NASA TECHNICAL MEMORANDUM

NASA TM X-53453

August, 1966

NASA TM X- 53453

THE FABRICATION OF BERYLLIUM - VOLUME III. METAL REMOVAL TECHNIQUES

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METAL REMOVAL TECHNIQUES

ABSTRACT

This report documents the metal removal techniques developed for the fabrication of beryllium aerospace vehicle structures. It is Volume III of a six volume set of technical reports entitled "The Fabrication of Beryllium." Proven production techniques for the drilling, routing, and abrasive wheel cutting of both sheet and plate gauges of material are presented. Established techniques for the precision machining of hot-pressed block and extruded rod are reviewed. Chemical milling solution strengths and metal removal rates are investigated; and the optimum Electrical Discharge Machining (EDM) power and frequency settings. and electrode materials, are correlated with the resulting metal removal rates, surface finishes and elapsed machine times. Metallographic and microphotographic techniques were used for comparison and failure analyses.

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METAL REMOVAL TECHNIQUES

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The other Volumes of Technical Memorandum X-53453 are:

Vol. I.	A Survey of Current Technology
Vol. II.	Forming Techniques for Beryllium Alloys
Vol. IV.	Surface Treatments for Beryllium Alloys
Vol. V.	Thermal Treatments for Beryllium Alloys
Vol. VI.	Joining Techniques for Beryllium Alloys

MANUFACTURING ENGINEERING LABORATORY

ACKNOWLEDGEMENT

The work accomplished to generate the information enclosed in this report was performed under Contract NAS8-11798 by Large Space Vehicle Programs, Space Systems Division, Lockheed Missiles and Space Company. The program encompasses the development and documentation of needed new manufacturing techniques and fabrication methods suitable for the application of beryllium and beryllium alloys in space flight vehicle structures.

Mr. R. F. Williams, NASA Advanced Manufacturing Programs, was the Project Manager of this effort under the management of Mr. A. J. Steele, Manager, NASA Engineering Programs, Lockheed Missiles and Space Company. The work was performed under the technical direction of Mr. S. E. Ingels assisted by Mr. C. Fruth in preparation of the final report.

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THE FABRICATION OF BERYLLIUM - VOLUME III.

METAL REMOVAL TECHNIQUES

SECTION I. INTRODUCTION

The objectives of this task are the definition, development and documentation of the beryllium fabrication operations classified as "Metal Removal" in the Beryllium Fabrication Methods Development Program Plan.

Maximum use was made of the established methods and procedures currently being utilized in production operations. In all cases, the verification and recording of pertinent data were necessary; in many cases, e.g., Electrical Discharge Machining (EDM), additional development work also was required.

The procedure used in compiling this report was as follows:

1. Conduct a detailed analysis of the metal removal practices being used within industry.

2. Investigate, evaluate and report upon the techniques currently utilized with certain Beryllium Shops.

3. Fabricate representative parts in accordance with the requirements of approved production procedures.

4. Vary the production techniques sufficiently to incur intentional failure, and thus circumscribe limits.

5. Utilize metallographic and microphotographic methods to evaluate both the satisfactory and the unsatisfactory results.

SECTION II. GENERAL

Due to the basic similarity of many facets of the various beryllium metal removal methods, they are discussed separately in this section to avoid repetition.

A. MATERIAL CHARACTERISTICS

The effect of the physical properties of beryllium must be considered in almost all metal removal operations. When subjected to chip-producing processes, it machines relatively easily (somewhat similar to cast iron). However, due to the abrasive nature of beryllium, carbide cutting tools must be used if adequate tool life is to be attained. Sharp edges and reasonable chip-loads must be maintained on the cutting tools to prevent the buildup of cutting pressures. Relatively low cutting speeds for carbide tools, ranging from 75 to 300 surface feet per minute, are used.

Due to the low ductility of beryllium at room temperature, the pressures applied to the workpiece during machining operations must be kept at a minimum level. During the entrance to, or the exit from a cut, the speeds, feeds, and pressures must be very low to avoid the fracturing or spalling of the workpiece.

The introduction of internal stresses into the workpiece due to clamping action must be avoided. During the subsequent machining operations any additional forces due to improper clamping can result in a cumulative stress level in excess of the elastic limit of the material.

A similar failure may occur because of the deflection of the workpiece due to excessive cutting force, or the lack of workpiece rigidity and/or fixture support. A common cause of excessive cutting force is the resistance generated by a dull or improperly ground cutter. Just as the cutting action nears completion, the cutting pressure is relieved sufficiently to permit the springback of the deflected workpiece to its unrestrained position. As this occurs, the chip-load of the cutter is increased greatly, a high radial force is generated, and failure of the workpiece may result.

The high-heat capacity of beryllium, i.e., its ability to absorb heat in a localized area, also must be given careful consideration. For example, the localized heat produced along one edge of the material by an abrasive saw used with insufficient coolant will cause considerable expansion of the edge grains. This heat tends to remain along the edge while the material a short distance into the workpiece remains cool and unexpanded. These differentials in temperature and expansion, if sufficiently large, can cause corresponding degrees of small edge fractures.

Beryllium is highly notch sensitive. It is mandatory, therefore, that the surfaces be protected from possible nicks and scratches during handling, processing and transportation. Storage shelves and transportation and handling devices should be free of protruding nails, chips, etc., and should be lined with felt or a similar protective material. During the processing phase, the parts should be stored temporarily in individual containers or nested with interleaves of protective paper. Operators must practice caution at all times; must avoid setting the workpieces on hard surfaces, dropping tools on, or striking the beryllium with other hard or sharp objects which could cause the fracture of the material.

Beryllium forms a surface film of beryllium oxide during its exposure to the high temperatures required for normal processing. This film must be removed by wet sanding or light grinding prior to mechanical or chemical cutting if reasonable tool life or consistent results are to be realized.

