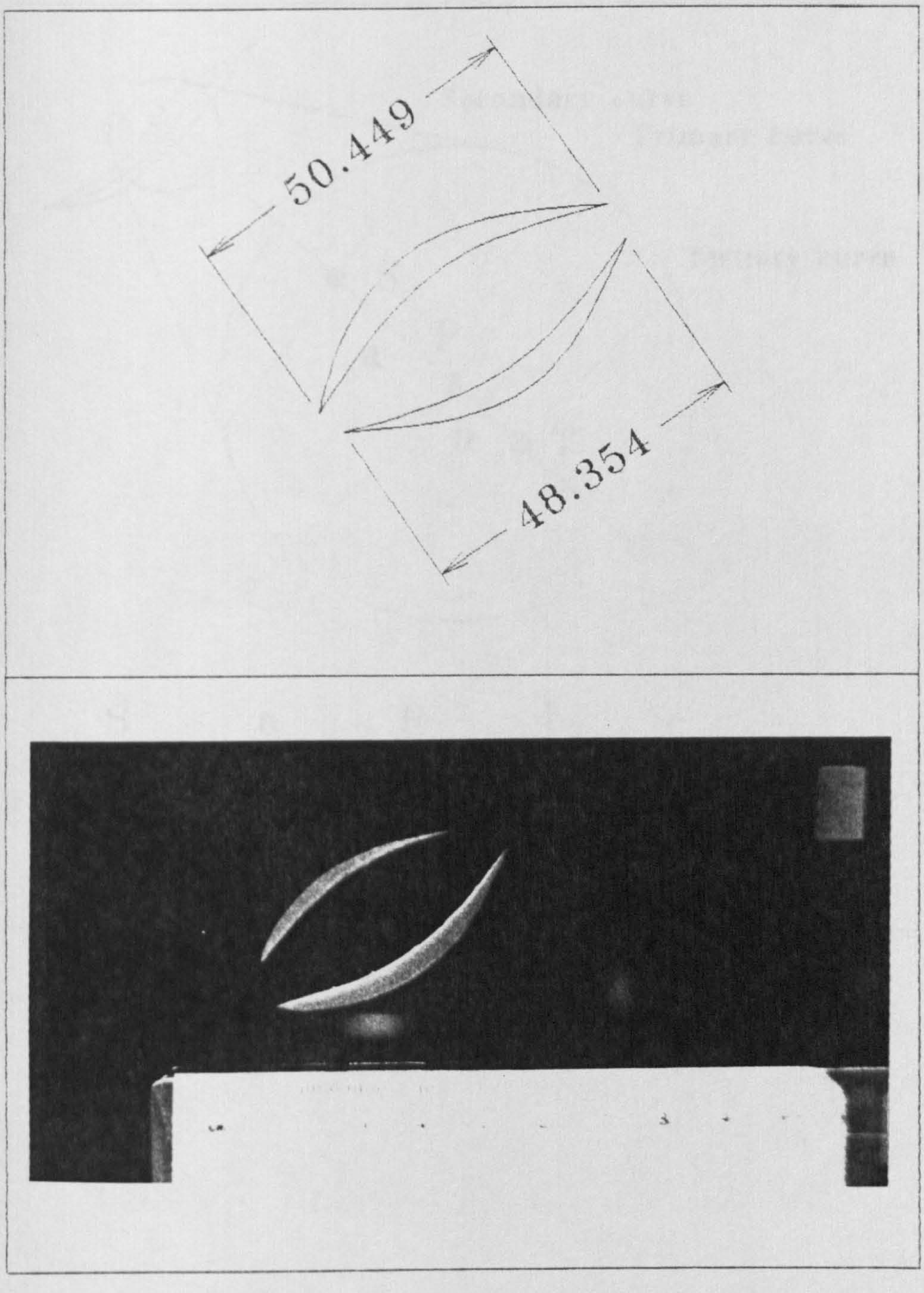


Figure 84. The cut cross-section for the MITRE5 module.

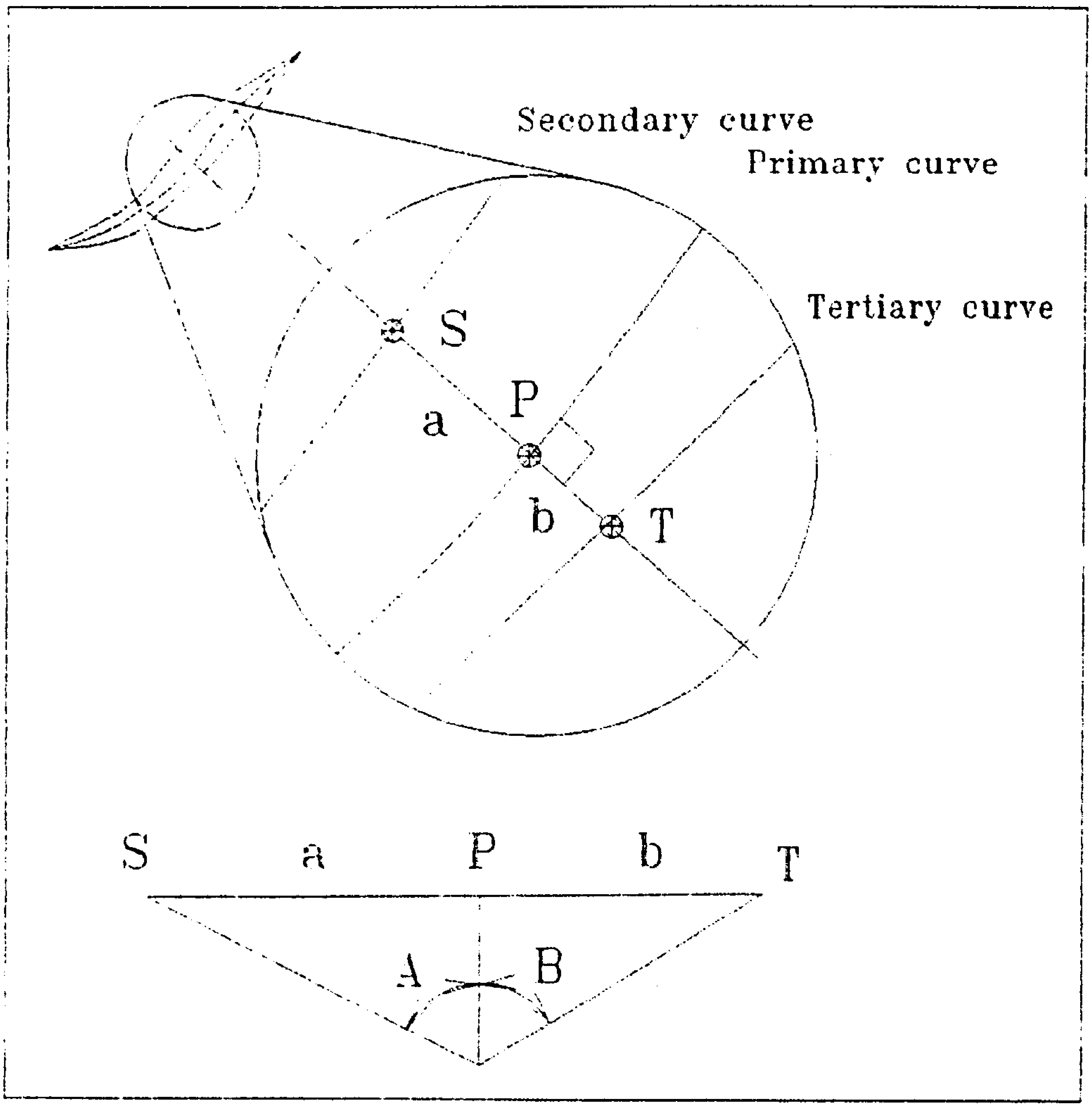


Figure 85. Data used to test the MITRE5 module. Dimensions where added for comparison with the cut panel below.

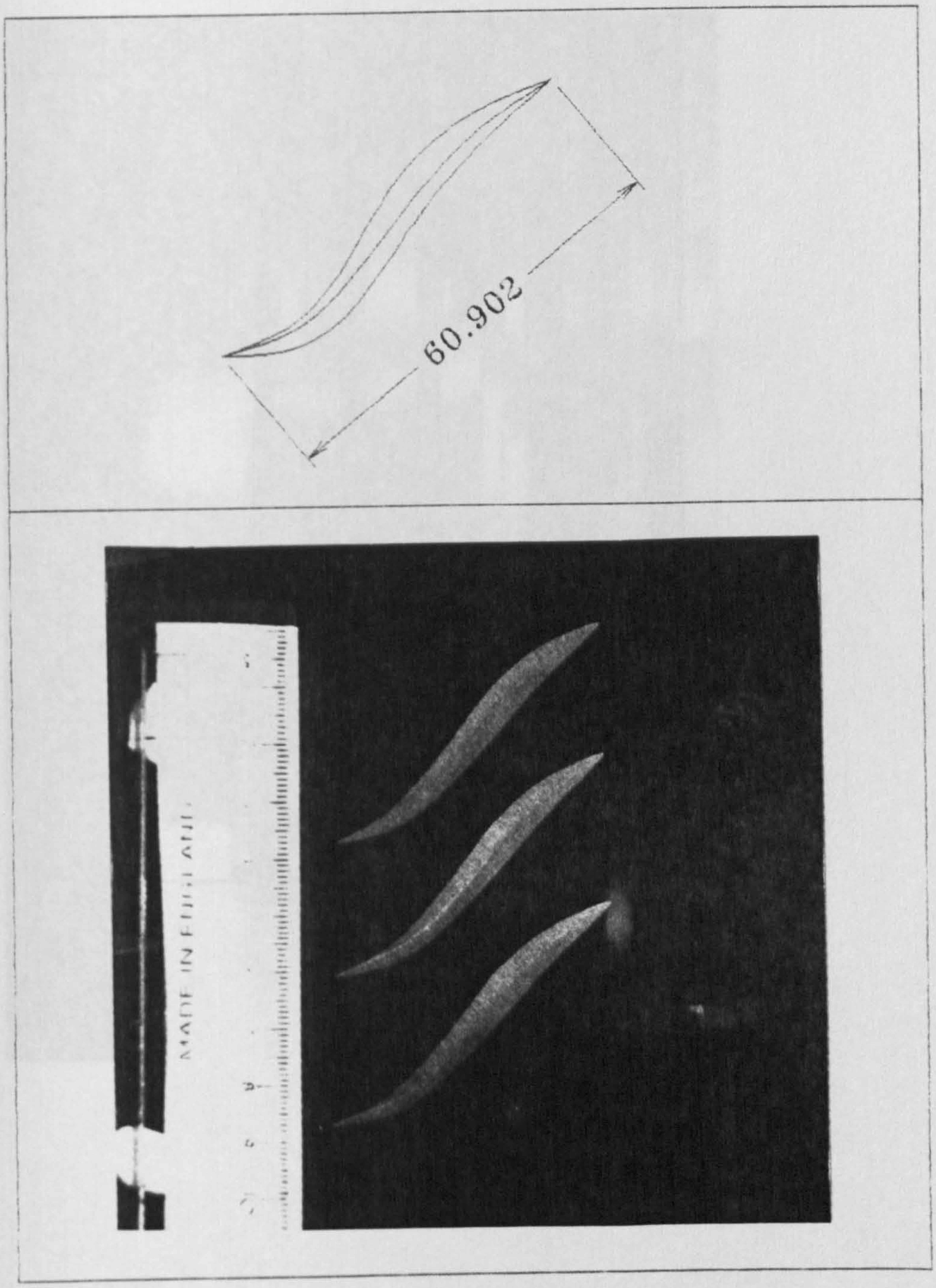


Figure 86. Deep mitred cuts, polished and unpolished.

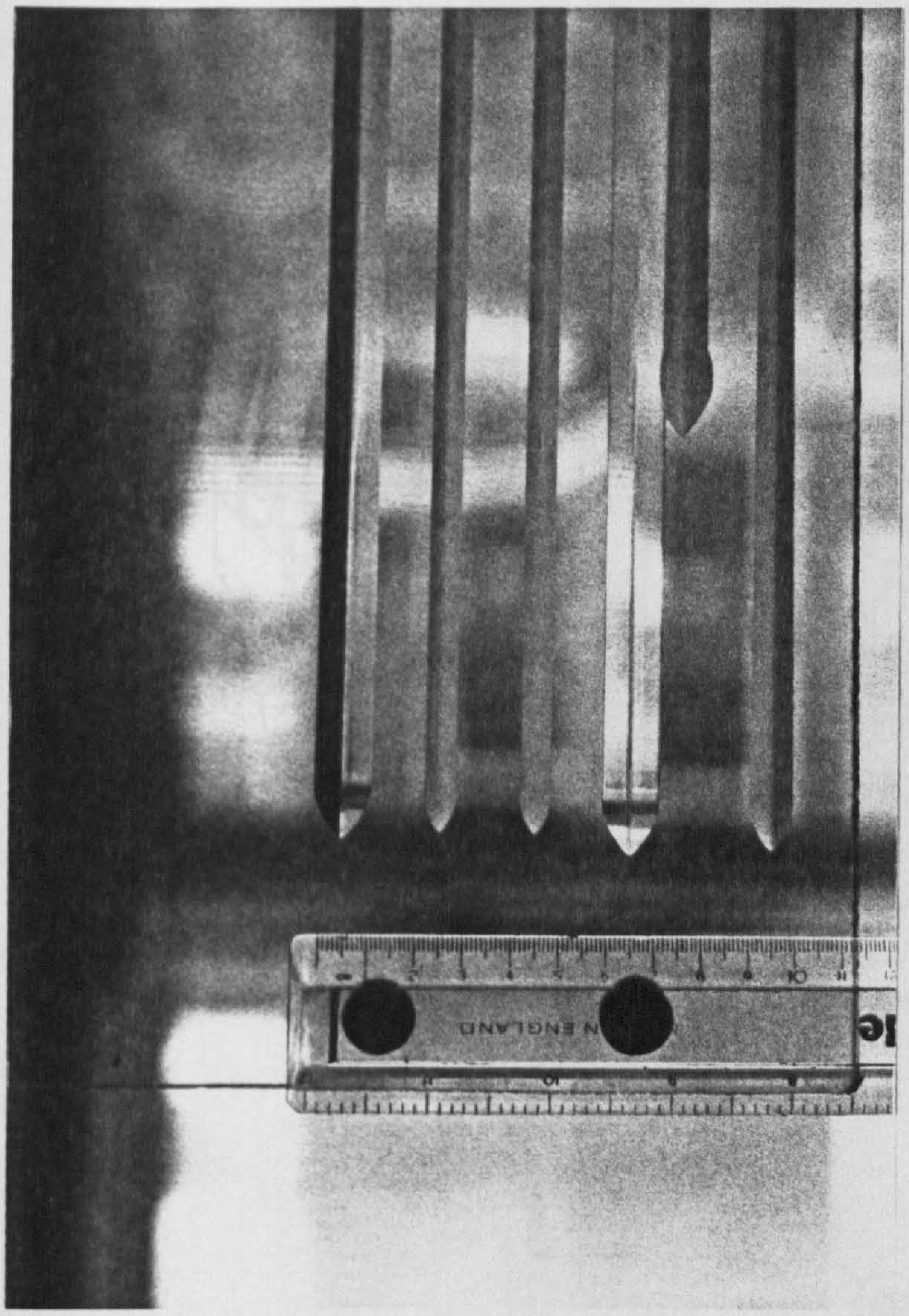


Figure 87. Sction of spindle/gearbox assembly through the spindle.