B. SAFETY AND INDUSTRIAL HYGIENE

The inhalation of high concentrations of beryllium dust can cause serious illness; however, with the establishment and maintenance of proper environmental controls, the material can be handled safely during all maching operations. Since the toxicity of beryllium was realized in the late 1940's and effective dust control methods were instituted, no chronic beryllium disease traceable to this cause has been reported.

The basic hazards encountered in working with beryllium are:

1. The inhalation of high concentrations of beryllium dust or fumes can have a deleterious effect on the respiratory system.

2. The presence of beryllium or its compounds in any cut or wound tends to inhibit healing until the foreign material is removed.

3. Contact with some of the compounds of beryllium can cause a temporary dermatitis condition.

Safe working conditions can be established by performing all beryllium metal removal operations in a separate "Beryllium Room." Each room is equipped with its own exhaust ventilation and chip collection systems, and is maintained at a slight negative pressure relative to the rest of the building to prevent the possible contamination of adjacent areas. All chip-producing machine tools must be equipped with close-capture high-velocity exhaust hoses which are maintained within one hose diameter (approximately 3 inches) of the working face of the cutting tool. A total enclosure must be used to control the fine dust or mist created during such operations as wet or dry sanding and abrasive wheel cutting. Acid-etching, chemical milling, and electrical discharge machining facilities are equipped with specialized exhaust systems. All dust-collecting surfaces, including machine tools, should be "wet-wiped" once each day, and the floor should be cleaned and mopped once each shift.

Employees assigned to the beryllium rooms receive medical examinations, including lung X-rays, prior to the initial assignment and at six-month intervals thereafter. Smoking is restricted in the beryllium rooms, and all normal safety practices such as the wearing of safety glasses, the reporting of all injuries, however slight, to the medical unit, etc., are rigidly enforced. Cotton shop coats are furnished, and the coats, towels, and cloths are laundered in special approved on-site facilities provided for this purpose. Only materials and equipment which are free from loose particles of beryllium are permitted to leave the beryllium rooms. All the beryllium exhaust, ventilation and air-cleaning equipment, as well as the industrial hygiene procedures, are monitored constantly by an independent Safety and Industrial Hygiene Organization.

C. PERSONNEL TRAINING

Employees working in the beryllium rooms must be fully informed of the correct methods, processes and handling procedures for fabricating beryllium hardware. The personnel also must be made aware of the basic hazards, and be thoroughly indoctrinated in safety and industrial hygiene practices. Each employee, therefore, is required to successfully complete a company-sponsored indoctrination and training course prior to his assignment in a beryllium room. The subjects covered in this course are outlined as follows:

1. Introduction
    a. Course Purpose
    b. Advantages of Beryllium
    c. Typical uses of Beryllium
    d. Production of Beryllium - Block and Sheet
2. Fabrication Techniques for Beryllium Sheet
    a. Forming
    b. Drilling
    c. Joining Parts
    d. Cutting and Trimming
3. Handling Techniques for Beryllium Sheet
    a. Specific Handling Requirements
    b. General Handling Techniques

4. Safety Techniques for Beryllium - All forms

a. Basic Hazards

b. Hazard Control Methods

D. EQUIPMENT MAINTENANCE

The primary responsibility for ensuring that the equipment is functioning properly falls upon the machine operator. Any malfunctions are reported to the supervisor.

The possibility of production delays resulting from machine malfunction or breakdown is greatly lessened, and machine accuracy is significantly preserved by the application of a program of preventative maintenance. The following inspections and maintenance services are provided by a plant engineering organization at the following scheduled intervals:

1. Visual inspection of hydraulic fluid levels in glass reservoirs - service as required - daily.

2. Check spindle, slide and ways - lubricate - weekly.

3. Inspect electrical and mechanical operation - quarterly.

4. Drain, clean and refill hydraulic system - semi-annually.

E. TOOL PROVING AND MAINTENANCE

Due to the abrasive characteristics of beryllium, the use of standard procedures for the initial proving and routine maintenance of tooling is mandatory. It is recommended that the fabrication of the first production pieces on a new tool be witnessed by the tool designer. Thus, any necessary repairs or modifications can be accomplished expeditiously, and the existence of any slight dimensional deviations, well within the allowable tolerances, can be noted and recorded. Periodic inspections at regular intervals, based on past experience and wear records, should be made by tool inspection personnel. Any dimensional deviations should be recorded and any necessary repairs be made. Rigid conformance with such procedures will preclude most, if not all, rejections due to tooling error.

F. QUALITY ASSURANCE

All beryllium hardware is inspected for quality assurance. In-process inspection is performed at appropriate stages of the fabrication process as well as 100 percent inspection at the completion of the part, sub-assembly, or assembly. Due to the very limited number of qualified repair procedures, perfection in workmanship is literally required.

Conventional measuring and checking equipment is used during the inspection operations. Visual examination for the existence of cracks, delamination, spalling, etc., normally is performed after chemical etching. This process tends to enlarge any such defects and make them readily detectable without magnification. This process is preferred over the more common "Zyglo" inspection method which may not reveal extremely small or tight cracks or fractures.

SECTION III. SHEET AND PLATE PROCESSES

A. GENERAL

Cross-rolled beryllium sheet produced from vacuum hot-pressed and sintered block is available commercially in standard thicknesses ranging from 0.020 to 0.250 inch, and in sizes up to 36 by 96 inches. Larger sizes are available on special order. Plate stock is available in thicknesses ranging from 0.250 to 1 inch. The standard thickness tolerance is approximately $\pm$ 10 percent of the nominal gauge. The variation from true flatness may be 2 to 3 percent as determined by measuring the point of greatest deviation from an applied straight edge, and expressing this measurement as a percentage of the distance between the contact points. Improper stress relieving operations also may result in "waviness" or deviations from the desired contour. It is important, therefore, that the holding devices be designed to accommodate such variations to avoid introducing high stresses into the workpiece during the subsequent locating, supporting and/or clamping operations.

Typical items fabricated from sheet and plate stock include exterior skin panels, doors, frames, rings, and assorted brackets. Most conventional sheet metal configurations can be fabricated within normal tolerances.

B. HOLE PRODUCTION ANALYSIS

Evaluation of the comparative merits of the most common methods for producing holes in sheet material has been made, verified, augmented, and reported in this report.

During the initial study, a series of holes, 0.167 and 0.191 inch in diameter, were punched and drilled in two thicknesses of material, 0.060 and 0.100-inch, and the resulting hole edges were metallurgically examined. In addition, the merits of reaming and etching also were investigated. The results of this investigation indicated that drilling followed by etching produced the highest quality holes. Reaming had a deleterious effect, and piercing was somewhat detrimental to the integrity of the beryllium surrounding the holes.

The extent and depth of microcracks and delamination, and the presence of twins and porosities on both the hole and edge surfaces were items of prime interest during the initial study. The various holes evaluated during this study are listed as follows:

1. Four holes pierced in 0.060 and 0.100-inch sheet.

2. Four holes pierced and reamed in 0.060 and 0.100-inch sheet.

3. Four holes drilled in 0.060 and 0.100-inch sheet.

4. Four holes pierced and etched in 0.060 inch and 0.100-inch sheet.

5. Four holes pierced, reamed, and etched in 0.060 and 0.100-inch sheet

6. Four holes drilled and etched in 0.060 and 0.100-inch sheet.

1. Analysis Procedure. All holes were photographed individually, from both sides of the sheet, at a magnification of ten diameters.

One specimen hole, representing each parameter, was mounted so that the plane of polish was the surface through which the punch or drill entered, i.e., the "top" surface. The other specimen, also representing each parameter, was cut across the hole, mounted, and polished to present a cross-sectional view of the hole.

All specimens were ground with silicon carbide papers, up through 600 grit, and then were etched to remove any surface delamination that had been produced by the grinding operation. The samples then were prepared for photographing by conventional abrasive polishing methods.

A metallograph was used to examine the specimens at low magnification. Both bright field and polarized light illumination were used.

2. Results. Pertinent aspects of the macroscopic and microscopic conditions of the holes are illustrated in Figures 1 through 11. The illustrated defective conditions are discussed as follows:

1. A satisfactorily drilled hole is apparent (Figure 1). However, basal plane delamination may occur as shown in Figure 6, and revealed by etching if improper drilling procedures are used.

2. Circumferential cracks are visible on the entrance surface of the punched hole (Figures 2, and 3). It may be noted that the defect is much more visible after etching.

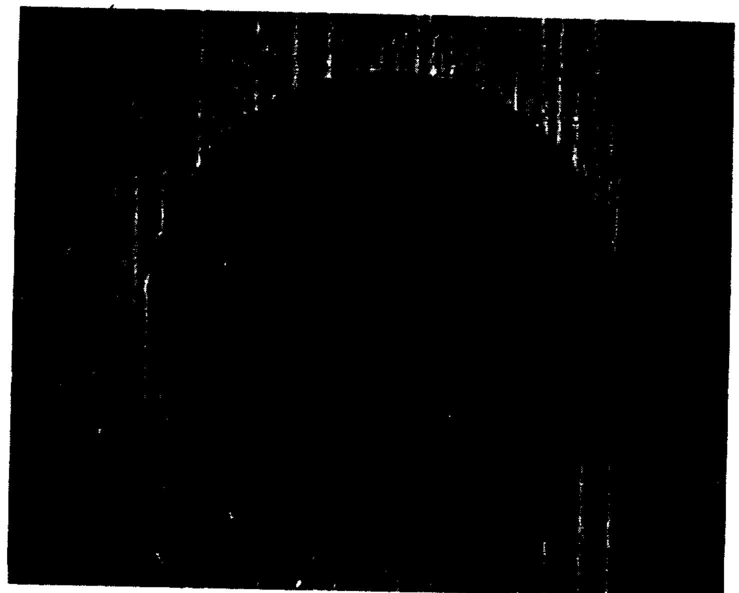

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FIGURE 1. DRILLED AND ETCHED HOLE - ENTRANCE SIDE - NO APPARENT CRACKING

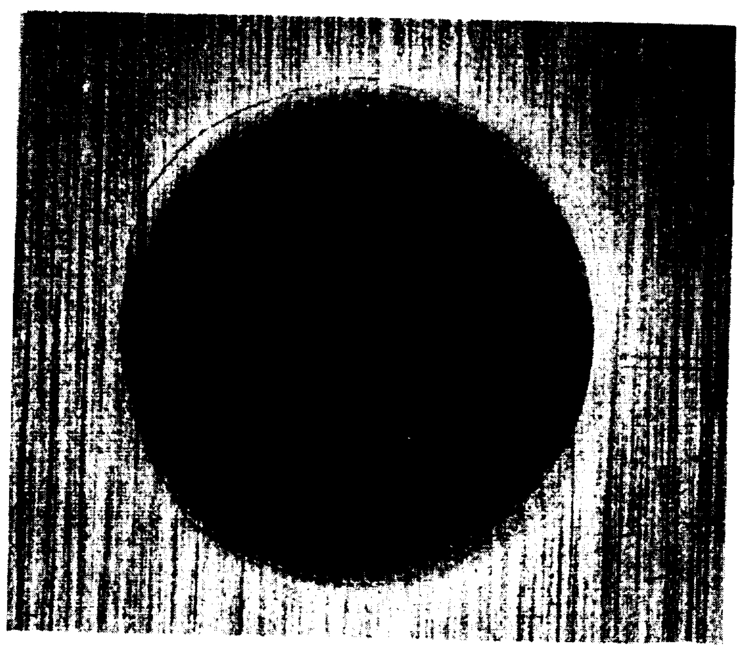

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FIGURE 2. CIRCUMFERENTIAL CRACKING AROUND PUNCHED HOLE (UNETCHED) - ENTRANCE SIDE