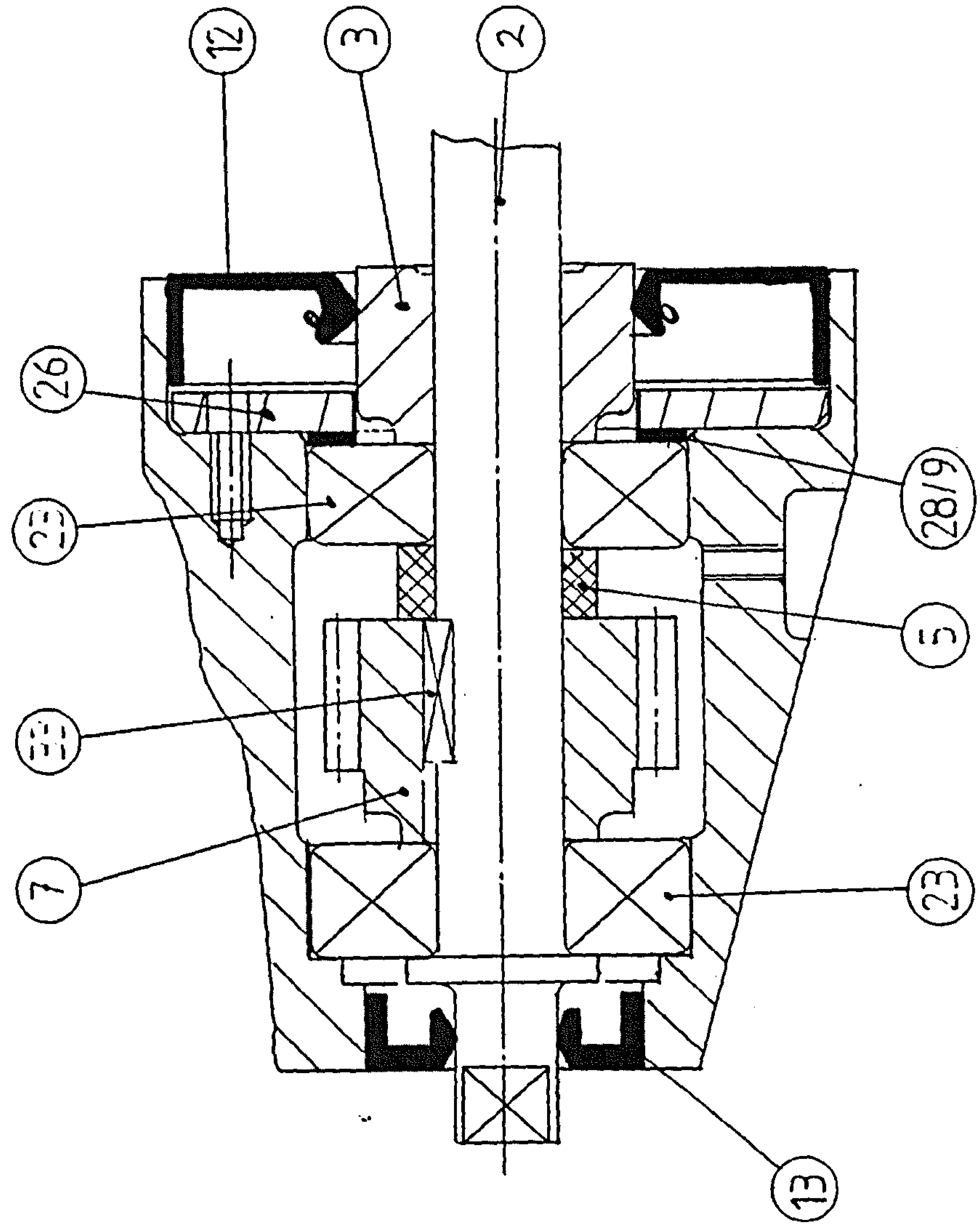
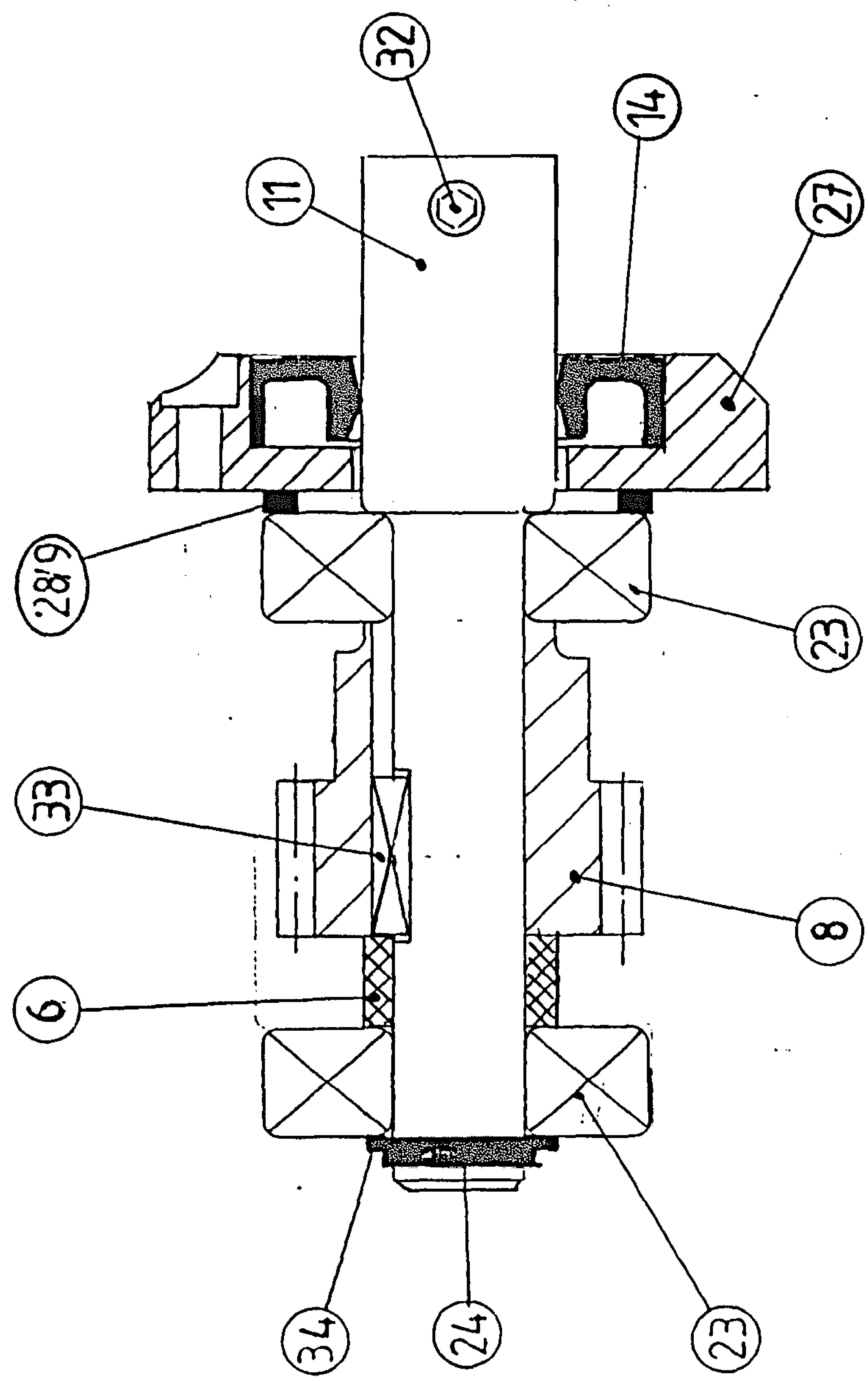


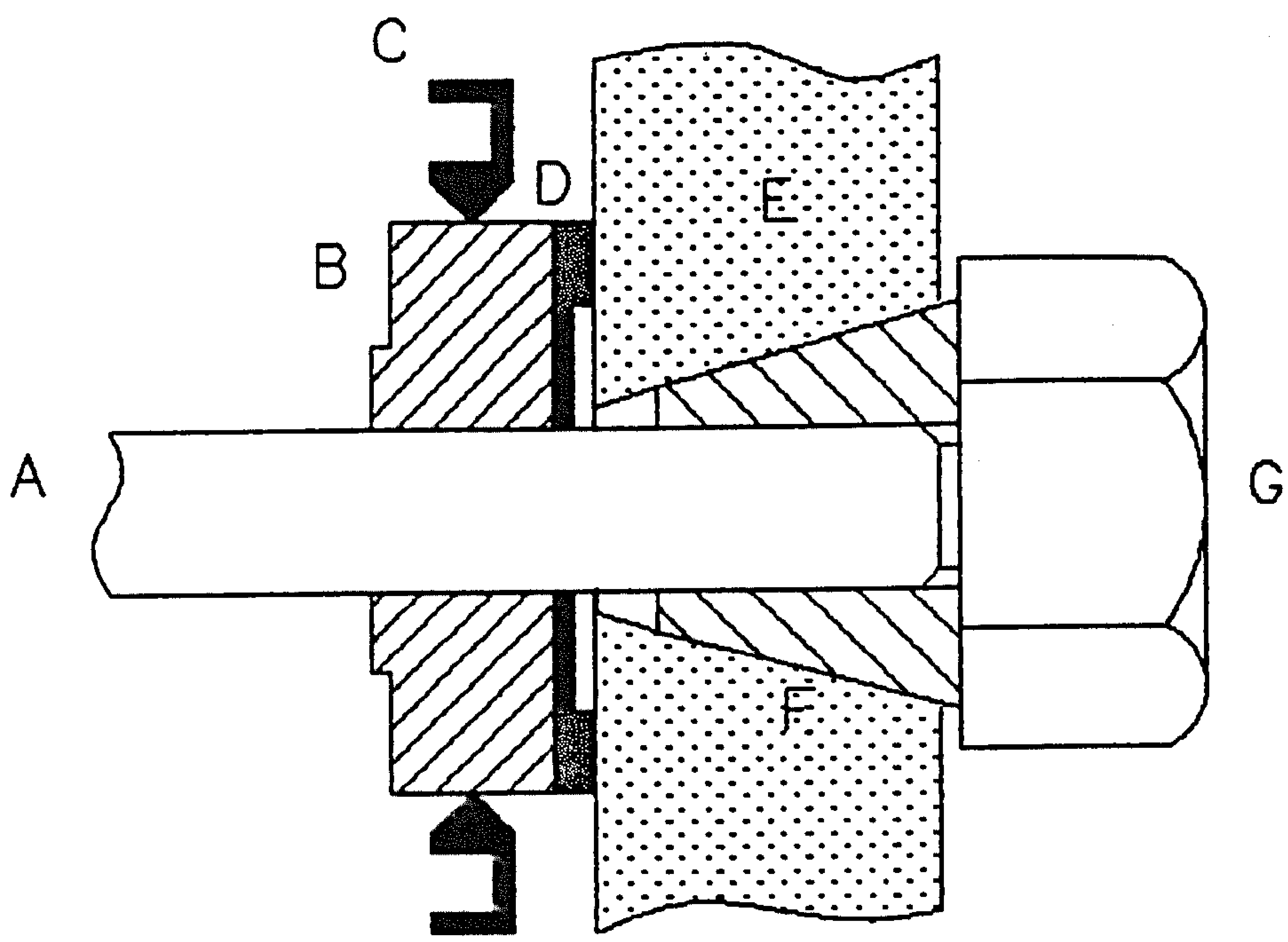
Figure 88. Section of the spindle /gearbox assembly through the input driveshaft.



Key to figures 87 and 88.

Part Number.	Componant.
TA-2	Spindle
TA-3	Inner flange (see fig 37)
TA-5	Spindle spacer
TA-6	Driveshaft spacer
TA-7	Spindle gear
TA-8	Driveshaft gear
TA-11	Driveshaft
TA-12	Spindle large oil seal
TA-13	Spindle small oil seal
TA-14	Drive shaft oil seal
TA-23	Bearings OD 30, ID 10, W 9mm.
TA-24	Circlip
TA-26	Spindle bearing cap
TA-27	Drive shaft bearing cap
TA-28	Thin shim
TA-29	Thick shim
TA-33	Key
TA-34	Washer

Figure 89. The method of wheel mounting, using a split cone, used on the brilliant cutting machine.



KEY TO FIGURE

A Spindle
B Inner flange, interference fit on shaft
C Oil seal
D Washer, clearance fit on shaft
E Wheel
F Split Cone
G Nut

Appendix A

Machine Specification circulated for tender to manufacturers of modular automation systems

--=--

MACHINE SPECIFICATION

General Description

A "gantry" style CNC machine of X, Y, rotation, Z configuration caperble of carrying a grinding head assembly. This assembly will involve a fifth axis. Mechanical power to the head will be from a 0.37 kW AC motor mounted on the Y axis carriage (which needs to be adapted accordingly) via a flexible drive. The Polytechnic are to design the grinding head assembly, flexible drive and motor, but the stepper motor for the fifth axis is part of the tender.

SPECIFICATIONS

Grinding head assembly

height 140mm

base area 180 x 220 mm symetrical about axis of rotation weight 3.5 kg. max

stepper motor 2 inch twin stack microstepping

(static torque approx 0.5 Nm)

A.C. motor (supplied by Leicester Polytechnic - info only)

0.37 kW @ 2800 rpm.

body 126 dia x 221 long

weight 6 kg approx

(flange mounted with terminal box, fully enclosed)

Loads experienced at point of contact between wheel and glass

Max resultant in horizontal plane = 50N (in any direction)

Max vertical reaction = 60N

1) Nominal Maximum Speed

X = 1m/s, Y = 1m/s, Z = 0.25m/s

2) Accuracy

Accuracy per axis = +/- 0.1mm

Repeatability per axis = +/- 0.01mm

3) Useable Stroke Length

X = 2m, Y = 1m, Z = 0.1m, R = 180^{o}

(Note: additional lengths of 0.2m may be required on the y gantry to accomodate flexible drive.)

4) Motors

All stepper motors, drives and power packs required. (Five or six if construction requires 2 motors to a particular axis).

5) Assembly and Wireing

To be carried out by the Supplier.

6) Controller

A controller ("indexer") that will

(a) allow full interpollation in five axes simultaneousl

APPENDIX B

The Spindle/Gearbox Assembly

Due to the 15 degree angle of tilt required there is little room in which to fit a spindle assembly, three major redesigns based on different bearing arrangements were required until all involved where satisfied. The gearbox body is machined from solid aluminium to tolerances down to one hundredth of a millimetre. It contains two stainless steel shafts carrying specially modified, crossed axis helical gears of case hardened EN32, Figures 87 and 88. These are the only type of gearing that could be made to fit in the space availiable and still transmit the torque. The reaction forces due to helical gearing, are several times that due to the cutting forces, hence the load on the input shaft is comparable with that of the spindle. The shafts are held in quality RJH angular contact ball bearings as no angular contact roller bearings of such small size are available. Correct bearing preload is set by means of shims and bearing caps. Backlash between the gears should not produce torsional vibration due to the helical gears. However listening with an ear to a screwdriver held to the gearbox reveals a harsh noise that betrays the presence of high frequency vibration. A hole tapped into the side of the gearbox allows the fitting of a temperature probe right next to the gears to give an accurate reading of the temperature of the oil.

A method of lubricating the SGA, (ie using Castrol EPX light gear oil), has been developed to overcome initial overheating problems. The final design constantly circulates oil from the temperature probe hole back to the top of an expansion tank. The expansion tank is mounted on the flexible drive support bracket. A tube ducts the oil from the expansion tank to the filler hole at the top of the SGA. The oil is propelled by pressure generated by the centrifugal action of the gear adjacent to the probe hole. The system has been found to be, in part, self bleeding. If the expansion tank becomes empty, bubbles of air drawn into the gearbox become mixed as small bubbles into the oil. The oil and air mixture will settle out of the oil. After several years use this system has kept the oil clean although changing the oil is now easy. The system would also appear effective at cooling the oil as running temperatures have remained at about 40C.

The wheels are mounted as in Figure 89. The spacer washer, part D, is required for accurate location on the spindle. All wheels are of different widths and the position of importance is midwidth so for correct use each wheel requires its own spacer. Radial location is provided by a split cone, locked into the conical hub by a nut. When tightening or releasing the nut the shaft is prevented from rotating by a wrench holding the other end of the spindle. Both the cone, washers and nut where manufactured in house to the highest standards to ensure the best possible balance of the spindle. The angle of the cone is such as to just lock. A slight tap being required to release the wheel. The nut is a normal right hand thread, the rotation of the spindle ensuring self-tightening. The thread is a 3/8inch and provides a greater clearance than would a 10mm thread for fitting the componants. This arrangement provides secure location and transmits torque so well that the machine can be stalled, although marks on the shaft might indicate that friction welding occurred on one occasion. The removable cone may be omitted to allow parallel bored wheels to be used.

APPENDIX C

Programme Listings

1	MPUNTS	Mitred punts module
2	MPUNTPAR	Parametric mitred punts CAD Macro
3	RPUNTS	Oval punts module
4	OPUNTPAR	Parametric oval punts CAD Macro
5	ROUNDP	Round punts module
6	PANEL	Panel cutting module
7	SEGMENT	Segment shaped edge cut module
8	CRESCENT	Crescent shaped edge cut module
9	MITRE5	Five axis mitred cutting module
10	LINEWORK	Linework cutting module

1 MPUNTS Mitred punts module

```
10 REM*********************************************
20 REM*    PARAMETRIC MITRED PUNTS ROUTINE       *
30 REM*    multi-file version 26/11/90       *
32 REM*    Cange to Barry offsets 20/12/90      *
40 REM*   PMPunts                *
50 REM*********************************************
60 WRAD=73.3/2: REM  wheel radius
70 X0=90 : REM  x axis offset
75 Y0=30: REM  x axis offset
80 Z0=100.48 : REM  z axis offset, z position of the surface of the glass
90 V=1: REM that volume of glass removed every....
100 T=1000 :REM  binary microseconds
110 FASTT=500/1024: REM  mean fast traverse velocity mm/bms
115 N=1 :REM  cut counter
120 REM
122 LPRINT "X offset= ";X0,"y offset= ";Y0
125 LPRINT "cut","CX","CY","R","DMAX"
126 FI$="layer6.DXF"
127 F1$="a:mP1.smc" :F2$="a:mP2.smc"
128 F3$="a:mP3.smc" :F4$="a:mP4.smc"
131 F5$="a:mP5.smc" :F6$="a:mP6.smc"
132 F7$="a:mP7.smc" :F8$="a:mP8.smc"
138 OPEN F1$ FOR OUTPUT AS #2
139 OPEN FI$ FOR INPUT AS #1
140 LPRINT F1$
150 PRINT#2,"AAz 1500"
160 PRINT#2,"t512"
170 INPUT#1,INFO$
180 IF INFO$="ENTITIES" THEN 200 ELSE 170
190 REM------------find the first line
200 INPUT#1,INFO$
202 IF INFO$="LINE" THEN GOTO 210
204 IF INFO$="EOF" THEN 370 ELSE 200
210 INPUT#1,O$,LAYER$
220 INPUT#1,O$,X1$,O$,Y1$ :X1=VAL(X1$) :Y1=VAL(Y1$)
230 INPUT#1,O$,X2$,O$,Y2$ :X2=VAL(X2$) :Y2=VAL(Y2$)
240 LET CX= X0+(X1+X2)/2: CY= Y0+(Y1+Y2)/2
250 IF X2=X1 THEN R=90  :GOTO 270 :REM  ANGLE IS 90 DEGREES
255 IF X2<X1 THEN SWAP X1,X2:SWAP Y1,Y2
260 R=90+(ATN(ABS(X2-X1)/(Y2-Y1))*180/3.142)
270 H=SQR((X2-X1)^2+(Y2-Y1)^2)
280 DMAX= WRAD-SQR(WRAD^2-H^2/4)
```

```
285 GOSUB 3000: REM round off to smcc format
290 GOSUB 1000 : REM------set up cut
295 LPRINT  N-1,CX,CY,R,DMAX
300 REM-------LOOP
310 D=(D^3+V)^(1/3): ZD=INT(D*100)/100
320 IF D<DMAX THEN L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+ZD)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$: GOTO 310
330 IF D>=DMAX THEN L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$
335 D=0
340 GOSUB 2000 :REM----------- feed out
341 IF N=24 THEN PRINT #2,"AA":CLOSE#2: OPEN F2$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F2$: LPRINT F2$
342 IF N=49 THEN PRINT #2,"AA":CLOSE#2: OPEN F3$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F3$: LPRINT F3$
343 IF N=74 THEN PRINT #2,"AA":CLOSE#2: OPEN F4$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F4$: LPRINT F4$
344 IF N=99 THEN PRINT #2,"AA":CLOSE#2: OPEN F5$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F5$: LPRINT F5$
345 IF N=124 THEN PRINT #2,"AA":CLOSE#2: OPEN F6$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F6$: LPRINT F6$
346 IF N=149 THEN PRINT #2,"AA":CLOSE#2: OPEN F7$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F7$: LPRINT F7$
347 IF N=174 THEN PRINT #2,"AA":CLOSE#2: OPEN F8$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F8$: LPRINT F8$
348 IF N>200 THEN LPRINT" WARNING- LARGE FILE PROBLEM!"
350 GOTO 200
360 REM
370 REM end of programme
375 PRINT#2,"AA": PRINT#2,"END"
380 CLOSE:END
381 REM----------------------------------
390 OPEN "c:\smcc\CLEMPUNT.smc" FOR INPUT AS#3
395 LPRINT :LPRINT "c:\smcc\CLEMPUNT.smc":LPRINT
400 INPUT#3,L$ :PRINT L$:T=T+1
410 IF L$="END" THEN CLOSE: LPRINT " Yhe number of lines in the file
is ";T: END
420 GOTO 400
1000 REM************************
1010 REM*    Set up the cut   *
1020 REM************************
1030 TIM= 1000+ (INT(SQR((OCX-CX)^2+(OCY-
CY)^2)/FASTT)*100)/100
1040 L$="AAT"+STR$(TIM)+"  ;****************** Cut number
"+STR$(N): N=N+1: PRINT#2,L$:PRINT#2,"AADWE100  ;  Move"
```

```
1050 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0-5)+"
Y"+STR$(R)+" A2 X0":PRINT#2,L$
1060 PRINT#2,"AAT500":PRINT#2,"AADWE100  ;  Touch"
1070 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0)+"
Y"+STR$(R)+" A2 X0":PRINT#2,L$
1080 PRINT
#2,"AAt"+STR$(T):PRINT#2,"AAT"+STR$(T):PRINT#2,"AADWE100":
PRINT#2,"STA  ;   Cutting"
1090 RETURN
2000 REM**************
2010 REM*  FEED OUT  *
2020 REM**************
2030 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$
2040 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0+DMAX-
.02)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$
2050 PRINT #2,"AAt500":PRINT#2,"AAT600":PRINT#2,"AADWE100  ;
Feed out"
2060 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0-5)+"
Y"+STR$(R)+" A2 X0":PRINT#2,L$
2070 OCX=CX: OCY=CY:RETURN
2080 REM
3000 REM  ****************************
3010 REM *  round off to smcc formatt *
3020 REM  ****************************
3030 CX=(INT(CX*100)/100)
3040 CY=(INT(CY*100)/100)
3050 R=(INT(R*100)/100)
3060 DMAX=(INT(DMAX*100)/100)
3070 RETURN
```
•