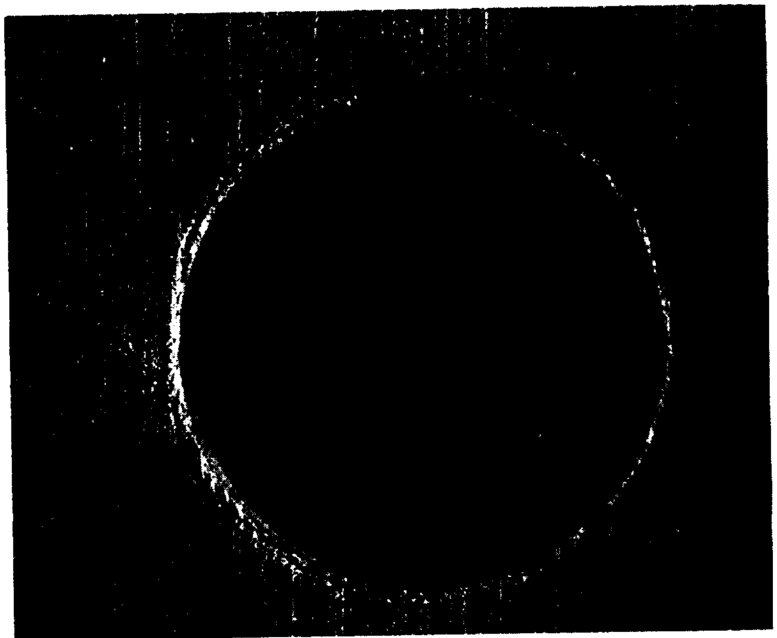

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FIGURE 3. CIRCUMFERENTIAL CRACKING AROUND PUNCHED AND ETCHED HOLE-ENTRANCE SIDE

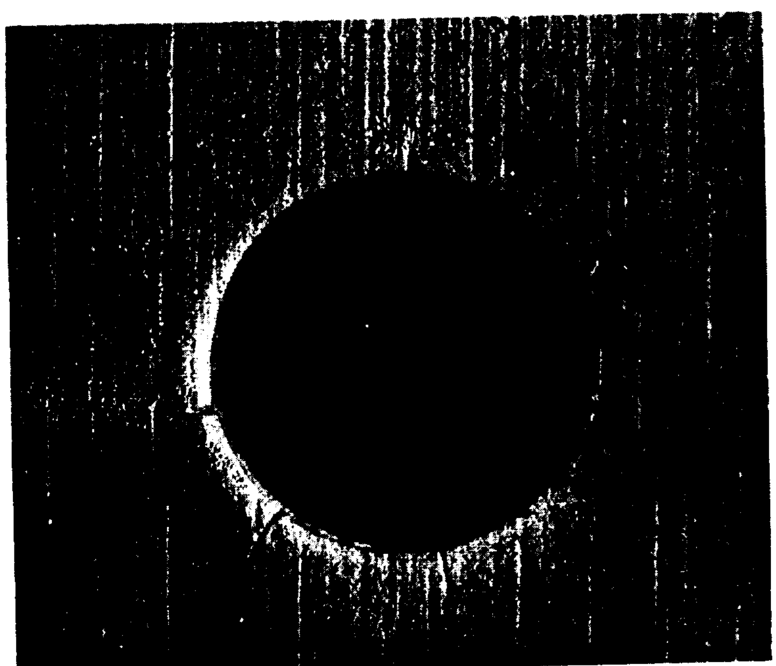

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FIGURE 4. RADIAL CRACKING AROUND PUNCHED AND ETCHED HOLE-ENTRANCE SIDE

3. Radial cracks are visible on the entrance surface of the punched hole (Figures 4 and 8). This type of fracture, although easily seen without the utilization of visual aids, is accentuated by etching. The extent of intra-grain damage, or twinning, is clearly evident in Figure 8.

4. Break-out or spalling is clearly visible on the exit surface of a drilled hole (Figure 5). This defect is typical of the results obtained from operating a drill press in the conventional manner with a normal two fluted drill of standard geometry.

5. Severe delaminations along basal planes are shown here (Figure 6). This defect results from improper drilling procedure.

6. The absence of surface damage around a drilled hole is very evident (Figure 7).

7. A radial crack and severe deformation (twinning) on the entrance side of a punched and etched hole are shown here (Figure 8).

8. Severe delamination is visible in this cross-section of a punched hole (Figure 9). It may be noted that the twinning increases progressively with hole depth.

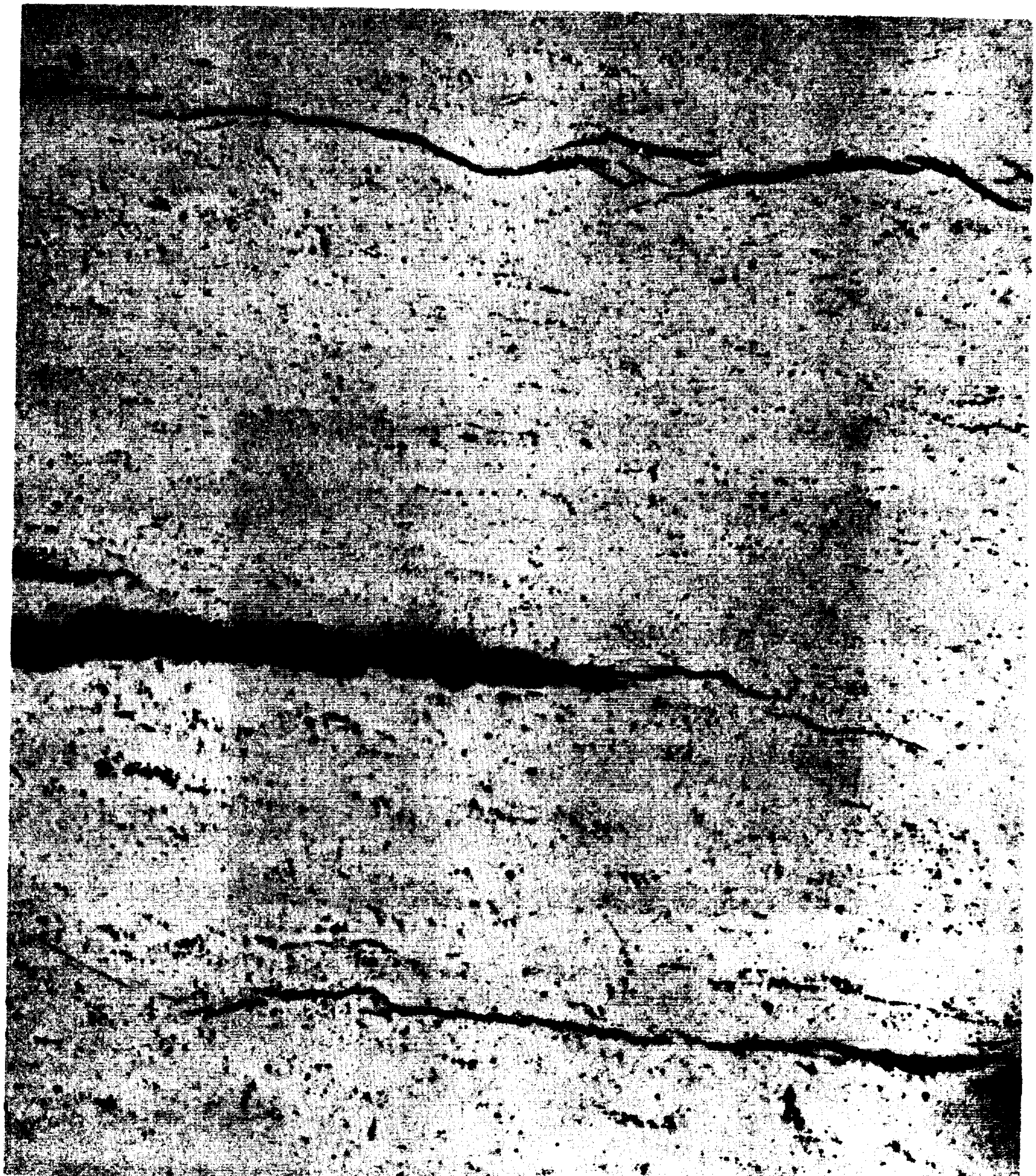
9. Extensive surface damage and twinning on the entrance side of a punched hole (Figure 10) are clearly visible.

10. Porosity and severe deformation are clearly visible in this cross-section of a punched hole (Figure 11). The material deformation along basal planes is obvious in this illustration. The porosity, due to the combination of grain separation from the basic matrix caused by the punching operation and the loss of the loosened grains during the polishing operation, is very apparent.

Tables I and II present the correlation of the observed defects with the method of hole production and treatment. A review of the data presented in Tables I and II reveals that the circumferential cracks, the radial cracks, and the deformation twinning, as measured from the wall of the hole, varied from

(10X)