2 MPUNTPAR Parametric mitred punts CAD Macro

```
'MPUNT
'PROGRAMME TO DRAW A MITRED PUNT
SYS(3)=1     'CHANGE LAYER TO ONE
SYS(2)=1     'CHANGE COLOUR TO ONE
SETPOINT "PARAMETRIC MITRED PUNT - SET TWO POINTS" 2
POINTVAL X1 Y1 1
POINTVAL X2 Y2 2
DX=(X2-X1)
DY=(Y2-Y1)
L=SQRT((DX*DX)+(DY*DY)) 'LENGTH OF PUNT
A$="MPUNT LENGTH = ",L,"INPUT WIDTH"
INPUT A$ W        'WIDTH OF PUNT
B=(W/L)*DY
H=(W/L)*DX
CX=(X1+X2)/2     'CALCULATE CO-ORDS
CY=(Y1+Y2)/2
FX=CX-B
FY=CY+H
EX=CX+B
EY=CY-H
>POINTXY [X1,Y1]
>POINTXY [X2,Y2]
>LINE
>POINTXY [X1,Y1]
>POINTXY [FX,FY]
>POINTXY [X2,Y2]
>ARC-3
>POINTXY [X1,Y1]
>POINTXY [EX,EY]
>POINTXY [X2,Y2]
>ARC-3
```

3 RPUNTS Oval punts module

```
10 REM************************************************
20 REM*    PARAMETRIC OVAL  PUNTS ROUTINE        *
30 REM*    multi-file version 9/01/91        *
32 REM*    Using Barry offsets              *
40 REM*    C:\GWBASIC\OVALPUNT                *
50 REM************************************************
60 WRAD=74.5/2: REM  wheel radius
70 X0=90 : REM  x axis offset
75 Y0=-20: REM  x axis offset
80 Z0=101.62 : REM  z axis offset, z position of the surface of the glass
90 V=.4: REM that volume of glass removed every....
100 T=1000 :REM  binary microseconds
110 FASTT=500/1024: REM  mean fast traverse velocity mm/bms
115 N=1 :REM  cut counter
120 REM
122 LPRINT "X offset= ";X0,"y offset= ";Y0
125 LPRINT "cut","CX","CY","R","DMAX"
126 FI$="A:MK11.DXF"
127 F1$="A:OP1.smc" :F2$="A:OP2.smc"
128 F3$="A:OP3.smc" :F4$="A:OP4.smc"
131 F5$="A:OP5.smc" :F6$="A:OP6.smc"
132 F7$="A:OP7.smc" :F8$="A:OP8.smc"
138 OPEN F1$ FOR OUTPUT AS #2
139 OPEN FI$ FOR INPUT AS #1
140 LPRINT F1$
150 PRINT#2,"AAz 1500"
160 PRINT#2,"t512"
170 INPUT#1,INFO$
180 IF INFO$="ENTITIES" THEN 200 ELSE 170
190 REM------------find the first line
200 INPUT#1,INFO$
202 IF INFO$="LINE" THEN GOTO 210
204 IF INFO$="EOF" THEN 370 ELSE 200
210 INPUT#1,O$,LAYER$
220 INPUT#1,O$,X1$,O$,Y1$ :X1=VAL(X1$) :Y1=VAL(Y1$)
230 INPUT#1,O$,X2$,O$,Y2$ :X2=VAL(X2$) :Y2=VAL(Y2$)
240 LET CX= X0+(X1+X2)/2: CY= Y0+(Y1+Y2)/2
250 IF X2=X1 THEN R=90  :GOTO 270 :REM  ANGLE IS 90 DEGREES
255 IF X2<X1 THEN SWAP X1,X2:SWAP Y1,Y2
260 R=90+(ATN(ABS(X2-X1)/(Y2-Y1))*180/3.142)
270 H=SQR((X2-X1)^2+(Y2-Y1)^2)
271 REM Determin if this is a centre line or part of an elipse
```

```
275 IF H<5 THEN 200
280 DMAX= WRAD-SQR(WRAD^2-H^2/4)
285 GOSUB 3000. REM round off to smcc format
290 GOSUB 1000 : REM······set up cut
295 LPRINT N-1,CX,CY,R,DMAX
300 REM·······LOOP
310 D=(D^3+V)^(1/3): ZD=INT(D*100)/100
320 IF D<DMAX THEN L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+ZD)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$: GOTO 310
330 IF D>=DMAX THEN L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$
335 D=0
340 GOSUB 2000 :REM············ feed out
341 IF N=24 THEN PRINT #2,"AA":CLOSE#2: OPEN F2$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F2$: LPRINT F2$
342 IF N=49 THEN PRINT #2,"AA":CLOSE#2: OPEN F3$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F3$: LPRINT F3$
343 IF N=74 THEN PRINT #2,"AA":CLOSE#2: OPEN F4$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F4$: LPRINT F4$
344 IF N=99 THEN PRINT #2,"AA":CLOSE#2: OPEN F5$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F5$: LPRINT F5$
345 IF N=124 THEN PRINT #2,"AA":CLOSE#2: OPEN F6$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F6$: LPRINT F6$
346 IF N=149 THEN PRINT #2,"AA":CLOSE#2: OPEN F7$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F7$: LPRINT F7$
347 IF N=174 THEN PRINT #2,"AA":CLOSE#2: OPEN F8$ FOR OUTPUT
AS #2:PRINT #2,"AA; 1500; "+F8$: LPRINT F8$
348 IF N>200 THEN LPRINT" WARNING- LARGE FILE PROBLEM!"
350 GOTO 200
360 REM
370 REM end of programme
375 PRINT#2,"AA": PRINT#2,"END"
380 CLOSE:END
381 REM·····································
390 OPEN "c:\smcc\CLEMPUNT.smc" FOR INPUT AS#3
395 LPRINT :LPRINT "c:\smcc\CLEMPUNT.smc":LPRINT
400 INPUT#3,L$ :PRINT L$:T=T+1
410 IF L$="END" THEN CLOSE: LPRINT " Yhe number of lines in the file
is ";T: END
420 GOTO 400
1000 REM*************************
1010 REM*    Set up the cut   *
1020 REM*************************
1030 TIM=1000*(INT(SQR((OCX-CX)^2+(OCY-
CY)^2)/FAST/)*100)/100
```

```
1040 L$="AAT"+STR$(TIM)+"  ;****************** Cut number
"+STR$(N): N=N+1: PRINT#2,L$:PRINT#2,"AADWE100  ;  Move"
1050 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0-5)+"
Y"+STR$(R)+" A2 X0":PRINT#2,L$
1060 PRINT#2,"AAT500":PRINT#2,"AADWE100 ; Touch"
1070 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0)+"
Y"+STR$(R)+" A2 X0":PRINT#2,L$
1080 PRINT
#2,"AAt"+STR$(T):PRINT#2,"AAT"+STR$(T):PRINT#2,"AADWE100":
PRINT#2,"STA  ;  Cutting"
1090 RETURN
2000 REM**************
2010 REM* FEED OUT *
2020 REM**************
2030 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$
2040 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0+DMAX-
.02)+" Y"+STR$(R)+" A2 X0":PRINT#2,L$
2050 PRINT #2,"AAt500":PRINT#2,"AAT600":PRINT#2,"AADWE100 ;
Feed out"
2060 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0-5)+"
Y"+STR$(R)+" A2 X0":PRINT#2,L$
2070 OCX=CX: OCY=CY:RETURN
2080 REM
3000 REM ****************************
3010 REM * round off to smcc formatt *
3020 REM ****************************
3030 CX=(INT(CX*100)/100)
3040 CY=(INT(CY*100)/100)
3050 R=(INT(R*100)/100)
3060 DMAX=(INT(DMAX*100)/100)
3070 RETURN
```

•

4 OPUNTPAR Parametric oval punts CAD Macro

```
'OPUNT
'PROGRAMME TO DRAW AN OVAL PUNT
SYS(3)=7      'CHANGE LAYER TO 7
SYS(2)=7      'CHANGE COLOUR TO 7
SETPOINT "PARAMETRIC OVAL PUNT - SET TWO POINTS" 2
DX=(X2-X1)
DY=(Y2-Y1)
L=SQR(DX^2+DY^2) 'LENGTH OF PUNT
A$="MPUNT LENGTH = ",L,"INPUT WIDTH"
INPUT A$ W          'WIDTH OF PUNT
B=(W/L)*DY
H=(W/L)*DX
CX=(X1=X2)/2      'CALCULATE CO-ORDS
CY=(Y1=Y2)/2
FX=CX-B
FY=CY+H
>POINTXY [X1,Y1]
>POINTXY [X2,Y2]
>LINE
>POINTXY [CX,CY]
>POINTXY [X2,Y2]
>POINTXY [FX,FY]
>ELIPSE
```

5 ROUNDP Round punts module

```
10 REM************************************************
20 REM*            ROUND PUNTS ROUTINE         *
30 REM*    multi-file version  22/02/91        *
32 REM*    TEST- STAND ALONE VERSION           *
40 REM*    C:\GWBASIC\ROUNDPNT                 *
50 REM************************************************
51 CLS:KEY OFF
56 DIM CIRC(500,3) :LET CC=1
60 WRAD=74.5/2: REM   wheel radius
62 R1=0:R2=180:R3=183: REM      Slew parameters
70 X0=175: REM        X axis offset
75 Y0=10: REM        Y axis offset
80 Z0=100: REM       Z axis offset, z position of the surface of the glass
90 V=5: REM          That volume of glass removed every....
100 T=10000 :REM     binary microseconds
105 TA=50:REM        Acceleration time
110 FASTT=500/1024:REM Mean fast traverse velocity mm/bms
115 N=1 :REM         Cut counter
120 REM
122 LPRINT "X offset= ";X0,"y offset= ";Y0
125 LPRINT "cut","CX","CY","R","DMAX"
126 FI$="a:ph11.DXF":PRINT "Processing file ";FI$:PRINT "Searching..."
127 F1$="a:rp1.smc" :F2$="a:rp2.smc"
128 F3$="a:rp3.smc" :F4$="a:rp4.smc"
131 F5$="a:rp5.smc" :F6$="a:rp6.smc"
132 F7$="a:rp7.smc" :F8$="a:rp8.smc"
138 OPEN F1$ FOR OUTPUT AS #2: LPRINT "Round punts stored in ";F1$
139 OPEN FI$ FOR INPUT AS #1
150 PRINT#2,"AAz 1500"
160 PRINT#2,"t512"
165 GOSUB 5000: REM --------------------- Input data into data array
170 REM --------------------------------- Loop for each data circle
180 FOR N=1 TO CC-1
185 OCX=CX:OCY=CY
190 CX=CIRC(N,1):CY=CIRC(N,2):CR=CIRC(N,3)
280 DMAX= WRAD-SQR(WRAD^2-CR^2)
285 GOSUB 3000: REM--------------------- Round off to smcc format
290 GOSUB 1000 : REM-------------------- Set up cut
295 REM LPRINT  N,CX,CY,CR,DMAX
300 REM--------------------------------- Feed in
310 D=(D^3+V)^(1/3): ZD=INT(D*100)/100
```

```
320 IF D<DMAX THEN L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+ZD)+" Y"+STR$(R1)+" A2 X0":PRINT#2,L$: GOTO 310
330 IF D>=DMAX THEN L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R1)+" A2 X0":PRINT#2,L$
335 D=0
340 GOSUB 6000 :REM--------------------- Generate circle
346 GOSUB 2000 :REM--------------------- Feed out
348 GOSUB 4000 :REM--------------------- Check file size
350 NEXT N
360 REM
370 REM end of programme
375 PRINT#2,"AA": PRINT#2,"END"
380 CLOSE:KEY ON:CLS:PRINT "Finished processing ";FI$:END
381 REM-----------------------------------------------------------------------
1000 REM************************
1010 REM*    Set up the cut   *
1020 REM************************
1030 TIM= 1000+ (INT(SQR((OCX-CX)^2+(OCY-
CY)^2)/FASTT)*100)/100
1040 L$="AAT"+STR$(TIM)+"  ;***************** Cut number
"+STR$(N): PRINT#2,L$:PRINT#2,"AADWE100  ;  Move"
1050 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0-5)+"
Y"+STR$(R1)+" A2 X0":PRINT#2,L$
1060 PRINT#2,"AAT500":PRINT#2,"AADWE100 ; Touch"
1070 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0)+"
Y"+STR$(R1)+" A2 X0":PRINT#2,L$
1080 PRINT
#2,"AAt"+STR$(TA):PRINT#2,"AAT"+STR$(T):PRINT#2,"AADWE100":
PRINT#2,"STA  ;  Cutting"
1090 RETURN
2000 REM**************
2010 REM* FEED OUT *
2020 REM**************
2040 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1 X"+STR$(Z0-5)+"
Y"+STR$(R1)+" A2 X0":PRINT#2,L$:PRINT #2,"AAt500"
2070 RETURN
2080 REM
3000 REM ****************************
3010 REM * round off to smcc formatt *
3020 REM ****************************
3030 CX=(INT(CX*100)/100)
3040 CY=(INT(CY*100)/100)
3060 DMAX=(INT(DMAX*100)/100)
3070 RETURN
4000 REM**********************
4010 REM* Check file size    *
```

```
4020 REM***********************
4050 IF N=20 THEN PRINT #2,"AA":CLOSE#2: OPEN F2$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F2$: LPRINT F2$
4060 IF N=40 THEN PRINT #2,"AA":CLOSE#2: OPEN F3$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F3$: LPRINT F3$
4070 IF N=60 THEN PRINT #2,"AA":CLOSE#2: OPEN F4$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F4$: LPRINT F4$
4080 IF N=80 THEN PRINT #2,"AA":CLOSE#2: OPEN F5$ FOR OUTPUT
AS #2:PRINT #2,"AAz 1500; "+F5$: LPRINT F5$
4090 IF N=100 THEN PRINT #2,"AA":CLOSE#2: OPEN F6$ FOR
OUTPUT AS #2:PRINT #2,"AAz 1500; "+F6$: LPRINT F6$
4100 IF N=120 THEN PRINT #2,"AA":CLOSE#2: OPEN F7$ FOR
OUTPUT AS #2:PRINT #2,"AAz 1500; "+F7$: LPRINT F7$
4110 IF N=140 THEN PRINT #2,"AA":CLOSE#2: OPEN F8$ FOR
OUTPUT AS #2:PRINT #2,"AAz 1500; "+F8$: LPRINT F8$
4120 IF N>160 THEN LPRINT" WARNING- LARGE FILE PROBLEM!"
4130 RETURN
5000 REM***********************
5010 REM* Input data to array *
5020 REM***********************
5030 REM
5040 INPUT#1,INFO$
5050 IF INFO$="ENTITIES" THEN 5060 ELSE 5040
5060 REM-----------find the first line
5062 PRINT "Found drawing entities."
5070 INPUT #1,O$:INPUT#1,INFO$
5080 IF INFO$="CIRCLE" THEN GOTO 5100
5090 IF INFO$="EOF" THEN 5120 ELSE 5070
5100 PRINT "Found circle ";CC:INPUT#1,O$,LAYER$
5110 INPUT#1,O$,X$,O$,Y$,O$,R$ :CIRC(CC,1)=VAL(X$)+X0
:CIRC(CC,2)=VAL(Y$)+Y0 :CIRC(CC,3)=VAL(R$):CC=CC+1:GOTO 5070
5120 RETURN
6000 REM ***********************
6010 REM * Generate circle    *
6020 REM ***********************
6030 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R2)+" A2 X0":PRINT#2,L$
6040 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R1)+" A2 X0":PRINT#2,L$
6050 L$="A0 X"+STR$(CX)+" Y"+STR$(CY)+" A1
X"+STR$(Z0+DMAX)+" Y"+STR$(R3)+" A2 X0":PRINT#2,L$
6060 RETURN
6070 REM -------------------------------------------------------------
•
```

```
10 REM          PANEL CUT MINI ROUTINE
20 REM          ORTHOGANAL CUTS ONLY
30 REM          6/4/93
40 REM          C:\BC\GWBASIC\PANEL.BAS
50  CLS: KEY OFF
60 DIM X(2,200) :DIM Y(2,200): DIM R(200)
70 XO=100  :REM...................X OFFSET OF GLASS
80 YO=100  :REM...................Y OFFSET OF GLASS
90 FASTV=500/1024   : REM.........FAST TRAVERSE
100 CUTV=10/1024    : REM.........CUTTING FEED RATE
105 ACCT=512        : REM.........ACCELERATION TIME
110 ZUP=95          : REM.........CLEAR POSITION
120 ZDOWN =100.4    : REM........ CUTTING POSITION
130 OFF=4           : REM.........CUTTING OFFSET
140 N=0             : REM ....... cut counter
150 FI$= "A:L15.DXF" : REM  .... input file
160 FO$="A:L15.SMC"  : REM....... OUTPUT FILE
170 OPEN FO$ FOR OUTPUT AS #2
180 OPEN FI$ FOR INPUT AS #1:PRINT:PRINT"  Processing file ";FI$
190 PRINT#2,"AAz 1500","t512"
200 GOSUB 1000 : REM.............. INPUT DATA
210 GOSUB 2000 : REM.............. CALCULATE POSITIONS
230 GOSUB 4000 : REM.............. OUTPUT TO FILE
240 PRINT#2,"AA","END"
250 CLOSE: KEY ON:CLS: PRINT"Finished processing ";FI$:END
260
REM=================================================================
============
1000 REM***************************************
1010 REM**        Input Data           **
1020 REM***************************************
1030 REM
1040 INPUT #1,INFO$: IF INFO$="ENTITIES" THEN 1050 ELSE 1040
1050 PRINT"  Found drawing entities in input file."
1060 INPUT #1,O$:INPUT#1,INFO$
1070 IF INFO$="LINE" THEN GOTO 1100
1080 IF INFO$="EOF" THEN 1150 ELSE 1060
1100 N=N+1: PRINT AT 3,0,"  Found line ";N: INPUT#1,O$,LAYER$
1110 INPUT #1,O$,X1,O$,Y1,O$,X2,O$,Y2
1120 X(1,N)=VAL(X1$):Y(1,N)=VAL(Y1$)
1130 X(2,N)=VAL(X2$):Y(2,N)=VAL(Y2$)
1140 GOTO 1060
```

```
1150 RETURN
1160 REM
2000 REM****************************************
2010 REM** Calculate Position and Time Data **
2020 REM****************************************
2030 REM
2040 FOR C= 1 TO N
2045 REM ............ Determin starts and ends of cuts
2050  IF X(1,C)=X(2,C) THEN
2060    R(C)=0
2070    IF Y(1,C) > Y(2,C) THEN SWAP Y(1,C),Y(2,C)
2080    Y1(1,C)=Y(1,C)+OFF : Y(2,C)=Y(2,C)-OFF: GOTO 2200
2090  IF Y(1,C) = Y(2,C) THEN
2100    R(C)=90
2110    IF X(1,C) > X(2,C) THEN SWAP X(1,C),X(2,C)
2120    X(1,C) =X(1,C)+OFF : X(2,C)=X(2,C)-OFF: GOTO 2200
2130  PRINT "  Non Orthoganal cut No ";C;" ERROR!!"
2190 REM
2200 REM ............ Add Offsets
2210 X(1,C)=X(1,C)+XO
2220 X(2,C)=X(2,C)+XO
2230 Y(1,C)=Y(1,C)+XO
2240 Y(2,C)=Y(2,C)+XO
2250 NEXT C
2255 REM
2260 FOR C=1 TO N
2265  REM............... CALCULATE FAST TRAVERSE TIME
2270  XFASTD= ABS(XP-X(1,C)
2280  YFASTD= ABS(YP-Y(1,C)
2290  IF XFASTD>YFASTD THE D=XFASTD ELSE D=YFASTD
2300  FT(C)= D/FASTV+ACCT
2305  XP=X(2,C):YP=Y(2,C)
2310  REM................ CALCULATE CUTTING TIME
2320  IF R$(C) ="0" THEN D= Y(2,C)-Y(1,C) ELSE D= X(2,C)-X(1,C)
2330  YFASTD= ABS(YP-Y(1,C)
2340  IF XFASTD>YFASTD THE D=XFASTD ELSE D=YFASTD
2350  CT(C)= D/CUTV+ACCT
2360 NEXT C
2400 RETURN
2410
REM===============================================================
==========
3000 REM****************************************
3010 REM**      Convert to SMCC format      **
3020 REM****************************************
3030 REM
```

```
4000 REM***************************************
4010 REM**      Output to File          **
4020 REM***************************************
4030 REM
4040 PRINT " Outputing programme to file ";FO$
4050 FOR C=1 TO N
4060 X1$=STR$(X(1,C))
4070 Y1$=STR$(Y(1,C))
4080 X2$=STR$(X(2,C))
4090 Y2$=STR$(Y(2,C))
4100 REM.............FAST TRAVERSE TO START OF CUT
.
```