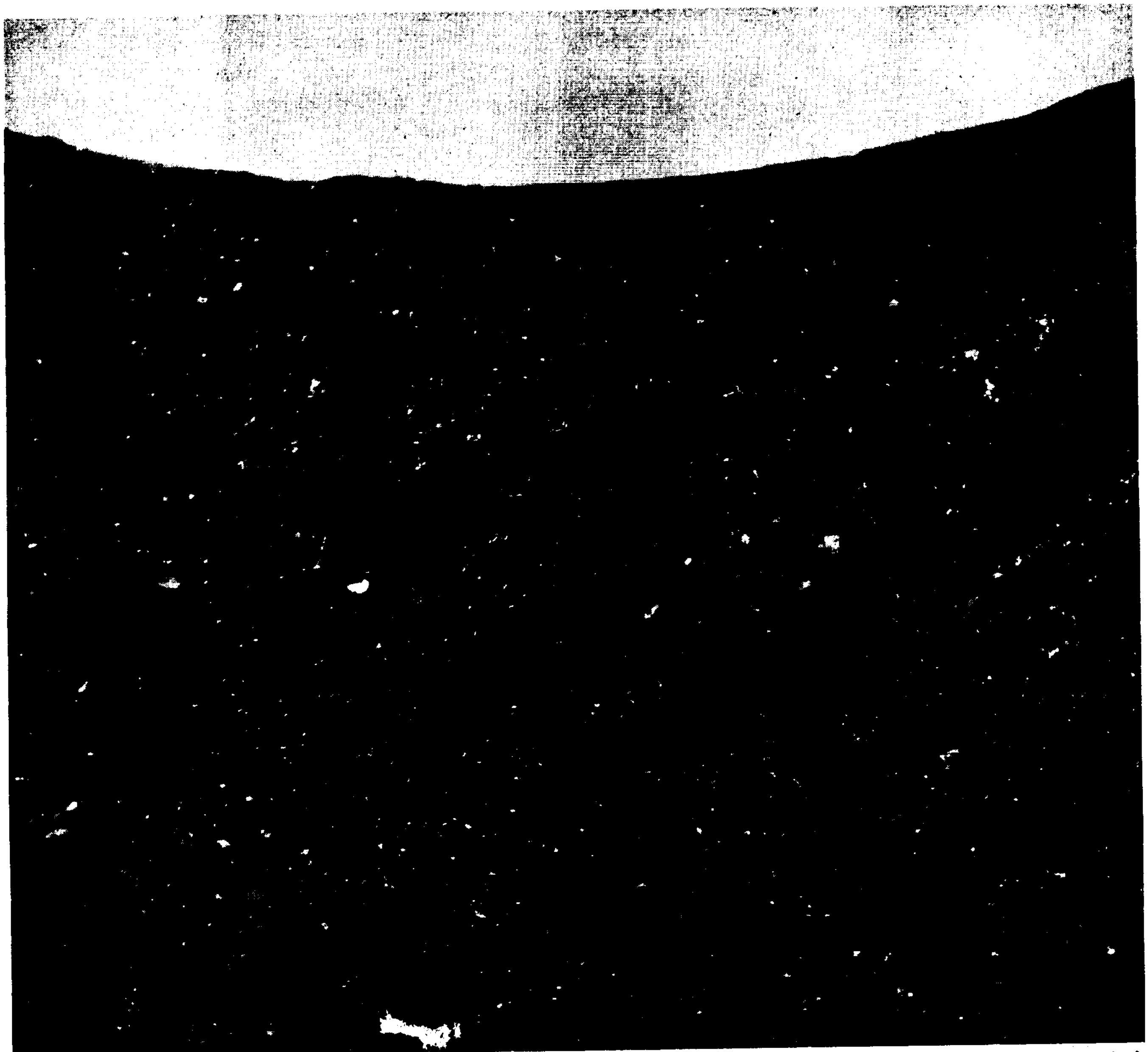
FIGURE 5. BREAK-OUT (SPALLING) OF EXIT SIDE OF IMPROPERLY DRILLED HOLE



(500X)

FIGURE 6. IMPROPERTLY DRILLED HOLE THROUGH 0.100-INCH SHEET SHOWING DELAMINATIONS. HOLE WALL NEAR LEFT OF PHOTOGRAPH

ENTRANCE SIDE



(144X)

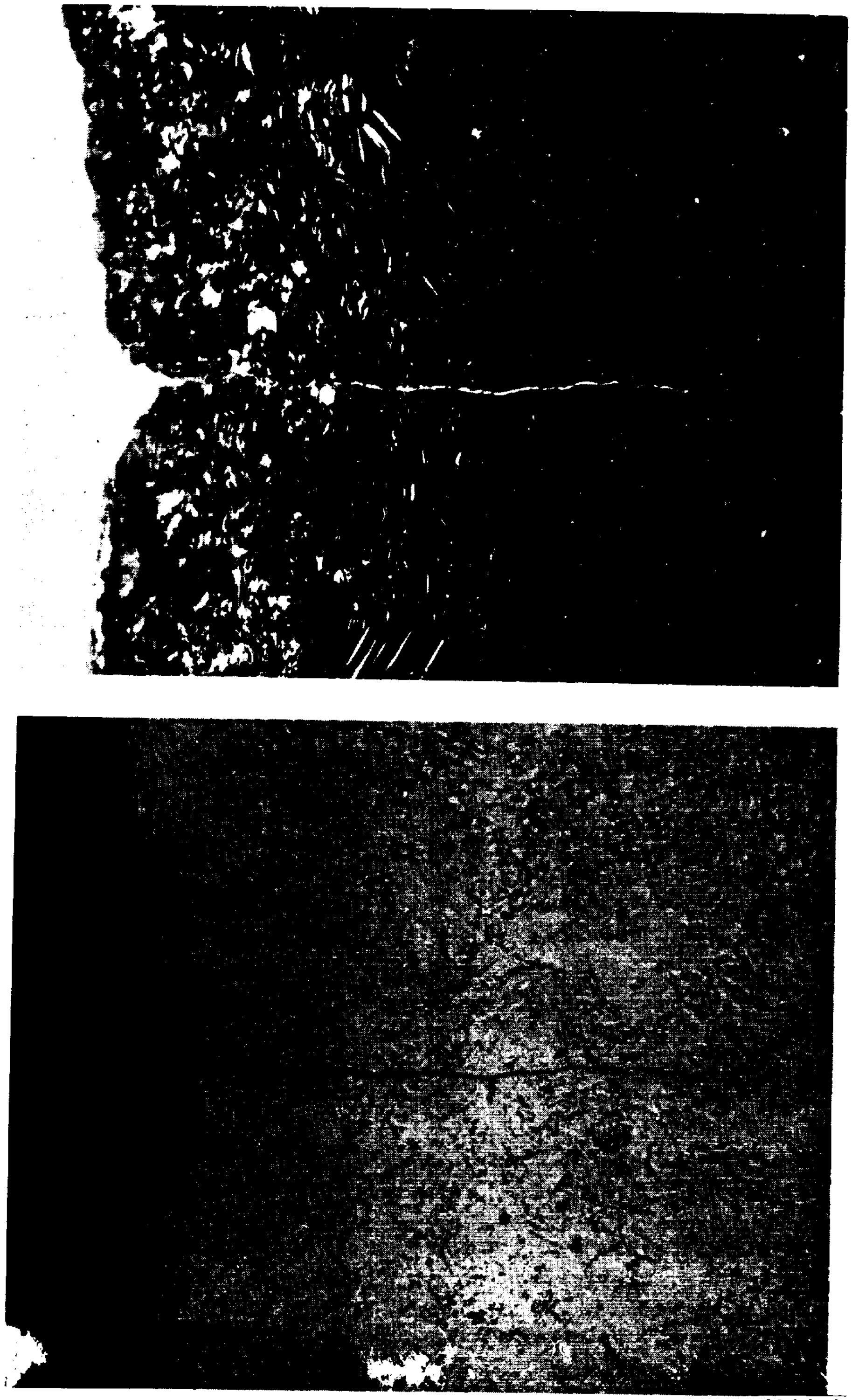
FIGURE 7. DRILLED HOLE IN 0.060-INCH SHEET - ENTRANCE SURFACE. REPRESENTATIVE OF ALL DRILLED HOLES

ENTRANCE SIDE

HOLE
SIDE

BEFORE
ETCH

POLARIZED
LIGHT



AFTER
ETCH

BRIGHT
FIELD

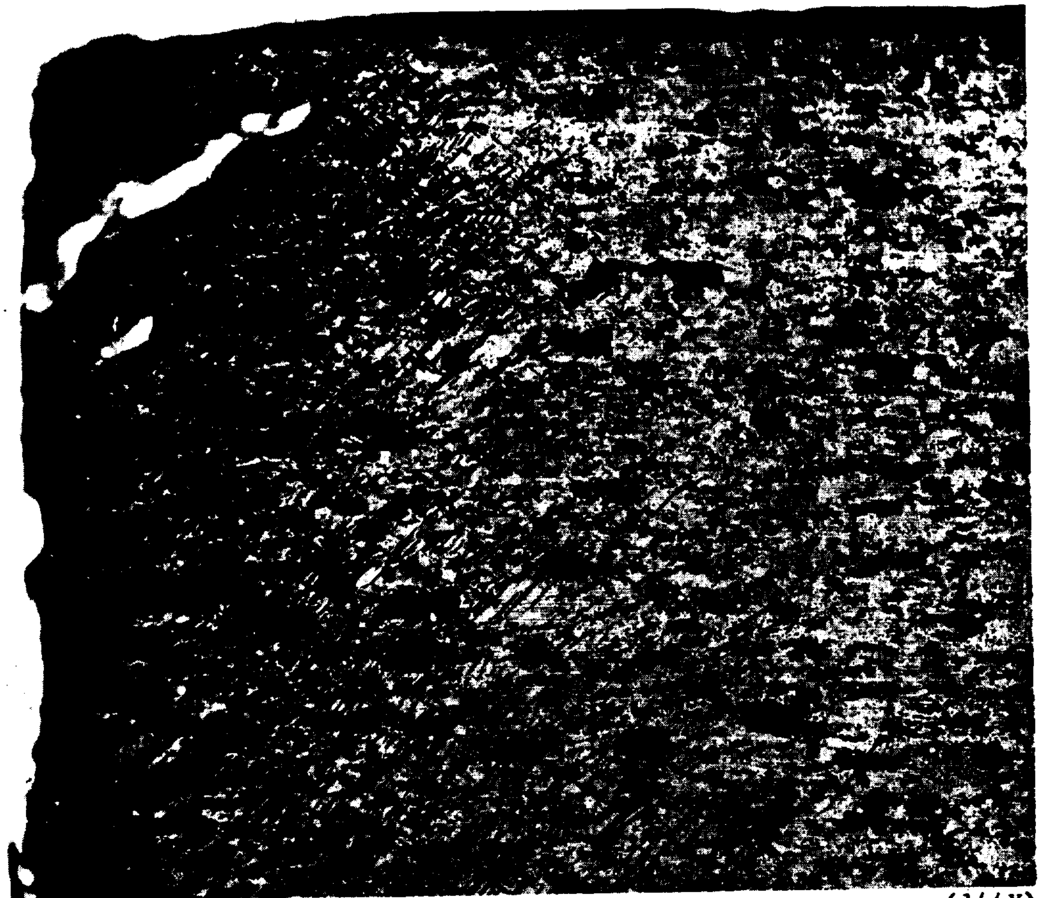
HOLE
SIDE

(144X)

FIGURE 8. PUNCHED AND ETCHED HOLES IN 0.010-INCH SHEET. PHOTOS SHOW EXTENT OF RADIAL CRACK ON ENTRANCE SIDE AND SURFACE DAMAGE (TWINNING) EXISTING EVEN AFTER ETCHING

ENTRANCE SIDE

HOLE
SIDE



(144X)

FIGURE 9. CROSS-SECTION THROUGH PUNCHED HOLE SHOWING EXTENT OF SURFACE DAMAGE AND TWINNING

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FIGURE 10. ENTRANCE SURFACE OF PUNCHED HOLE SHOWING EXTENSIVE DEFORMATION TWINNING (POLARIZED LIGHT)