7 SEGMENT Segment shaped edge cut module

```
10 REM
*****************************************************************
****
20 REM **     EDGE CUT SEGMENT MODULE                    ***
30 REM **     Multi cut - Stand alone version           ***
40 REM **     14/5/93      /GWBASIC/SEGMENTS             ***
50 REM
*****************************************************************
****
60 REM
70 CLS: KEY OFF          : REM    Clear GWBASIC from display
80 REM
90 REM ----- Initialise variables --------------------------------------
100 DIM DX(1500): DIM DY(1500): REM  raw data points on curve
110 D=0                  : REM    number of data points read
120 DIM CADRES(20,2)       : REM    address within X & Y where each cut
is
130 CADRES(1,1)=1
140 CUTN=1               : REM    number of cuts read from file
150 I$="":O$="":LAYER$="":V$="":REM  input fields
160 DIM PX(300): DIM PY(300): REM    selected step points
170 DIM X(100):DIM Y(100):DIM Z(100):DIM R(100):DIM T(100):REM
axis positions
180 X(100)=5:Y(100)=5:Z(100)=20:R(100)=5:T(100)=5 :REM near home
position
190 XA=0:YA=0:XB=0:YB=0    : REM    extremities of cut under
consideration
200 FLAG=0               : REM    straight line found flag
210 NP=0                 : REM    number of selected points
220 MS=0:                : REM    slope of segment
230 DDH=0:DDY=0:DDX=0      : REM    sides of slope triangle
240 SX=0:SY=0:S=3          : REM    step distance in X,Y and absolute
distance
250 MN=0:CN=0             : REM    normal slope, intercept of normal
260 ME=0:CE=0             : REM    slope,intercept of elemental line on curve
270 DIM PIX(100):DIM PIY(100):REM    point of intersection coordinates
280 EC=0                 : REM    search counter to find intercept
290 P=0                  : REM    point counter for working through in turn
300 EY=0:EX=0             : REM    coords of a point on the elemental line
310 DIY=0:DIX=0            : REM    distances between intersept and point
320 TS=0                 : REM    tilt direction flag
330 AC=0:BC=0:ACUT=0       : REM    sides of the triangular cut shape
```

```
340 PE=0               : REM    distance from point to TCP
350 ME=0:CE=0           : REM    slope,intercept of elemental line on curve
360 PIC=180/3.141592     : REM    conversion factor rads to degrees
370 CC=0               : REM    counter for numbering cuts in output file
380 TCALIB=13/15        : REM    conversion factor for tilt axis
390 REM  == Application Specific Parameters ==
400 A=.5               : REM    shoulder depth of cut
410 W=12               : REM    width of wheel
420 WD=75              : REM    diameter of wheel
430 ZUP=-3             : REM    depth clear of glass relative to ZTOUCH
440 ZTOUCH=100          : REM    depth to just touch glass
450 XOF=175            : REM    X-axis offset
460 YOF=10             : REM    Y-axis offset
470 FIN$ = "c:\dc\l.DXF"  : REM    input file
480 FO$  = "A:SEG.SMC"    : REM    output file
490 REM-----------------------------------------------------------------
600 GOSUB 1000          : REM    Establish communications
610 GOSUB 2000          : REM    Read data into array
620 FOR C= 1 TO CUTN      : REM    For each cut....
630  GOSUB 3000         : REM    Select step points & calculate intercepts
640  IF FLAG=1 THEN FLAG=0:GOTO 670:REM  straight line ignored
650  GOSUB 4000         : REM    Calculate wheel positions
660  GOSUB 5000         : REM    Output data to file
670 NEXT C
680 GOSUB 6000          : REM    Terminate communications
690 END
700
REM=============================================================
====================
1000 REM     ********************************
1010 REM     ** ESTABLISH COMMUNICATIONS  **
1020 REM     ********************************
1030 PRINT"                EDGE CUT SEGMENTS MODULE"
1040 PRINT"                ==== === ======== ======"
1050 PRINT:PRINT"               For use with Edge cutting wheels only"
1060 PRINT"           For use with DesignCAD Version 4.2 only
1070 PRINT"                Input file ";FIN$:PRINT "                    Output
file ";FO$:GOTO 1130
1080 LPRINT,"-----------------------------------------------------------------
------"
1090 LPRINT"       EDGE CUT SEGMENTS MODULE"
1100 LPRINT"       ==== === ======== ======"
1110 LPRINT"    For use with Edge cutting wheels only"
1120 LPRINT"    Input file ";FIN$:LPRINT "     Output file ";FO$
1130 OPEN FO$ FOR OUTPUT AS #1
1140 OPEN FIN$ FOR INPUT AS #2
```

```
1150 PRINT#1,"AAz 1500; ";FO$;" X ";XOF;" Y ";YOF
1160 RETURN
1170 REM-----------------------------------------------------------------------
2000 REM      ********************************
2010 REM      ** READ DATA INTO ARRAY      **
2020 REM      ********************************
2030 PRINT"  Reading Data - Warning on no account disturb disk!"
2040 REM -------------- FIND DATA -----------------
2050 INPUT #2, I$: IF I$="ENTITIES" THEN 2060 ELSE 2050
2060 INPUT #2, I$
2070 IF I$="POLYLINE" THEN 2090: REM    Found first line
2080 IF I$="ENDSEC" THEN PRINT "FILE EMPTY": GOTO 2240 ELSE
2060
2090 REM -------------- INPUT DATA -----------------
2100 INPUT #2,O$,LAYER$,O$,O$,O$,O$,O$,O$ : REM polyline system
variables
2110 REM PRINT LAYER$
2120 INPUT #2,O$,V$,O$,O$
2130 REM PRINT V$
2140 IF V$="SEQEND" THEN GOTO 2190      : REM end of that cut
2150 IF V$="VERTEX" THEN 2160 ELSE
PRINT:PRINT"V$=";V$;"error":CLOSE:END
2160 D=D+1:INPUT #2,O$,O$,O$,O$,O$,DX(D),O$,DY(D):REM read data
point
2170 GOTO 2120
2180 REM ------------- End of cut -------------
2190 CADRES(CUTN,2)=D
2200 INPUT #2, O$,E$
2210 IF E$="ENDSEC" THEN GOTO 2220 ELSE CUTN=CUTN+1:INPUT
#2,O$,LAYER$,O$,O$,O$,O$,O$,O$:CADRES(CUTN,1)=D+1:GOTO 2120
2220 CLOSE #2
2230 PRINT"  ";CUTN;" Entities read from file."
2240 RETURN
2250 REM -----------------------------------------------------------------
3000 REM      ************************************************
3010 REM      ** SELECT STEP POINTS & CALCULATE INTERCEPTS
**
3020 REM      ************************************************
3030 PRINT "  Selecting points for cut number ";C
3040 IF CADRES(C,2)=CADRES(C,1)+1 THEN PRINT  "line detected":
FLAG=1:GOTO 3300
3050 XA=DX(CADRES(C,1)):YA=DY(CADRES(C,1))
3060 XB=DX(CADRES(C,2)):YB=DY(CADRES(C,2))
3070 DDY=YB-YA :DDX=XB-XA
3080 MS=DDY/DDX
3090 DDH=SQR(DDY^2+DDX^2)
```

```
3100 SX=S*DDX/DDH
3110 SY=S*DDY/DDH
3120 MN=-1/MS
3130 NP=INT(DDH/S)
3140 EC=1 : ECMAX=CADRES(C,2)-CADRES(C,1)
3150 REM ======== select points ==========
3160 FOR P=1 TO NP
3170  PX(P)=XA+P*SX:PY(P)=YA+P*SY
3180 NEXT P
3190 REM ======== calculate intercepts =========
3200 IF MN<1 THEN GOSUB 8000 : REM  -ve gradient normal
3210 IF MN>1 THEN GOSUB 9000 : REM  +ve gradient normal
3220 REM ------ CHECK DATA ---------------------
3230 LPRINT:LPRINT "CALCULATED POINTS"
3240 LPRINT"PX or PIX no.","POINT X","POINT Y","INTERCEPT
X","INTERCEPT Y"
3250  LPRINT,XA,YA,"(POINT A)
3260 FOR X=1 TO NP
3270  LPRINT X,PX(X),PY(X),PIX(X),PIY(X)
3280 NEXT X
3290  LPRINT,XB,YB,"(POINT B)
3300 RETURN
3310 REM-----------------------------------------------------------
4000 REM     ***********************************
4010 REM     ** CALCULATE WHEEL POSITIONS    **
4020 REM     ***********************************
4030 PRINT"  Calculating five axis position from data."
4040 REM------ R-Axis position --------
4050 IF DDX>1 THEN R=(ATN(DDX/DDY)*PIC+90)
4060 IF DDX<1 THEN R=(ATN(DDY/ABS(DDX))*PIC)
4070 IF DDX=0 THEN R=90
4080 REM ------ T axis direction -----------
4090  P=1:DIY=PY(P)-PIY(P)
4100  DIX=PX(P)-PIX(P)
4110 IF DIX<0 AND DIY>0 THEN TS=1
4120 IF DIX>0 AND DIY<0 THEN TS=-1
4130 IF DIX>0 AND DIY>0 THEN TS=-1
4140 IF DIX<0 AND DIY<0 THEN TS= 1
4150 REM ------- positions between ends ------
4160 FOR P=1 TO NP
4170  DIY=PY(P)-PIY(P)
4180  DIX=PX(P)-PIX(P)
4190  AC= SQR(DIY^2+DIX^2)
4200  BC= SQR(A^2+AC^2)
4210  T=ATN(A/BC)
```

```
4220 IF T>=15/PIC THEN T=15/PIC:ACUT=AC*SIN(T):BC=AC*COS(T):
GOTO 4240
4230 ACUT =A
4240 PE= ACUT*SIN(T)+(W/2)*COS(T)
4250 X(P)=PX(P)+DIX/AC*PE
4260 Y(P)=PY(P)+DIY/AC*PE
4270 Z(P)=ZTOUCH+(BC-W/2)*SIN(T)
4280 T(P)=T*PIC*TS*TCALIB
4290 R(P)=R+TS
4300 NEXT P
4310 REM--------- start point ----------
4320 PE =W/2*COS(15/PIC)
4330 X(0)=XA+DIX/AC*PE
4340 Y(0)=YA+DIY/AC*PE
4350 Z(0)=ZTOUCH-W/2*SIN(15/PIC)
4360 R(0)=R+TS
4370 T(0)=(15*TS*TCALIB)
4380 REM ---------- end point ------------
4390 P=P+1
4400 X(P)=XB+DIX/AC*PE
4410 Y(P)=YB+DIY/AC*PE
4420 Z(P)=Z(0)
4430 R(P)=R(0)
4440 T(P)=T(0)
4450 REM
4460 REM-------- CHECK DATA -----
4470 LPRINT "CUT ";CC;"  FIVE AXIS DATA"
4480 FOR X=0 TO  P
4490 LPRINT X(X),Y(X),Z(X),R(X),T(X)
4500 NEXT X
4510 LPRINT:LPRINT
4520 REM-------------------------
4530 RETURN
4540 REM-----------------------------------------------------------------
5000 REM     ****************************
5010 REM     **  Output Data to file  **
5020 REM     ****************************
5030 PRINT"  Writing SMCC programme to output file.":CC=CC+1
5040 REM--------- Move to first position ---------
5050 PRINT#1,"AAt512":PRINT#1,"AAT2000":PRINT#1,"AADWE100;-----
----CUT ";CC;"-----"
5060 P=0: Z=ZUP:GOSUB 7000
5070 P=0: Z=0:GOSUB 7000:PRINT#1,"AADWE100":PRINT#1,"STA
5080 REM -------- Cut
5090 FOR P=1 TO NP+1
5100  GOSUB 7000
```

```
5110 NEXT P
5120 REM --------- Move away
5130 PRINT#1,"AADWE100":Z=UP:GOSUB 7000
5140 RETURN
5150 REM-----------------------------------------------------------------
6000 REM     ********************************
6010 REM     ** TERMINATE COMMUNICATIONS **
6020 REM     ********************************
6030 PRINT#1,"T2000"
6040 P=100:GOSUB 7000
6050 PRINT#1,"HOM":PRINT#1,"END"
6060 CLOSE #1,#2
6070 PRINT" Programme finished, the disk may now be removed."
6080 REM LPRINT,"---------------------------------------------------------------
-------------"
6090 INPUT;" Do you wish to view the SMCC code?",I$
6100 IF I$="y" OR I$="Y" THEN PRINT:GOTO 6110 ELSE 6160
6110 OPEN FO$ FOR INPUT AS #1
6120 INPUT #1,L$
6130 IF L$="END" THEN 6150
6140 LPRINT L$:GOTO 6120
6150 LPRINT L$:CLOSE
6160 KEY ON: RETURN
6170 REM-----------------------------------------------------------------
7000 REM
****************************************************************
*
7010 REM   * Convert data to axis position in units and send line to file *
7020 REM
****************************************************************
*
7030 REM
7040 N$=STR$(INT((X(P)+XOF)*100+.5)):GOSUB 7170: X$=M$
7050 N$=STR$(INT((Y(P)+YOF)*100+.5)):GOSUB 7170:Y$=M$
7060 N$=STR$(INT((Z(P)+Z)*100+.5)):GOSUB 7170:Z$=M$
7070 N$=STR$(INT(R(P)*100+.5)):GOSUB 7170:R$=M$
7080 N$=STR$(INT(T(P)*100+.5)):GOSUB 7170:T$=M$
7090 L$="A0 X"+X$+" Y"+Y$+" A1 X"+Z$+" Y"+R$+" A2 X"+T$:PRINT
#1,L$
7100 RETURN
7110 REM
7120 REM---------------------------------------------------------------
7130 REM          **********************************
7140 REM          * Reduce variable to SMCC format *
7150 REM          **********************************
7160 REM
```

```
7170 IF SGN(VAL(N$))= 0 THEN M$="0":GOTO 7240
7180 M$=RIGHT$(N$,LEN(N$)-1)
7190 M=LEN(M$)
7200 IF M=1 THEN M$="0.0"+M$
7210 IF M=2 THEN M$="0."+M$
7220 IF M>2 THEN M$=LEFT$(M$,M-2)+"."+RIGHT$(M$,2)
7230 IF SGN(VAL(N$))=-1 THEN M$="-"+M$
7240 RETURN
7250 REM-------------------------------------------------------------
8000 REM     ***************************************************
8010 REM     ** calculate intercept for -ve gradient normal **
8020 REM     ***************************************************
8030 EC=CADRES(C,1)+1:ECMAX=CADRES(C,2)
8040 FOR P=1 TO NP
8050  CN=PY(P)-MN*PX(P): REM   calculate equation of normal
8060  EY= DY(EC)      : REM   select a data point
8070  EX= DX(EC)
8080  IF EY>(MN*EX+CN) THEN GOTO 8120  : REM is normal stradled
8090  EC=EC+1:IF EC= EMAX THEN 8190
8100  GOTO 8060 : REM  select the next point
8110  REM ======= calculate elemental line equation ======
8120  ME=(EY-DY(EC-1))/(EX-DX(EC-1))
8130  CE= EY-ME*EX
8140  REM ======= calculate intercept ==========
8150  PIX(P)=(CN-CE)/(ME-MN)
8160  PIY(P)=MN*PIX(P)+CN
8170 NEXT P
8180 RETURN
8190 REM   error intercept not found
8200 PRINT "EY = ";EY
8210 PRINT "EX = ";EX
8220 PRINT "MN = ";MN
8230 PRINT "CN = ";CN
8240 PRINT "MN*EX+CN = ";MN*EX+CN
8250 CLOSE:END
8260 REM-------------------------------------------------------------
9000 REM     ***************************************************
9010 REM     ** calculate intercept for -ve gradient normal **
9020 REM     ***************************************************
9030 EC=CADRES(C,1)+1:ECMAX=CADRES(C,2)
9040 FOR P=1 TO NP
9050  CN=PY(P)-MN*PX(P): REM   calculate equation of normal
9060  EY= DY(EC)      : REM   select a data point
9070  EX= DX(EC)
9080  IF EY<(MN*EX+CN) THEN GOTO 9120  : REM    normal stradled
9090  EC=EC+1:IF EC= EMAX THEN 9190
```

```
9100  GOTO 8060 : REM  select the next point
9110  REM ======= calculate elemental line equation ======
9120  ME=(EY-DY(EC-1))/(EX-DX(EC-1))
9130  CE= EY-ME*EX
9140  REM ======= calculate intercept ==========
9150  PIX(P)=(CN-CE)/(ME-MN)
9160  PIY(P)=MN*PIX(P)+CN
9170 NEXT P
9180 RETURN
9190 REM   error intercept not found
9200 PRINT "EY = ";EY
9210 PRINT "EX = ";EX
9220 PRINT "MN = ";MN
9230 PRINT "CN = ";CN
9240 PRINT "MN*EX+CN = ";MN*EX+CN
9250 REM---------------------------------------------------------------
•
```

8 CRESCENT Crescent shaped edge cut module

```
10 REM
**************************************************************
****
20 REM **     EDGE CUT CRESCENT MODULE                    ***
30 REM **     Multi cut - Stand alone version        ***
40 REM **     25/5/93     /GWBASIC/CRESCENT               ***
50 REM
**************************************************************
****
60 REM
70 CLS: KEY OFF          : REM    Clear GWBASIC from display
80 REM
90 REM ----- Initialise variables --------------------------------------
100 DIM PDX(1500): DIM PDY(1500): REM   raw data points on primary
curves
102 DIM SDX(1500): DIM SDY(1500): REM   raw data points on secondary
curves
110 PD=0               : REM    number of primary data points read
112 SD=0               : REM    number of secondary data points read
120 DIM PCADRES(20,3)      : REM    address in data array for cut
122 DIM SCADRES(20,3)      : REM    address in data array for cut
130 PCADRES(1,1)=1
132 SCADRES(1,1)=1
140 CUTN=0              : REM    number of cuts read from file
141 CURN=0              : REM    number of secondary curves read from file
150 I$="":O$="":LAYER$="":V$="":REM   input fields
160 DIM PX(300): DIM PY(300): REM     selected step points on primary
curve
170 DIM X(100):DIM Y(100):DIM Z(100):DIM R(100):DIM T(100):REM
axis positions
180 X(100)=5:Y(100)=5:Z(100)=20:R(100)=5:T(100)=5 :REM near home
position
190 XA=0:YA=0:XB=0:YB=0     : REM    extremities of cut under
consideration
200 FLAG=0              : REM    straight line found flag
210 NP=0               : REM    number of selected points
220 MS=0:              : REM    slope of segment
230 DDH=0:DDY=0:DDX=0      : REM    sides of slope triangle
240 SX=0:SY=0:S=3         : REM    step distance in X,Y and absolute
distance
260 ME=0:CE=0            : REM    slope,intercept of elemental line on curve
270 DIM PIX(100):DIM PIY(100):REM    point of intersection coordinates
```

```
271 DIM AX(100):DIM AY(100)  :REM    position of deepest point
272 DBEG=0:DND=0             :REM    dist to begining and end of cut
273 DD=0                :REM    cut profile length at point
274 DIM ACUT(100)            :REM    cut depth at point
275 CHECKFLAG=0              :REM    printout flag
276 DIM TDY(100):DIM TDX(100):REM    tangent componants
277 DIM MT(100):DIM CT(100)  :REM    tangent slope and intercept
278 DIM AC(100)          : REM    dist from A to C for section
279 DIM BC(100)          : REM    dist from B to C for section
280 EC=0                : REM    search counter to find intercept
290 P=0                 : REM    point counter for working through in turn
300 EY=0:EX=0            : REM    coords of a point on the elemental line
310 DIY=0:DIX=0          : REM    distances between intersept and point
320 TS=0                : REM    tilt direction flag
330 AC=0:BC=0:ACUT=0      : REM    sides of the triangular cut shape
340 PE=0                : REM    distance from point to TCP
350 ME=0:CE=0            : REM    slope,intercept of elemental line on curve
360 PIC=180/3.141592      : REM    conversion factor rads to degrees
370 CC=0                : REM    counter for numbering cuts in output file
380 TCALIB=13/15          : REM    conversion factor for tilt axis
390 REM   == Application Specific Parameters ==
400 A=.5                : REM    shoulder depth of cut
402 LIN=10               : REM    lead in
404 LOUT=10               : REM    lead out
410 W=12                : REM    width of wheel
420 WD=75                : REM    diameter of wheel
425 DDMAX=2*SQR((WD/2)^2-(WD/2-A)^2):REM max length of cut
profile
430 ZUP=-3               : REM    depth clear of glass relative to ZTOUCH
440 ZTOUCH=100            : REM    depth to just touch glass
450 XOF=200              : REM    X-axis offset
460 YOF=100              : REM    Y-axis offset
470 FIN$ = "A:CRES.DXF"    : REM    input file
480 FO$  = "A:CRES.SMC"    : REM    output file
490 REM----------------------------------------------------------------------
600 GOSUB 1000           : REM    Establish communications
610 GOSUB 2000           : REM    Read data into array
615 GOSUB 10000          : REM    Match primary and secondary cuts
620 FOR C= 1 TO CUTN       : REM    For each cut....
630  GOSUB 3000          : REM    Select cut section
640  IF FLAG=1 THEN FLAG=0:GOTO 670:REM  straight line ignored
650  GOSUB 4000          : REM    Calculate wheel positions
660  GOSUB 5000          : REM    Output data to file
665 CHEKFLAG=0
670 NEXT C
680 GOSUB 6000           : REM    Terminate communications
```

```
690 END
700
REM=======================================================
===================
1000 REM     ********************************
1010 REM     ** ESTABLISH COMMUNICATIONS **
1020 REM     ********************************
1030 PRINT"                EDGE CUT CRESCENT MODULE"
1040 PRINT"                ==== === ======== ======"
1050 PRINT:PRINT"          For use with Edge cutting wheels only"
1060 PRINT"            For use with DesignCAD Version 4.2 only
1070 PRINT"                Input file ";FIN$:PRINT "                Output
file ";FO$
1072 INPUT "  Is a full printout required?";Y$
1073 IF Y$="y" OR Y$="Y" THEN CHEKFLAG=1
1074 IF CHEKFLAG=0 THEN 1130
1080 LPRINT,"----------------------------------------------------------------
------"
1090 LPRINT"      EDGE CUT CRESCENT MODULE"
1100 LPRINT"      ==== === ======== ======"
1110 LPRINT"   For use with Edge cutting wheels only"
1120 LPRINT"   Input file ";FIN$:LPRINT "    Output file ";FO$
1130 OPEN FO$ FOR OUTPUT AS #1
1140 OPEN FIN$ FOR INPUT AS #2
1150 PRINT#1,"AAz 1500; ";FO$;" X ";XOF;" Y ";YOF
1160 RETURN
1170 REM---------------------------------------------------------------
2000 REM     ********************************
2010 REM     ** READ DATA INTO ARRAY      **
2020 REM     ********************************
2030 PRINT" Reading Data - Warning on no account disturb disk!"
2040 REM -------------- FIND DATA -----------------
2050 INPUT #2, I$: IF I$="ENTITIES" THEN 2060 ELSE 2050
2060 INPUT #2, I$
2070 IF I$="POLYLINE" THEN 2090: REM   Found first line
2080 IF I$="ENDSEC" THEN PRINT "FILE EMPTY": GOTO 2240 ELSE
2060
2090 REM -------------- INPUT DATA -----------------
2100 INPUT #2,O$,LAYER$,O$,O$,O$,O$,O$,O$ : REM polyline system
variables
2106 IF LAYER$="LAYER13" THEN
CUTN=CUTN+1:PCADRES(CUTN,1)=PD+1
2108 IF LAYER$="LAYER14" THEN
CURN=CURN+1:SCADRES(CUTN,1)=SD+1
2110 REM PRINT LAYER$
2120 INPUT #2,O$,V$,O$,O$
```

```
2130 REM PRINT V$
2140 IF V$="SEQEND" THEN GOTO 2190      : REM end of that cut
2150 IF V$="VERTEX" THEN 2160 ELSE
PRINT:PRINT"V$=";V$;"error":CLOSE:END
2160 IF LAYER$="LAYER13" THEN PD=PD+1:INPUT
#2,O$,O$,O$,O$,O$,PDX(PD),O$,PDY(PD):REM IF CHEKFLAG=1 THEN
LPRINT"(primary)",PD,PDX(PD),PDY(PD)
2162 IF LAYER$="LAYER14" THEN SD=SD+1:INPUT
#2,O$,O$,O$,O$,O$,SDX(SD),O$,SDY(SD):REM IF CHEKFLAG=1 THEN
LPRINT"(secondary)",SD,SDX(SD),SDY(SD)
2170 REM PRINT
2172 GOTO 2120
2180 REM ------------- End of cut -------------
2190 IF LAYER$="LAYER13" THEN PCADRES(CUTN,2)=PD
2194 IF LAYER$="LAYER14" THEN SCADRES(CURN,2)=SD
2200 INPUT #2, O$,E$
2210 IF E$="ENDSEC" THEN GOTO 2220
2211 INPUT #2,O$,LAYER$,O$,O$,O$,O$,O$,O$
2216 IF LAYER$="LAYER13" THEN
CUTN=CUTN+1:PCADRES(CUTN,1)=PD+1
2218 IF LAYER$="LAYER14" THEN
CURN=CURN+1:SCADRES(CURN,1)=SD+1
2219 GOTO 2120
2220 CLOSE #2
2230 PRINT:PRINT"  ";CUTN;" Primary entities read from file."
2232 PRINT"  ";CURN;" Secondary entities read from file.":PRINT
2235 IF CURN<>CUTN THEN PRINT" ODD NUMBER OF ENTITIES
ERROR!!":END
2237 REM------------------------------------------------------------
2240 IF CHEKFLAG=0 THEN 2900
2241 LPRINT "------------------------------------------------------------
2245 LPRINT:LPRINT "CUT ADDRESSES"
2250 LPRINT "-primaries":LPRINT "n","(n,1)","(n,2)","(n,3)"
2260 FOR X=1 TO CUTN
2270 LPRINT X,PCADRES(X,1),PCADRES(X,2),PCADRES(X,3)
2280 NEXT X
2290 LPRINT "-secondaries":LPRINT "n","(n,1)","(n,2)","(n,3)"
2300 FOR X=1 TO CURN
2310 LPRINT X,SCADRES(X,1),SCADRES(X,2),SCADRES(X,3)
2320 NEXT X
2900 RETURN
2910 REM ---------------------------------------------------------------
3000 REM    ************************************************
3010 REM    ** SELECT CUT SECTION                        **
3020 REM    ************************************************
3030 PRINT "  Selecting points for cut number ";C
```

```
3040 IF PCADRES(C,2)=PCADRES(C,1)+1 THEN PRINT  "line detected":
FLAG=1:GOTO 3900
3050 GOSUB 11000       : REM  Select primary data points & tangent
3060 FOR P=1 TO NOP-1
3070 DBEG=SQR((PX(P)-PX(0))^2+(PY(P)-PY(0))^2):REM-- dist of point
from begining
3075 IF DBEG<LIN THEN DD=DDMAX*DBEG/LIN:GOTO 3089:REM-
set cut section length
3080 DND=SQR((PX(NOP)-PX(P))^2+(PY(NOP)-PY(P))^2):REM-- dist of
point from end
3085 IF DND<LOUT THEN DD=DDMAX*DND/LOUT:GOTO 3089
3087 DD=DDMAX
3089 ACUT(P)=(WD/2)-SQR((WD/2)^2-(DD/2)^2) :REM ------
corresponding cut depth
3090 GOSUB 12000                  :REM ------ Calculate section
3100 IF T(P)<15/PIC THEN 3140          :REM ------ check if OK
3110 DD=DD-.2                    :REM ------ reduce depth of cut
3112 ACUT(P)=(WD/2)-SQR((WD/2)^2-(DD/2)^2) :REM ------
corresponding cut depth
3120 GOSUB 12000                  :REM ------ recalculate
3130 IF T(P)>15/PIC THEN 3110          :REM ------ recheck
3140 NEXT P
3145 REM-----------------------------------------------------------
3150 IF CHEKFLAG=0 THEN 3998
3820 REM ------ CHECK DATA ---------------------
3825 LPRINT "------------------------------------------------------------------
------"
3830 LPRINT "CALCULATED POINTS AND GEOMETRY FOR CUT
";C:LPRINT
3846  LPRINT "n" TAB(11) "PX(n)" TAB(22) "PY(n)" TAB(33) "MT(n)"
TAB(44)      TAB(55) "AX(n)" TAB(66) "AY(n)":LPRINT
3860 FOR X=0 TO NOP
3870  LPRINT X TAB(11) PX(X) TAB(22) PY(X) TAB(33) MT(X) TAB(44)
TAB(55) AX(X) TAB(66) AY(X)
3880 NEXT X:LPRINT
3890  LPRINT "n" TAB(11) "PIX(n)" TAB(22) "PIY(n)" TAB(33) "AC(n)"
TAB(44) "BC(n)" TAB(55) "ACUT(n)" TAB(68) "T(n)*PIC":LPRINT
3900 FOR X=0 TO NOP
3910  LPRINT X TAB(11) PIX(X) TAB(22) PIY(X) TAB(33) AC(X)
TAB(44) BC(X) TAB(55) ACUT(X) TAB(68) T(X)*PIC
3920 NEXT X:LPRINT
3998 RETURN
3999 REM-----------------------------------------------------------
4000 REM    ***********************************
4010 REM    **  CALCULATE WHEEL POSITIONS   **
4020 REM    ***********************************
```

```
4030 PRINT"        Calculating five axis position from data for cut ";C
4040 REM ---------- Intermediate points ------------
4075 FOR P=1 TO NOP-1
4160  DIX=PIX(P)-AX(P)
4170  DIY=PIY(P)-AY(P)
4180  GOSUB 4600 :REM  R & T-Axis directions
4240   PE= (ACUT(P)*SIN(T(P)))+((W/2)*COS(T(P)))
4250  X(P)=PX(P)+(DIX/AC(P))*PE
4260  Y(P)=PY(P)+(DIY/AC(P))*PE
4270  Z(P)=ZTOUCH+(BC(P)-W/2)*SIN(T(P))
4280  T(P)=T(P)*PIC*TS*TCALIB
4300 NEXT P
4310 REM---------- start point ----------
4315 P=0:GOSUB 4640 :REM  R axis directions
4316  IF P=0 THEN TS= SGN(T(1))
4320 PE =W/2*COS(15/PIC)
4330  GOSUB 4700 :REM  X & Y position
4350  Z(P)=ZTOUCH-(W/2)*SIN(15/PIC)
4370  T(P)=(15*TS*TCALIB)
4380 REM ---------- end point ------------
4390 P=NOP:GOSUB 4640 :REM  R-Axis directions
4395  IF P=NOP THEN TS= SGN(T(NOP-1))
4400  GOSUB 4700 :REM  X & Y position
4420  Z(P)=Z(0)
4440  T(P)=(15*TS*TCALIB)
4450 REM
4455 IF CHEKFLAG=0 THEN 4530
4460 REM-------- CHECK DATA -----
4470 LPRINT:LPRINT "CUT ";C;"  FIVE AXIS DATA"
4475 LPRINT  TAB(14)"X(n)" TAB(26) "Y(n)" TAB(40) "Z(n)" TAB(52)
"R(n)" TAB(64) "T(n)"
4480 FOR X=0 TO NOP
4490 LPRINT X TAB(14) X(X) TAB(26) Y(X) TAB(40) Z(X) TAB(52) R(X)
TAB(64) T(X)
4500 NEXT X
4510 LPRINT:LPRINT
4520 REM-------------------------
4530 RETURN
4540 REM-----------------------------------------------------------------
4590  REM ------ T axis direction -----------
4600   IF DIX>=0 AND DIY>=0 THEN TS= 1
4610   IF DIX<0 AND DIY<0 THEN TS=-1
4620   IF DIX>=0 AND DIY<0 THEN TS= 1
4630   IF DIX<0 AND DIY>=0 THEN TS=-1
4640   IF TDX(P)>0 THEN R=(ATN(1/MT(P))*PIC+90)
4650   IF TDX(P)<0 THEN R=(ATN(TDY(P)/ABS(TDX(P)))*PIC)
```

```
4660  IF TDX(P)=0 THEN R=90
4665   R(P)=R+TS
4670 RETURN
4680 REM-----------------------------------------------------------------------
4700 REM  X & Y for end positions
4710 DS=SQR(MT(P)^2+1)
4720  X(P)=PX(P)+(MT(P)/DS)*PE
4730  Y(P)=PY(P)+PE/DS
4740 RETURN
4750 REM-----------------------------------------------------------------------
5000 REM    ***************************
5010 REM    **  Output Data to file  **
5020 REM    ***************************
5030 PRINT"  Writing SMCC programme to output file.":CC=CC+1
5040 REM--------- Move to first position ---------
5050 PRINT#1,"AAt512":PRINT#1,"AAT2000":PRINT#1,"AADWE100;-----
----CUT ";CC;"-----"
5060 P=0: Z=ZUP:GOSUB 7000
5070 P=0: Z=0:GOSUB 7000:PRINT#1,"AADWE100":PRINT#1,"STA
5080 REM -------- Cut
5090 FOR P=1 TO NOP
5100  GOSUB 7000
5110 NEXT P
5120 REM --------- Move away
5130 PRINT#1,"AADWE100":Z=UP:GOSUB 7000
5140 RETURN
5150 REM-----------------------------------------------------------------------
6000 REM     ********************************
6010 REM     ** TERMINATE COMMUNICATIONS  **
6020 REM     ********************************
6030 PRINT#1,"T2000"
6040 P=100:GOSUB 7000
6050 PRINT#1,"HOM":PRINT#1,"END"
6060 CLOSE #1,#2
6070 PRINT"  Programme finished, the disk may now be removed."
6080 REM LPRINT,"-----------------------------------------------------------------
-------------"
6090 INPUT;"  Do you wish to view the SMCC code?",I$
6100 IF I$="y" OR I$="Y" THEN PRINT:GOTO 6110 ELSE 6160
6110 OPEN FO$ FOR INPUT AS #1
6120 INPUT #1,L$
6130 IF L$="END" THEN 6150
6140 LPRINT L$:GOTO 6120
6150 LPRINT L$:CLOSE
6160 CLS:KEY ON: RETURN
6170 REM-----------------------------------------------------------------------
```

```
7000 REM
*************************************************************
*
7010 REM    * Convert data to axis position in units and send line to file *
7020 REM
*************************************************************
*
7030 REM
7040 N$=STR$(INT((X(P)+XOF)*100+.5)):GOSUB 7170: X$=M$
7050 N$=STR$(INT((Y(P)+YOF)*100+.5)):GOSUB 7170:Y$=M$
7060 N$=STR$(INT((Z(P)+Z)*100+.5)):GOSUB 7170:Z$=M$
7070 N$=STR$(INT(R(P)*100+.5)):GOSUB 7170:R$=M$
7080 N$=STR$(INT(T(P)*100+.5)):GOSUB 7170:T$=M$
7090 L$="A0 X"+X$+" Y"+Y$+" A1 X"+Z$+" Y"+R$+" A2 X"+T$:PRINT
#1,L$
7100 RETURN
7110 REM
7140 REM === Reduce variable to SMCC format ======
7170 IF SGN(VAL(N$))= 0 THEN M$="0":GOTO 7240
7180 M$=RIGHT$(N$,LEN(N$)-1)
7190 M=LEN(M$)
7200 IF M=1 THEN M$="0.0"+M$
7210 IF M=2 THEN M$="0."+M$
7220 IF M>2 THEN M$=LEFT$(M$,M-2)+"."+RIGHT$(M$,2)
7230 IF SGN(VAL(N$))=-1 THEN M$="-"+M$
7240 RETURN
7250 REM-----------------------------------------------------------------
8000 REM      ****************************************************
8010 REM      **          calculate intercept            **
8020 REM      ****************************************************
8030 IF P=1 THEN EC=SCADRES(PCADRES(C,3),1)+1:REM  reset
element count for new cut
8040 ECMAX=SCADRES(PCADRES(C,3),2)
8060  EY= SDY(EC)      : REM   select a data point
8070  EX= SDX(EC)
8080  IF MAC<1 AND EY>(MAC*EX+CN) THEN GOTO 8120  : REM
normal stradled
8085  IF MAC>1 AND EY<(MAC*EX+CN) THEN GOTO 8120  : REM
normal stradled
8090  EC=EC+1:IF EC= EMAX THEN 8190            : REM  error
8100  GOTO 8060 : REM  select the next point
8110  REM ======= calculate elemental line equation ======
8120  ME=(EY-SDY(EC-1))/(EX-SDX(EC-1))
8130  CE= EY-ME*EX
8140  REM ======= calculate intercept ==========
8150  PIX(P)=(CN-CE)/(ME-MAC)
```

```
8160 PIY(P)=MAC*PIX(P)+CN
8170 RETURN
8190 REM   error intercept not found
8195 PRINT "p  = ";P
8200 PRINT "EY = ";EY
8210 PRINT "EX = ";EX
8220 PRINT "MAC = ";MAC
8230 PRINT "CN = ";CN
8240 PRINT "MAC*EX+CN = ";MAC*EX+CN
8250 CLOSE:END
8260 REM-----------------------------------------------------------------
10000 REM  ****************************************
10010 REM  **  Match primary and secondary cuts **
10020 REM  ****************************************
10040 FOR Q=1 TO CUTN
10045  PRINT"  Matching cut ";Q;" of ";CUTN;
10046  U=0
10047   U=U+1:PRINT" to secondary line ";U;
10048   IF U>CURN THEN PRINT "error seconday curve not found":END
10049   IF SCADRES(U,3)=1 THEN 10047 :REM   curve already allocated
10050   PAX=PDX(PCADRES(Q,1)):REM PRINT PAX,
10060   PAY=PDY(PCADRES(Q,1)):REM PRINT PAY,
10070   PBX=PDX(PCADRES(Q,2)):REM PRINT PBX,
10080   PBY=PDY(PCADRES(Q,2)):REM PRINT PBY
10100   SAX=SDX(SCADRES(U,1)):REM PRINT SAX,
10110   SAY=SDY(SCADRES(U,1)):REM PRINT SAY,
10120   SBX=SDX(SCADRES(U,2)):REM PRINT SBX,
10130   SBY=SDY(SCADRES(U,2)):REM PRINT SBY
10140   IF PAX=SAX AND PAY=SAY AND PBX=SBX AND PBY=SBY
THEN 10200
10150   GOTO 10047: REM -- try next curve
10200  PCADRES(Q,3)=U:SCADRES(U,3)=1: PRINT "Match made!"
10210 NEXT Q
10220 IF CHEKFLAG=0 THEN 10900
10230 LPRINT:LPRINT "MATCHED CURVES"
10240 LPRINT "Primary curve number","Secondary curve number"
10250 FOR X=1 TO CUTN
10260 LPRINT X,,PCADRES(X,3)
10270 NEXT X
10900  RETURN
10910 REM-----------------------------------------------------------------
11000 REM
**************************************************
11010 REM     **   Select primary data points & tangent      **
11020 REM
**************************************************
```

```
11025 NOP=0 :REM reset selected points counter for new cut
11026 REM ===== Start point ========
11030 PX(0)=PDX(PCADRES(C,1)):PY(0)=PDY(PCADRES(C,1))
11040
P=0:TPAX=PX(0):TPAY=PY(0):TPBX=PDX(PCADRES(C,1)+1):TPBY=PD
Y(PCADRES(C,1)+1):GOSUB 11280
11041 REM ===== Near start point ====
11042 PX(1)=PDX(PCADRES(C,1)+1):PY(1)=PDY(PCADRES(C,1)+1)
11045
NOP=1:TPAX=PX(0):TPAY=PY(0):TPBX=PDX(PCADRES(C,1)+2):TPBY
=PDY(PCADRES(C,1)+2):GOSUB 11280
11050 XA=PX(0):YA=PY(0)
11060 REM ==== Find following data points:- ====
11070 FOR P=PCADRES(C,1)+2 TO PCADRES(C,2)-2
11080  XB=PDX(P):YB=PDY(P)
11090  H=SQR((XA-XB)^2+(YA-YB)^2)          :REM dist between
points
11100  BP=SQR((PDX(PCADRES(C,2))-XB)^2+(PDY(PCADRES(C,2))-
YB)^2) :REM dist to end
11110  IF H>S OR H>BP THEN TPAX=PDX(P-1):
TPAY=PDY(P+1):TPBX=PDX(P+1):TPBY=PDY(P+1):GOSUB 11200:
REM Found next point
11120 NEXT P
11130 REM ==== Near end point:- =====
11140 NOP=NOP+1
11150 PX(NOP)=PDX(PCADRES(C,2)-1):PY(NOP)=PDY(PCADRES(C,2)-
1)
11160 TPAY=PDX(PCADRES(C,2)-2): TPAY= PDY(PCADRES(C,2)-2)
11170 TPBY=PDX(PCADRES(C,2)): TPBY= PDY(PCADRES(C,2))
11180 GOSUB 11280: REM calculate tangent
11182 REM ===== End point:- =======
11184 NOP=NOP+1
11186 PX(NOP)=PDX(PCADRES(C,2)):PY(NOP)=PDY(PCADRES(C,2))
11187 TPAY=PDX(PCADRES(C,2)-2): TPAY= PDY(PCADRES(C,2)-
2):REM "2" 'cos points can be close together causing one of these variables to
be zero.
11188 TPBY=PDX(PCADRES(C,2)): TPBY= PDY(PCADRES(C,2))
11189 GOSUB 11280: REM calculate tangent
11190 RETURN
11200 REM ============= Found next point ============
11210 NOP=NOP+1
11220 PX(NOP)=XB:PY(NOP)=YB
11230 TPAX=PDX(P-1):TPAY=PDY(P-1)
11240 TPBX=PDX(P+1):TPBY=PDY(P+1)
11250 GOSUB 11280: REM calculate tangent
11260 XA=XB:YA=YB
```

```
11270 RETURN
11280 REM ====== Calculate tangent at a point ====================
11290 TDY(NOP)=TPBY-TPAY:TDX(NOP)=TPBX-TPAX
11300 MT(NOP)= TDY(NOP)/TDX(NOP)
11320 RETURN
11330 REM----------------------------------------------------------------
12000 REM ***********************************************
12010 REM ** CALCULATE SECTION FROM POINT AND TANGENT
**
12020 REM ***********************************************
12040 DS=SQR(MT(P)^2+1)
12050 DY=(DD*MT(P))/(DS*2)
12060 DX=DD/(2*DS)
12070 AX(P)=PX(P)-DX
12080 AY(P)=PY(P)-DY
12090 MAC=-1/MT(P)
12100 CN=AY(P)-MAC*AX(P)
12110 GOSUB 8000 :REM determine intercept point
12120 AC(P)=SQR((PIX(P)-AX(P))^2+(PIY(P)-AY(P))^2)
12130  BC(P)= SQR(AC(P)^2-ACUT(P)^2)
12135  T(P)=ATN(ACUT(P)/BC(P))
12140 RETURN
12150 REM----------------------------------------------------------------
•
```

9 MITRE5 Five axis mitred cutting module

```
10 REM
**********************************************************************
20 REM **    FIVE AXIS MITRED CUT MODULE                    ***
30 REM **    SINGLE cut - Stand alone version          ***
40 REM **    22/6/93     /GWBASIC/MITRE5                ***
50 REM
**********************************************************************
60 REM
70 CLS: KEY OFF          : REM    Clear GWBASIC from display
80 REM
90 REM ----- Initialise variables --------------------------------------
100 DIM PDX(1500): DIM PDY(1500): REM   raw data points on primary
curves
102 DIM SDX(1500): DIM SDY(1500): REM   raw data points on secondary
curves
110 PD=0                : REM    number of primary data points read
112 SD=0                : REM    number of secondary data points read
120 DIM PCADRES(20,4)       : REM    address in data array for cut
122 DIM SCADRES(20,3)       : REM    address in data array for cut
130 PCADRES(1,1)=1
132 SCADRES(1,1)=1
140 CUTN=0              : REM    number of cuts read from file
141 CURN=0              : REM    number of secondary curves read from file
150 I$="":O$="":LAYER$="":V$="":REM   input fields
160 DIM PX(300): DIM PY(300): REM    selected step points on primary
curve
170 DIM X(100):DIM Y(100):DIM Z(100):DIM R(100):DIM T(100):REM
axis positions
180 X(100)=5:Y(100)=5:Z(100)=20:R(100)=5:T(100)=5 :REM near home
position
190 XA=0:YA=0:XB=0:YB=0    : REM    extremities of cut under
consideration
200 FLAG=0              : REM    straight line found flag
210 NP=0                : REM    number of selected points
220 MS=0:               : REM    slope of segment
230 DDH=0:DDY=0:DDX=0      : REM    sides of slope triangle
240 SX=0:SY=0:S=3          : REM    step distance in X,Y and absolute
distance
260 ME=0:CE=0              : REM    slope,intercept of elemental line on curve
270 DIM PIX(100):DIM PIY(100):REM    point of intersection coordinates
```

```
271 DIM TIX(100):DIM TIY(100):REM     point of intersection coordinates
275 CHECKFLAG=0            :REM    printout flag
276 DIM TDY(100):DIM TDX(100):REM    tangent componants
277 DIM MT(100)           :REM    tangent slope
278 DIM A(100)          : REM    dist from 1st intercept to point for section
279 DIM B(100)          : REM    dist from 2nd intercept to point for section
280 EC=0              : REM    search counter to find intercept
290 P=0              : REM    point counter for working through in turn
300 EY=0:EX=0           : REM    coords of a point on the elemental line
310 DIY=0:DIX=0          : REM    distances between intersept and point
320 TS=0              : REM    tilt direction flag
330 AC=0:BC=0:ACUT=0      : REM    sides of the triangular cut shape
340 PE=0              : REM    distance from point to TCP
350 ME=0:CE=0           : REM    slope,intercept of elemental line on curve
360 PIC=180/3.141592      : REM    conversion factor rads to degrees
370 CC=0              : REM    counter for numbering cuts in output file
380 TCALIB=13/15         : REM    conversion factor for tilt axis
390 REM  == Application Specific Parameters ==
410 ANGLE =140/PIC        : REM    inclusive V angle
420 WD=75             : REM    diameter of wheel
430 ZUP=-3            : REM    depth clear of glass relative to ZTOUCH
440 ZTOUCH=100          : REM    depth to just touch glass
450 XOF=200           : REM    X-axis offset
460 YOF=100           : REM    Y-axis offset
470 FIN$ = "A:MITRE5.DXF"  : REM    input file
480 FO$  = "A:MITRE5.SMC"  : REM    output file
490 REM-----------------------------------------------------------------
600 GOSUB 1000          : REM    Establish communications
610 GOSUB 2000          : REM    Read data into array
615 GOSUB 10000         : REM    Match primary and secondary cuts
620 FOR C= 1 TO CUTN      : REM    For each cut....
630  GOSUB 3000         : REM    Select cut section
650  GOSUB 4000         : REM    Calculate wheel positions
660  GOSUB 5000         : REM    Output data to file
665 CHEKFLAG=0
670 NEXT C
680 GOSUB 6000          : REM    Terminate communications
690 END
700
REM=========================================================
===================
1000 REM    ********************************
1010 REM    ** ESTABLISH COMMUNICATIONS **
1020 REM    ********************************
1030 PRINT"          5-AXIS MITRED CUTTING MODULE"
1040 PRINT"          ====== ====== ======= ======"
```

```
1050 PRINT:PRINT"            For use with Mitred cutting wheels only"
1060 PRINT"            For use with DesignCAD Version 4.2 only
1070 PRINT"                Input file ";FIN$:PRINT "                Output
file ";FO$
1072 INPUT "  Is a full printout required?";Y$
1073 IF Y$="y" OR Y$="Y" THEN CHEKFLAG=1
1074 IF CHEKFLAG=0 THEN 1130
1080 LPRINT,"----------------------------------------------------------------------
------"
1090 LPRINT"              5-AXIS MITRED CUTTING MODULE"
1100 LPRINT"              ====== ====== ======= ======"
1110 LPRINT:LPRINT"              For use with Mitred cutting wheels only"
1120 LPRINT"   Input file ";FIN$:LPRINT "    Output file ";FO$
1130 OPEN FO$ FOR OUTPUT AS #1
1140 OPEN FIN$ FOR INPUT AS #2
1150 PRINT#1,"AAz 1500; ";FO$;" X ";XOF;" Y ";YOF
1160 RETURN
1170 REM---------------------------------------------------------------
2000 REM    ********************************
2010 REM    ** READ DATA INTO ARRAY     **
2020 REM    ********************************
2030 PRINT"  Reading Data - Warning on no account disturb disk!"
2040 REM -------------- FIND DATA -----------------
2050 INPUT #2, I$: IF I$="ENTITIES" THEN 2060 ELSE 2050
2060 INPUT #2, I$
2070 IF I$="POLYLINE" THEN 2090: REM   Found first line
2080 IF I$="ENDSEC" THEN PRINT "FILE EMPTY": GOTO 2240 ELSE
2060
2090 REM -------------- INPUT DATA -----------------
2100 INPUT #2,O$,LAYER$,O$,O$,O$,O$,O$,O$ : REM polyline system
variables
2106 IF LAYER$="LAYER18" THEN
CUTN=CUTN+1:PCADRES(CUTN,1)=PD+1
2108 IF LAYER$="LAYER19" THEN
CURN=CURN+1:SCADRES(CUTN,1)=SD+1
2110 REM PRINT LAYER$
2120 INPUT #2,O$,V$,O$,O$
2130 REM PRINT V$
2140 IF V$="SEQEND" THEN GOTO 2190     : REM end of that cut
2150 IF V$="VERTEX" THEN 2160 ELSE
PRINT:PRINT"V$=";V$;"error":CLOSE:END
2160 IF LAYER$="LAYER18" THEN PD=PD+1:INPUT
#2,O$,O$,O$,O$,O$,PDX(PD),O$,PDY(PD):REM IF CHEKFLAG=1 THEN
LPRINT"(primary)",PD,PDX(PD),PDY(PD)
```

```
2162 IF LAYER$="LAYER19" THEN SD=SD+1:INPUT
#2,O$,O$,O$,O$,O$,SDX(SD),O$,SDY(SD):REM IF CHEKFLAG=1 THEN
LPRINT"(secondary)",SD,SDX(SD),SDY(SD)
2170 REM PRINT
2172 GOTO 2120
2180 REM ------------- End of cut -------------
2190 IF LAYER$="LAYER18" THEN PCADRES(CUTN,2)=PD
2194 IF LAYER$="LAYER19" THEN SCADRES(CURN,2)=SD
2200 INPUT #2, O$,E$
2210 IF E$="ENDSEC" THEN GOTO 2220
2211 INPUT #2,O$,LAYER$,O$,O$,O$,O$,O$,O$
2216 IF LAYER$="LAYER18" THEN
CUTN=CUTN+1:PCADRES(CUTN,1)=PD+1
2218 IF LAYER$="LAYER19" THEN
CURN=CURN+1:SCADRES(CURN,1)=SD+1
2219 GOTO 2120
2220 CLOSE #2
2230 PRINT:PRINT"  ";CUTN;" Primary entities read from file."
2232 PRINT"  ";CURN;" Secondary entities read from file.":PRINT
2235 IF CURN<>2*CUTN THEN PRINT" ODD NUMBER OF ENTITIES
ERROR!!":END
2237 REM------------------------------------------------------------
2240 IF CHEKFLAG=0 THEN 2900
2241 LPRINT "-------------------------------------------------------
2245 LPRINT:LPRINT "CUT ADDRESSES"
2250 LPRINT "-primaries":LPRINT "n","(n,1)","(n,2)","(n,3)"
2260 FOR X=1 TO CUTN
2270 LPRINT X,PCADRES(X,1),PCADRES(X,2),PCADRES(X,3)
2280 NEXT X
2290 LPRINT "-secondaries":LPRINT "n","(n,1)","(n,2)","(n,3)"
2300 FOR X=1 TO CURN
2310 LPRINT X,SCADRES(X,1),SCADRES(X,2),SCADRES(X,3)
2320 NEXT X
2900 RETURN
2910 REM -----------------------------------------------------------------
3000 REM     **************************************************
3010 REM     ** SELECT CUT SECTION                          **
3020 REM     **************************************************
3030 PRINT " Selecting points for cut number ";C
3050 GOSUB 11000      : REM Select primary data points & tangent
3060 FOR P=1 TO NOP-1
3070 MAC=-1/MT(P)
3080 CN=PY(P)-MAC*PX(P)
3085 GOSUB 8000 :REM  calculate intercept on first secondary curve
3095 NEXT P
3100 FOR P=1 TO NOP-1
```

```
3105 MAC=-1/MT(P)
3110 CN=PY(P)-MAC*PX(P)
3120 GOSUB 8500 :REM   calculate intercept on second secondary curve
3140 NEXT P
3145 REM--------------------------------------------------------
3150 IF CHEKFLAG=0 THEN 3998
3820 REM ------ CHECK DATA ---------------------
3825 LPRINT "-------------------------------------------------------------------
------"
3830 LPRINT "CALCULATED POINTS AND GEOMETRY FOR CUT
";C:LPRINT
3846  LPRINT "n" TAB(11) "PX(n)" TAB(22) "PY(n)" TAB(33) "MT(n)"
TAB(44)        TAB(55) "TIX(n)" TAB(66) "TIY(n)":LPRINT
3860 FOR X=0 TO NOP
3870  LPRINT X TAB(11) PX(X) TAB(22) PY(X) TAB(33) MT(X) TAB(44)
TAB(55) TIX(X) TAB(66) TIY(X)
3880 NEXT X:LPRINT
3890  LPRINT "n" TAB(11) "PIX(n)" TAB(22) "PIY(n)" :LPRINT
3900 FOR X=0 TO NOP
3910  LPRINT X TAB(11) PIX(X) TAB(22) PIY(X)
3920 NEXT X:LPRINT
3998 RETURN
3999 REM--------------------------------------------------------
4000 REM      ***********************************
4010 REM      ** CALCULATE WHEEL POSITIONS    **
4020 REM      ***********************************
4030 PRINT"         Calculating five axis position from data for cut ";C
4035 IF CHEKFLAG=1 THEN LPRINT:LPRINT "n","A","B","T(n)","ZD"
4040 REM ---------- Intermediate points -----------
4075 FOR P=1 TO NOP-1
4080 A=SQR((PIX(P)-PX(P))^2+(PIY(P)-PY(P))^2)
4090 B=SQR((TIX(P)-PX(P))^2+(TIY(P)-PY(P))^2)
4100 ZD=.5*( SQR( 4*A*B + ((A+B)^2/(TAN(ANGLE)^2)) ) +
(A+B)/TAN(ANGLE) )
4180  GOSUB 4590 :REM  R-Axis directions
4250  X(P)=PX(P)
4260  Y(P)=PY(P)
4270  Z(P)= ZTOUCH+ZD
4280  T(P)=((70/PIC)-ATN(A/ZD))*PIC*TCALIB
4290 IF CHEKFLAG=1 THEN LPRINT P,A,B,T(P),ZD
4300 NEXT P
4310 REM---------- start point ----------
4315 P=0:GOSUB 4640 :REM  R axis directions
4320  X(P)=PX(P)
4330  Y(P)=PY(P)
4350  Z(P)=ZTOUCH
```

```
4370  T(P)=T(1)
4380 REM ---------- end point ------------
4390 P=NOP:GOSUB 4640 :REM  R-Axis directions
4395  X(P)=PX(P)
4400  Y(P)=PY(P)
4420  Z(P)=ZTOUCH
4440  T(P)=T(P-1)
4450 REM
4455 IF CHEKFLAG=0 THEN 4530
4460 REM-------- CHECK DATA -----
4470 LPRINT:LPRINT "CUT ";C;"  FIVE AXIS DATA"
4475 LPRINT  TAB(14)"X(n)" TAB(26) "Y(n)" TAB(40) "Z(n)" TAB(52)
"R(n)" TAB(64) "T(n)"
4480 FOR X=0 TO NOP
4490 LPRINT X TAB(14) X(X) TAB(26) Y(X) TAB(40) Z(X) TAB(52) R(X)
TAB(64) T(X)
4500 NEXT X
4510 LPRINT:LPRINT
4530 RETURN
4540 REM----------------------------------------------------------------
4590  REM ------ R axis direction -----------
4640  IF TDX(P)>0 THEN R=(ATN(1/MT(P))*PIC+90)
4650  IF TDX(P)<0 THEN R=(ATN(TDY(P)/ABS(TDX(P)))*PIC)
4660  IF TDX(P)=0 THEN R=90
4665   R(P)=R
4670 RETURN
4750 REM-----------------------------------------------------------------
5000 REM     ****************************
5010 REM     **  Output Data to file  **
5020 REM     ****************************
5030 PRINT"  Writing SMCC programme to output file.":CC=CC+1
5040 REM--------- Move to first position ---------
5050 PRINT#1,"AAt512":PRINT#1,"AAT2000":PRINT#1,"AADWE100;-----
----CUT ";CC;"-----"
5060 P=0: Z=ZUP:GOSUB 7000
5070 P=0: Z=0:GOSUB 7000:PRINT#1,"AADWE100":PRINT#1,"STA
5080 REM -------- Cut
5090 FOR P=1 TO NOP
5100  GOSUB 7000
5110 NEXT P
5120 REM --------- Move away
5130 PRINT#1,"AADWE100":Z=UP:GOSUB 7000
5140 RETURN
5150 REM--------------------------------------------------------------
6000 REM     ********************************
6010 REM     **  TERMINATE COMMUNICATIONS  **
```

```
6020 REM     *******************************
6030 PRINT#1,"T2000"
6040 P=100:GOSUB 7000
6050 PRINT#1,"HOM":PRINT#1,"END"
6060 CLOSE #1,#2
6080 REM LPRINT,"------------------------------------------------------------------
-------------"
6090 INPUT;" Do you wish to view the SMCC code?",I$
6100 IF I$="y" OR I$="Y" THEN GOTO 6110 ELSE 6160
6110 OPEN FO$ FOR INPUT AS #1
6115 LPRINT:LPRINT"PROGRAMME LISTING":LPRINT
6120 INPUT #1,L$
6130 IF L$="END" THEN 6150
6140 LPRINT L$:GOTO 6120
6150 LPRINT L$:CLOSE
6152 REM LPRINT,"------------------------------------------------------------------
-------------"
6155 CLS:PRINT" Programme finished, the disk may now be removed."
6160 KEY ON: RETURN
6170 REM-----------------------------------------------------------------
7000 REM
****************************************************************
*
7010 REM   * Convert data to axis position in units and send line to file *
7020 REM
****************************************************************
*
7030 REM
7040 N$=STR$(INT((X(P)+XOF)*100+.5)):GOSUB 7170: X$=M$
7050 N$=STR$(INT((Y(P)+YOF)*100+.5)):GOSUB 7170:Y$=M$
7060 N$=STR$(INT((Z(P)+Z)*100+.5)):GOSUB 7170:Z$=M$
7070 N$=STR$(INT(R(P)*100+.5)):GOSUB 7170:R$=M$
7080 N$=STR$(INT(T(P)*100+.5)):GOSUB 7170:T$=M$
7090 L$="A0 X"+X$+" Y"+Y$+" A1 X"+Z$+" Y"+R$+" A2 X"+T$:PRINT
#1,L$
7100 RETURN
7110 REM
7140 REM === Reduce variable to SMCC format ======
7170 IF SGN(VAL(N$))= 0 THEN M$="0":GOTO 7240
7180 M$=RIGHT$(N$,LEN(N$)-1)
7190 M=LEN(M$)
7200 IF M=1 THEN M$="0.0"+M$
7210 IF M=2 THEN M$="0."+M$
7220 IF M>2 THEN M$=LEFT$(M$,M-2)+"."+RIGHT$(M$,2)
7230 IF SGN(VAL(N$))=-1 THEN M$="-"+M$
7240 RETURN
```

```
7250 REM-------------------------------------------------------------
8000 REM     ***************************************************
8010 REM     ** calculate intercept on 1st secondary curve **
8020 REM     ***************************************************
8030 IF P=1 THEN EC=SCADRES(PCADRES(C,3),1)+1:REM reset element count for new cut
8040 ECMAX=SCADRES(PCADRES(C,3),2)
8060 EY= SDY(EC)     : REM  select a data point
8070 EX= SDX(EC)
8080 IF MAC<1 AND EY>(MAC*EX+CN) THEN GOTO 8120 : REM normal stradled
8085 IF MAC>1 AND EY<(MAC*EX+CN) THEN GOTO 8120 : REM normal stradled
8090 EC=EC+1:IF EC= EMAX THEN 8190          : REM error
8100 GOTO 8060 : REM select the next point
8110 REM ======= calculate elemental line equation ======
8120 ME=(EY-SDY(EC-1))/(EX-SDX(EC-1))
8130 CE= EY-ME*EX
8140 REM ======= calculate intercept ==========
8150 PIX(P)=(CN-CE)/(ME-MAC)
8160 PIY(P)=MAC*PIX(P)+CN
8170 RETURN
8190 REM  error intercept not found
8195 PRINT "p  = ";P
8200 PRINT "EY = ";EY
8210 PRINT "EX = ";EX
8220 PRINT "MAC = ";MAC
8230 PRINT "CN = ";CN
8240 PRINT "MAC*EX+CN = ";MAC*EX+CN
8250 CLOSE:END
8260 REM---------------------------------------------------------------
8500 REM
8510 REM     ***************************************************
8515 REM     ** calculate intercept on 2nd secondary curve **
8520 REM     ***************************************************
8530 IF P=1 THEN EC=SCADRES(PCADRES(C,4),1)+1:REM reset element count for new cut
8540 ECMAX=SCADRES(PCADRES(C,4),2)
8560 EY= SDY(EC)     : REM  select a data point
8570 EX= SDX(EC)
8580 IF MAC<1 AND EY>(MAC*EX+CN) THEN GOTO 8620 : REM normal stradled
8585 IF MAC>1 AND EY<(MAC*EX+CN) THEN GOTO 8620 : REM normal stradled
8590 EC=EC+1:IF EC= EMAX THEN 8190          : REM error
8600 GOTO 8560 : REM select the next point
```

```
8610 REM ======= calculate elemental line equation ======
8620 ME=(EY-SDY(EC-1))/(EX-SDX(EC-1))
8630 CE= EY-ME*EX
8640 REM ======= calculate intercept ==========
8650 TIX(P)=(CN-CE)/(ME-MAC)
8660 TIY(P)=MAC*PIX(P)+CN
8670 RETURN
10000 REM ********************************************
10010 REM ** Match primary cut to two secondary cuts **
10020 REM ********************************************
10040 FOR Q=1 TO CUTN
10045 PRINT" Matching cut ";Q;" of ";CUTN;
10046 U=0:MC=0
10047 U=U+1:PRINT" to secondary line ";U;
10048 IF U>CURN THEN PRINT "error seconday curve not found":END
10049 IF SCADRES(U,3)=1 THEN 10047 :REM curve already allocated
10050 PAX=PDX(PCADRES(Q,1)):REM PRINT PAX,
10060 PAY=PDY(PCADRES(Q,1)):REM PRINT PAY,
10070 PBX=PDX(PCADRES(Q,2)):REM PRINT PBX,
10080 PBY=PDY(PCADRES(Q,2)):REM PRINT PBY
10100 SAX=SDX(SCADRES(U,1)):REM PRINT SAX,
10110 SAY=SDY(SCADRES(U,1)):REM PRINT SAY,
10120 SBX=SDX(SCADRES(U,2)):REM PRINT SBX,
10130 SBY=SDY(SCADRES(U,2)):REM PRINT SBY
10140 IF PAX=SAX AND PAY=SAY AND PBX=SBX AND PBY=SBY
THEN 10200
10150 GOTO 10047: REM -- try next curve
10200 IF MC=0 THEN PCADRES(Q,3)=U:SCADRES(U,3)=1:MC=1:
PRINT "First match made!":GOTO 10047
10205 PCADRES(Q,4)=U:SCADRES(U,3)=1:MC=0: PRINT "Second match
made!"
10210 NEXT Q
10220 IF CHEKFLAG=0 THEN 10900
10230 LPRINT:LPRINT "MATCHED CURVES"
10240 LPRINT "Primary curve number","Secondary curve number"
10250 FOR X=1 TO CUTN
10260 LPRINT X,,PCADRES(X,3)
10270 NEXT X
10900 RETURN
10910 REM-------------------------------------------------------------
11000 REM
************************************************
11010 REM    ** Select primary data points & tangent    **
11020 REM
************************************************
11025 NOP=0 :REM reset selected points counter for new cut
```

```
11026 REM ===== Start point ========
11030 PX(0)=PDX(PCADRES(C,1)):PY(0)=PDY(PCADRES(C,1))
11040
P=0:TPAX=PX(0):TPAY=PY(0):TPBX=PDX(PCADRES(C,1)+1):TPBY=PD
Y(PCADRES(C,1)+1):GOSUB 11280
11041 REM ===== Near start point ====
11042 PX(1)=PDX(PCADRES(C,1)+1):PY(1)=PDY(PCADRES(C,1)+1)
11045
NOP=1:TPAX=PX(0):TPAY=PY(0):TPBX=PDX(PCADRES(C,1)+2):TPBY
=PDY(PCADRES(C,1)+2):GOSUB 11280
11050 XA=PX(0):YA=PY(0)
11060 REM ==== Find following data points:- ====
11070 FOR P=PCADRES(C,1)+2 TO PCADRES(C,2)-2
11080 XB=PDX(P):YB=PDY(P)
11090 H=SQR((XA-XB)^2+(YA-YB)^2)            :REM dist between
points
11100 BP=SQR((PDX(PCADRES(C,2))-XB)^2+(PDY(PCADRES(C,2))-
YB)^2) :REM dist to end
11110 IF H>S OR H>BP THEN TPAX=PDX(P-1):
TPAY=PDY(P+1):TPBX=PDX(P+1):TPBY=PDY(P+1):GOSUB 11200:
REM Found next point
11120 NEXT P
11130 REM ==== Near end point:- =====
11140 NOP=NOP+1
11150 PX(NOP)=PDX(PCADRES(C,2)-1):PY(NOP)=PDY(PCADRES(C,2)-
1)
11160 TPAY=PDX(PCADRES(C,2)-2): TPAY= PDY(PCADRES(C,2)-2)
11170 TPBY=PDX(PCADRES(C,2)): TPBY= PDY(PCADRES(C,2))
11180 GOSUB 11280: REM calculate tangent
11182 REM ===== End point:- =======
11184 NOP=NOP+1
11186 PX(NOP)=PDX(PCADRES(C,2)):PY(NOP)=PDY(PCADRES(C,2))
11187 TPAY=PDX(PCADRES(C,2)-2): TPAY= PDY(PCADRES(C,2)-
2):REM "2" 'cos points can be close together causing one of these variables to
be zero.
11188 TPBY=PDX(PCADRES(C,2)): TPBY= PDY(PCADRES(C,2))
11189 GOSUB 11280: REM calculate tangent
11190 RETURN
11200 REM ============= Found next point ============
11210 NOP=NOP+1
11220 PX(NOP)=XB:PY(NOP)=YB
11230 TPAX=PDX(P-1):TPAY=PDY(P-1)
11240 TPBX=PDX(P+1):TPBY=PDY(P+1)
11250 GOSUB 11280: REM calculate tangent
11260 XA=XB:YA=YB
11270 RETURN
```

```
11280 REM ====== Calculate tangent at a point ====================
11290 TDY(NOP)=TPBY-TPAY:TDX(NOP)=TPBX-TPAX
11300 MT(NOP)= TDY(NOP)/TDX(NOP)
11320 RETURN
11330 REM-------------------------------------------------------------------
```

•

10 LINEWORK Linework Cutting Module

```
10 REM
*************************************************************
20 REM    *  SMOOTH/TILTED CURVE GENERATION MODULE
*
30 REM    *  MULTI CURVE - STAND ALONE  -MODIFIED VERSION
*
40 REM    *  15/03/91    /GWBASIC/MCURVES                    *
50 REM
*************************************************************
51 REM---------------------------- Start screen----------------------
52 CLS: KEY OFF:N=1
54 PRINT"           MULTIPLE CURVE TRANSLATION MODULE"
55 PRINT"           ======== ===== =========== ======"
56 PRINT"           For use with mitre or lineing wheels
59 REM
60 REM---------------------------- Initialise variables ---------------
70 REM  Raw data:-
79 DIM X(1500):DIM Y(1500)
81 REM  Calculated data:-
83 DIM PX(300):DIM PY(300):DIM PN(300)
84 DIM RTRUE(300):DIM RMOD(300)
85 FOR X=0 TO 300:RMOD(X)=999:NEXT X
90 DIM TILT(300)
92 XMAX=0:XMIN=2000:YMIN=1000:YMAX=0:D=0
94 CX=0:CY=0:DX=0:DY=0:PICONV=180/3.141592
95 REM
96 REM  Offsets:-
97 XOF=250        :REM    X-axis offset
98 YOF=10         :REM    Y-axis offset
99  REM  Wheel dependant data:-
101 DT=13/15*8    :REM    Maximum tilt used by automatic algorithm
102 ZUP=99        :REM    Depth clear of glass
103 ZTOUCH=100.1  :REM    Depth to just touch glass
104 ZDOWN=100.4   :REM    Depth for cutting
109 REM
110 REM  Files:-
120 LET FIN$ ="A:mctest.dxf"
130 FO$="A:cur1.smc" :FLC=1
160 OPEN FO$ FOR OUTPUT AS #1
170 OPEN FIN$ FOR INPUT AS #2
180 LN=1
182 FLIMIT=1300
184 LPRINT FO$
190 REM
```

```
200 REM------------------------ Start printer --------------------------------
210 PRINT:PRINT" DXF file being processed- ";FIN$
212 PRINT :PRINT " SMCC filenames are output to printer."
220 PRINT :PRINT "Cut 1-":PRINT " Reading input file."
221 LPRINT " The design :";FIN$
222 LPRINT " === ====== :";"================="
223 LPRINT" SMCC files for use with MITRE or LINEING wheels"
224 LPRINT" ==== ===== === === ==== ===== == =======
======":LPRINT :LPRINT F1$
230 REM
240 REM------------------ Read data into internal data arrays ------------------
245 REM  Find data:-
246 REM
250 INPUT #2,I$:IF I$="ENTITIES" THEN 260 ELSE 250
260 INPUT #2,I$
270 IF I$="LINE" THEN 300:REM          found first line
280 IF I$="ENDSEC" THEN PRINT "FILE EMPTY?": GOTO 440 ELSE
260: REM (Check for empty file.)
290 REM  Input first line:-
295 REM
300  INPUT #2,O$,LAYER$
310  INPUT#2,O$,X1$,O$,Y1$,O$,X2$,O$,Y2$
320
X(0)=VAL(X1$):Y(0)=VAL(Y1$):X(1)=VAL(X2$):Y(1)=VAL(Y2$):XO$=
X2$:YO$=Y2$
330 REM  Input subsequent line:-
335 REM
340  INPUT #2,O$,I$
350  IF I$="ENDSEC" THEN GOSUB 1000:GOTO 430
360  INPUT #2,O$,LAYER$
370  INPUT#2,O$,X1$,O$,Y1$,O$,X2$,O$,Y2$
380  IF X1$<>XO$ OR Y1$<>YO$ THEN GOSUB 2000:GOTO 340:REM
End of this cut
390  N=N+1:X(N)=VAL(X2$):Y(N)=VAL(Y2$):XO$=X2$:YO$=Y2$
400  GOTO 340
410 REM  End of data:-
420 REM
430 PRINT #1,"AAt512":PRINT #1,"HOM":PRINT #1,"END"
435 TLN=TLN+N:LN=LN+1:LPRINT "Cut ";LN
440 CLOSE:KEY ON:LPRINT:PRINT TAB(17);"=======    CURVES
GENERATED    ======"
445 END
450 REM  (OR RETURN?)
999 REM-----------------------------------------------------------------
1000 REM------------------*****************************------------------
---
```

```
1010 REM***           * First level subroutines *           ***
1020 REM------------------******************************------------------
---
1022 REM          **************************************
1030 REM          *  Process data, one step at a time  *
1032 REM          **************************************
1040 REM--------------- 1) Calculate spread and range of data ----------------
1045 REM
1047 PRINT " Cut data input."
1050 PRINT" Number of points in input file- ";N
1060 PRINT" Calculating parameters."
1070 FOR C=0 TO N
1080 IF X(C)<XMIN THEN XMIN=X(C)
1090 IF X(C)>XMAX THEN XMAX=X(C)
1100 IF Y(C)<YMIN THEN YMIN=Y(C)
1110 IF Y(C)>YMAX THEN YMAX=Y(C)
1120 IF C<>N THEN D=SQR((X(C+1)-X(C))^2+(Y(C+1)-Y(C))^2) ELSE
D=0
1130 IF C<>N AND D>DMAX THEN DMAX=D
1140 DTOT=DTOT+D
1150 NEXT C
1160 CX=(XMAX+XMIN)/2
1170 DMEAN=DTOT/N
1180 D=DMAX*3
1190 DX=(XMAX-XMIN)/2
1200 PRINT" Average distance between data points- ";DMEAN
1210 PRINT" Selected distance between output points- ";D
1220 T= INT(.5+ D*333):ACC$="AAt"+STR$(T):T$="T"+STR$(T)
1230 REM
1240 REM--------------- 2) Search for points of approx equal distance ---------
1250 PRINT " Searching for points of equal distance."
1260 REM  Start:-
1270  PX(0)=X(0):PY(0)=Y(0)
1280  XA=X(0):YA=Y(0)
1290 REM  Find following data points:-
1300  FOR C=1 TO N-1
1310   XB=X(C):YB=Y(C)
1320   IF SQR((XA-XB)^2+(YA-YB)^2)>D THEN GOSUB 4000: REM
Found next point
1330  NEXT C
1340 REM  End point:-
1350  NOP=NOP+1
1360  PX(NOP)=X(N):PY(NOP)=Y(N):PN(NOP)=N
1365 PRINT " Number of points in output file will be:-";NOP
1370 REM
1380 REM------------------ 3) Determine true r-axis direction ----------------
```

```
1385 PRINT" Calculating rotary axis directions."
1390 REM  Start direction:-
1400  PXA=X(0):PXB=X(1):PYA=Y(0):PYB=Y(1):C=0
1405  GOSUB 9000
1410 REM  Intermediate positions:-
1420  FOR C=1 TO NOP-1
1430   PXA=X(PN(C)-1):PXB=X(PN(C)+1):PYA=Y(PY(C)-
1):PYB=Y(PY(C)+1)
1440   GOSUB 9000
1445  NEXT C
1450 REM   End direction
1460  PXA=X(PN(NOP)-1):PXB=X(PN(NOP)):PYA=Y(PY(NOP)-
1):PYB=Y(PY(NOP))
1470  GOSUB 9000
1480 REM
1490 REM------------ 4) Determine R to be used and break points --------------
1500 GOSUB 7050
1640 REM
1650 REM------------------------ 5) Determine tilt angle  ------------------
1660 GOSUB 6035
1670 REM
1675 REM------------------------ 6) Check file size ------------------------
1677 GOSUB 3040
1679 REM
1680 REM------------------------ 7) Output SMC programme to file -----------
-
1690 GOSUB 18000:REM  check data
1700 RETURN
1710 REM 5025 usualy
2000 REM-----------------------------------------------------------------
2010 REM ************************************
2020 REM * End of this cut, but more to come  *
2030 REM ************************************
2040 LN=LN+1:PRINT "Cut ";LN;" found"
2050 GOSUB 1000 :REM   Process the cut
2060 N=1
2070
X(0)=VAL(X1$):Y(0)=VAL(Y1$):X(1)=VAL(X2)$:Y(1)=VAL(Y2$):XO$=
X2$:YO$=Y2$
2080 RETURN
2090 REM
2100 REM
2970 REM-----------------**************************--------------------
---
2980 REM---           * Second level subroutines *         ---
```

```
2999 REM------------------*****************************-------------------
---
3000 REM              *********************
3010 REM              * Check file size *
3020 REM              *********************
3030 REM  Need to change file?-
3040 IF (NOP+SWITCHC*12+5)+TLN<FLIMIT THEN
TLN=TLN+NOP+SWITHC*12+5 :RETURN
3050 REM  Yes-
3060 FLC=FLC+1:FLC$=STR$(FLC)
3070 FO$="A:CUR"+RIGHT$(FLC$,LEN(FLC$)-1)+".SMC"
3100 PRINT #1,"AA":CLOSE#1:OPEN FO$ FOR OUTPUT AS #1:PRINT
#1,"AAz 1500; "+FO$: LPRINT FO$
3105 IF (NOP+SWITCH*12+5)>FLIMIT THEN LPRINT "       -LARGE
FILE!!"
3110 RETURN
3120 REM
3130 REM------------------------------------------------------------------
4000 REM              ********************
4010 REM              * Found next point *
4020 REM              ********************
4030 NOP=NOP+1
4040 PX(NOP)=XB:PY(NOP)=YB :PN(NOP)=C
4050 XA=XB:YA=YB
4060 RETURN
4070 REM
4990 REM------------------------------------------------------------------
5000 REM              ****************************
5010 REM              * Output SMCC code to file *
5020 REM              ****************************
5025 PRINT " Downloading SMCC code for cut";LN;" to disk."
5027 LPRINT "Cut ";LN
5030 REM Feed in:-
5040 PRINT #1,"AAt512":PRINT #1,"AAT2000":PRINT #1,"AADWE100; --
------ Cut ";LN
5050 X=PX(0):Y=PY(0):Z=ZU:TILT=T(0)
5060 IF RMOD(0)=999 THEN R=RTRUE(0) ELSE R=RMOD(0)
5070 GOSUB 14000:REM   Convert data to axis position and send line to file
5080 PRINT #1,ACC$:PRINT #1,T$:PRINT #1,"AADWE100":PRINT
#1,"STA"
5090 Z=ZTOUCH:GOSUB 14000:Z=ZD:GOSUB 14000
5100 REM
5110 REM Continue along line:-
5120 C=1
5130 IF RMOD(C)=999 THEN GOTO 5150 ELSE 5190
5140 REM  Normal cutting:-
```

```
5150
X=PX(C):Y=PY(C):Z=ZDOWN:R=RTRUE(C):TILT=TILT(C):GOSUB
14000
5160  IF RMOD(C)<>999 THEN GOSUB 16000: GOTO 5190: REM switch
round
5170  C=C+1:IF C>NOP THEN 5230 ELSE GOTO 5150
5180 REM Abnormal cutting:-
5190  X=PX(C):Y=PY(C):Z=ZDOWN:R=RMOD(C):TILT=-
TILT(C):GOSUB 14000
5200  IF RMOD(C+1)=999 THEN GOSUB 17000: GOTO 5140: REM switch
back
5210  C=C+1:IF C>NOP THEN 5230 ELSE GOTO 5190
5220 REM
5230 REM  Feed out:-
5240  Z=ZUP: GOSUB 14000
5910 RETURN
5920 REM
6000 REM-----------------------------------------------------------------
6010 REM                ************************
6020 REM                * Determine tilt angle *
6030 REM                ************************
6035 PRINT " Calculating tilt angles."
6040 TILT(0)=-(PX(0)-CX)/DX*DT
6050 FOR C=1 TO NOP-1
6060  TILT(C)=-(PX(C)-CX)/DX*DT
6070 NEXT C
6080 TILT(NOP)=-(PX(NOP)-CX)/DX*DT
6090 RETURN
6100 REM
7000 REM-----------------------------------------------------------------
7010 REM         ********************************************
7020 REM         * Determine R to be used and break points *
7030 REM         ********************************************
7040 REM
7050 C=0:SWITCHC=0
7060 IF RTRUE(0)<180 AND RTRUE(0)>0 THEN 7140
7070 REM  loop - abnormal cutting
7080  IF RTRUE(C)>170 THEN LET RMOD(C)=RTRUE(C)-180
7090  IF RTRUE(C)<10 THEN LET RMOD(C)=RTRUE(C)+180
7100  C=C+1:IF C>NOP THEN 7180 :REM Finished
7110  IF RTRUE(C)<170 AND RTRUE(C)>10 THEN
SWITCHC=SWITCHC+1:GOTO 7140
7120  GOTO 7080
7130 REM Loop - normal cutting
7140  C=C+1:IF C>NOP THEN 7180 :REM Finished
```

```
7150 IF RTRUE(C)>190 OR RTRUE(C)<-10 THEN
SWITCHC=SWITCHC+1:GOTO 7080
7160 GOTO 1610
7180 RETURN
7190 REM
9000 REM------------------------------------------------------------
9001 REM***            Third level subroutines              ***
9002 REM------------------------------------------------------------
9005 REM        *********************************************
9010 REM        * Determine the quadrant of the direction *
9020 REM        *********************************************
9025 REM
9050 IF PYA=PYB AND PXA<PXB THEN RTRUE(C)=0:GOTO 9450
9060 IF PYA>PYB AND PXA<PXB THEN GOSUB 10020:REM 1st Q:goto
9450
9070 IF PYA>PYB AND PXA=PXB THEN RTRUE(C)=90:GOTO 9450
9080 IF PYA>PYB AND PXA>PXB THEN GOSUB 11020:REM 2nd Q:goto
9450
9090 IF PYA=PYB AND PXA>PXB THEN RTRUE(C)=180:GOTO 9450
9100 IF PYA<PYB AND PXA>PXB THEN GOSUB 12020:REM 3rd Q:goto
9450
9110 IF PYA<PYB AND PXA=PXB THEN RTRUE(C)=270:GOTO 9450
9120 IF PYA<PYB AND PXA<PXB THEN GOSUB 13020:REM 4th Q:goto
9450
9450 RETURN
9990 REM
10000 REM------------------------------------------------------------
10005 REM
**************************************************
10010 REM    * Calculate true r-axis direction for 1st.quadrant *
10015 REM
**************************************************
10017 REM
10020 ANGLE=ATN((PYB-PYA)/(PXA-PXB))*PICONV
10030 RTRUE(C)=ANGLE
10100 RETURN
11000 REM------------------------------------------------------------
11005 REM
**************************************************
11010 REM    * Calculate true r-axis direction for 2nd.quadrant *
11015 REM
**************************************************
11017 REM
11020 ANGLE=ATN((PXB-PXA)/(PYB-PYA))*PICONV
11030 RTRUE(C)=ANGLE+90
11100 RETURN
```

```
12000 REM------------------------------------------------------------
12005 REM
*************************************************
12010 REM   * Calculate true r-axis direction for 3rd.quadrant *
12015 REM
*************************************************
12017 REM
12020 ANGLE=ATN((PYA-PYB)/(PXB-PXA))*PICONV
12030 RTRUE(C)=ANGLE+180
12100 RETURN
13000 REM------------------------------------------------------------
13005 REM
*************************************************
13010 REM   * Calculate true r-axis direction for 4th.quadrant *
13015 REM
*************************************************
13017 REM
13020 ANGLE=ATN((PXA-PXB)/(PYA-PYB))*PICONV
13030 RTRUE(C)=ANGLE+270
13100 RETURN
13990 REM-------------------------------------------------------------
14000 REM
**************************************************************
*
14010 REM   * Convert data to axis position in units and send line to file *
14020 REM
**************************************************************
*
14025 REM
14030 N$=STR$(INT((X+XOF)*100+.5)):GOSUB 15030: X$=M$
14040 N$=STR$(INT((Y+YOF)*100+.5)):GOSUB 15030:Y$=M$
14050 N$=STR$(INT(Z*100+.5)):GOSUB 15030:Z$=M$
14060 N$=STR$(INT(R*100+.5)):GOSUB 15030:R$=M$
14070 N$=STR$(INT(TILT*100+.5)):GOSUB 15030:TILT$=M$
14080 L$="A0 X"+X$+" Y"+Y$+" A1 X"+Z$+" Y"+R$+" A2
X"+TILT$:PRINT #1,L$
14090 RETURN
14100 REM
15000 REM-------------------------------------------------------------
15005 REM          ***********************************
15010 REM          * Reduce variable to SMCC format *
15020 REM          ***********************************
15025 REM
15030 IF SGN(VAL(N$))= 0 THEN M$="0":GOTO 15100
15040 M$=RIGHT$(N$,LEN(N$)-1)
15050 M=LEN(M$)
```

```
15060 IF M=1 THEN M$="0.0"+M$
15070 IF M=2 THEN M$="0."+M$
15080 IF M>2 THEN M$=LEFT$(M$,M-2)+"."+RIGHT$(M$,2)
15090 IF SGN(VAL(N$))=-1 THEN M$="-"+M$
15100 RETURN
15110 REM------------------------------------------------------------
16000 REM
***************************************************
16010 REM        * Switch round from normal to abnormal cutting  *
16020 REM
***************************************************
16030 REM
16040 X=PX(C+1):Y=PX(C+1):Z=ZD-
.25:R=RTRUE(C+1):TILT=TILT(C+1):GOSUB 14030
16050 PRINT #1,"AAt200":PRINT #1,"T1500":PRINT
#1,"AADWE100":PRINT #1,"STA"
16060 X=PX(C+1):Y=PX(C+1):Z=ZT-
1:R=RTRUE(C+1):TILT=TILT(C+1):GOSUB 14030
16070 IF RTRUE(C-1)>170 THEN LET RM=RTRUE(C-1)-180
16080 IF RTRUE(C-1)<10 THEN LET RM=RTRUE(C-1)+180
16090 X=PX(C-1):Y=PX(C-1):Z=ZT-1:R=RM:TILT=-TILT(C-1):GOSUB
14030
16100 X=PX(C-1):Y=PX(C-1):Z=ZD-.2:R=RM:TILT=-TILT(C-1):GOSUB
14030
16110 PRINT #1,ACC$:PRINT #1,T$:PRINT #1,"AADWE100":PRINT
#1,"STA"
16120 RETURN
16130 REM-----------------------------------------------------------------------
17000 REM
***************************************************
17010 REM        * Switch round from abnormal to normal cutting  *
17020 REM
***************************************************
17030 REM
17040 IF RTRUE(C+1)>170 THEN LET RM=RTRUE(C+1)-180
17050 IF RTRUE(C+1)<10 THEN LET RM=RTRUE(C+1)+180
17060 X=PX(C+1):Y=PX(C+1):Z=ZD-.25:R=RM:TILT=-
TILT(C+1):GOSUB 14030
17070 PRINT #1,"AAt200":PRINT #1,"T1500":PRINT
#1,"AADWE100":PRINT #1,"STA"
17080 X=PX(C+1):Y=PX(C+1):Z=ZT-1:R=RM:TILT=TILT(C+1):GOSUB
14030
17090 X=PX(C-1):Y=PX(C-1):Z=ZT-1:R=RTRUE(C-1):TILT=TILT(C-
1):GOSUB 14030
17100 X=PX(C-1):Y=PX(C-1):Z=ZD-.2:R=RTRUE(C-1):TILT=TILT(C-
1):GOSUB 14030
```

```
17110 PRINT #1,ACC$:PRINT #1,T$:PRINT #1,"AADWE100":PRINT
#1,"STA"
17120 RETURN
17130 REM------------------------------------------------------------------
18000 REM check data
18005 LPRINT "px(c)","py(c)","pn(c)","rtrue(c)","rmod(c)","tilt(c)" :LPRINT
18010 FOR C=0 TO NOP
18020 LPRINT PX(C),PY(C),PN(C),RTRUE(C),RMOD(C)
18030 NEXT C
18040 RETURN
```
•