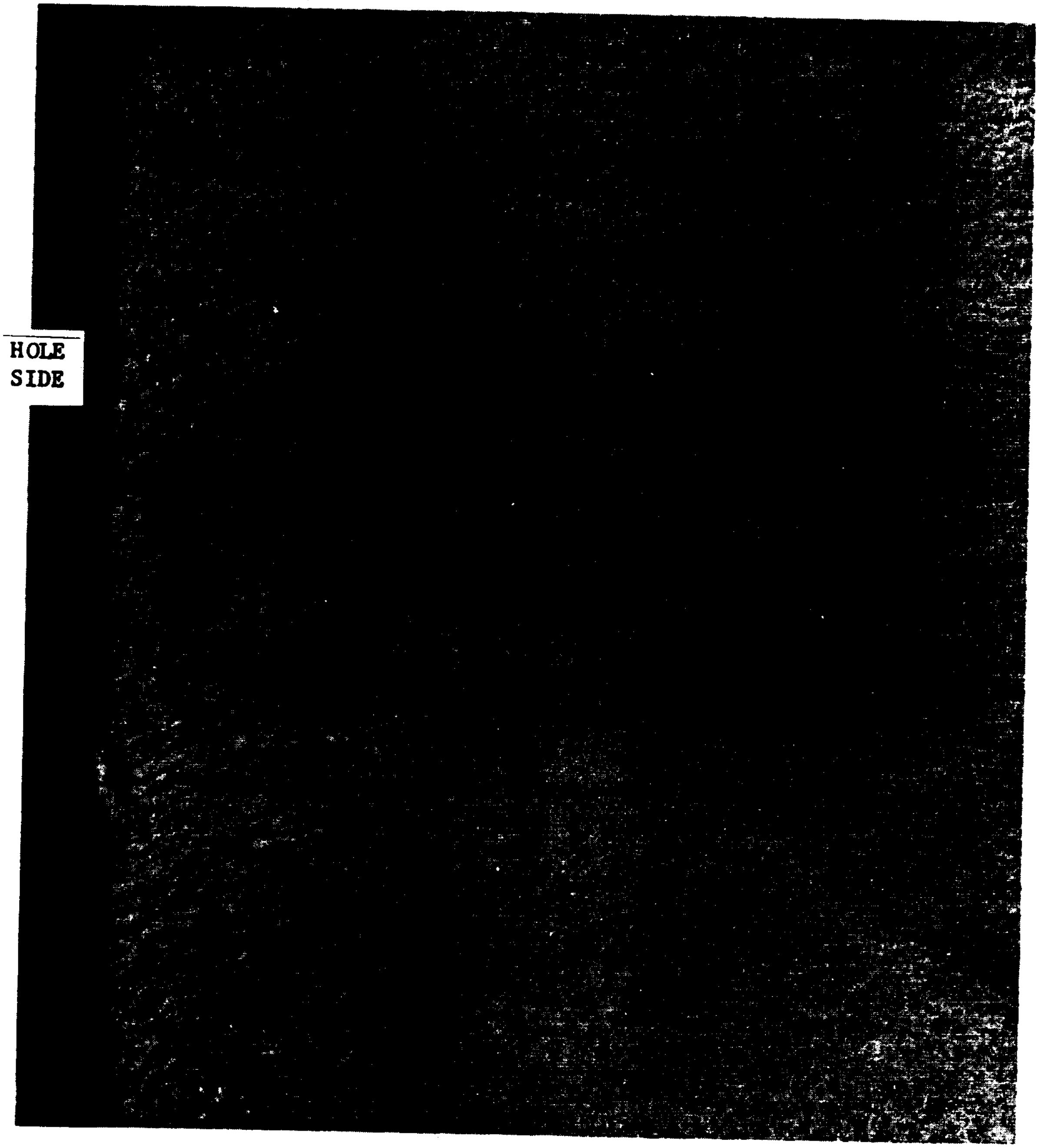

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FIGURE 11. PUNCHED HOLE CROSS-SECTION.
NOTE GRAIN PULLOUT (POROSITY) AND
LINES OF BASAL PLANE DEFORMATION.

TABLE I. CORRELATION OF DEFECTS WITH METHOD OF HOLE PRODUCTION TREATMENT - (SMALL HOLES 0.167 INCH)

Holes	Material Thickness	Radial Cracks	Circum-ferential Cracks	Break-Outs	Steps	Severe Lamination	Mild Lamination	Severe De-formation	Moderate De-formation
Punched	0.100							X	
Punched	0.060							X	
Punched Reamed	0.100	X	X						X
Punched Reamed	0.060						X		X
Punched Etched	0.100	X							X
Punched Etched	0.060							X	
Punched Reamed Etched	0.100	X							
Drilled	0.100			X	X				
Drilled	0.600				X				
Drilled Etched	0.100			X	X				
Drilled Etched	0.060				X	X			

TABLE II. CORRELATION OF DEFECTS WITH METHOD OF HOLE PRODUCTION TREATMENT - (LARGE HOLES 0.191 INCH)

Holes	Material Thickness	Radial Cracks	Circumferential Cracks	Break-Outs	Steps	Severe Lamination	Mild Lamination	Severe Deformation	Moderate Deformation
Punched	0.100		X						
Punched	0.060		X				X	X	X
Punched Reamed	0.100		X						X
Punched Reamed	0.060								X
Punched Etched	0.100		X				X		X
Punched Etched	0.060		X			X			X
Punched Reamed Etched	0.100		X				X	X	
Punched Reamed Etched	0.060		X				X		X
Drilled	0.100						X		
Drilled	0.060		(No defects - one specimen)						
Drilled Etched	0.100					X	X		
Drilled Etched	0.060		(No defects - one specimen)						

0.020 to 0.030 inch in depth. The extent of the delaminations also varied considerably, ranging from short hairline cracks observable only under high magnification, to very long, wide, and open cracks easily seen with the unaided eye.

The circumferential cracks were shallow and usually toward the wall of the hole a short distance below the surface of the material. The circumferential cracking that occured around the punched holes could, perhaps, be considered similar to the breakout that can occur around improperly drilled holes.

The presence of radial cracks around punched holes was very evident after the surface had been etched, whereas only one small radial crack could be seen with the unaided eye on the "as-punched" unetched holes.

The defective conditions associated with drilled holes were delaminations, breakouts, and steps. The latter two conditions are considered to be minor as they can be avoided if the proper "set-up" and drilling procedures are used. Thus, only one major deleterious condition is associated with the drilled holes, compared with four such conditions associated with pierced/punched, reamed and etched holes.

3. <u>Conclusions</u>. The results of this investigation indicate that punching or piercing should not be used for the production of holes in beryllium sheet material; the proper drilling procedure should be used.

C. PIERCING

As indicated in the previous analysis, piercing/punching at ambient temperatures does not appear to be a practical beryllium fabrication method. However, since the ductility of this metal increases significantly at elevated temperatures (above 1000°F), improved results may be obtainable at high temperatures. The disadvantages (time, specialized equipment, cost) of this added complication, however, appear to outweigh any possible advantage piercing might conceivably have over the drilling or electrical discharge machining processes.

The primary advantage of the conventional piercing/punching process is the very low cost in production manhours per unit. The relatively high cost of beryllium material, however, makes the quality of product, and the reliability and repeatability of a production process, of far greater economic importance than a minor saving in manhours. Further investigation, therefore, will depend upon future developments.

D. DRILLING

1. Present Capability. Drilling procedures, specialized facilities, equipment, holding devices, and cutting tools, etc., have been developed to a high level of reliability, repeatability, and efficiency. The process is being conveniently performed without an immediate environmental enclosure. A unique torque sensing system (Figure 12) is used to control the spindle speed and feed. Special carbide drills are used, which are capable of drilling a great many high-quality holes, totally without cracks, delamination or spalling, and with negligible tool wear. The final sizing and surface finishing are attained by carefully controlled chemical etching. Probable future developments include the drilling of panels on assembly and the accomplishment of "open" repairs utilizing portable zone environmental control.

2. Recommendations. The current drilling procedures are adequate for all production line requirements; no additional developmental effort is recommended at this time.

3. Current Procedures.

a. Safety and Environmental Control. Beryllium chips produced as the results of proper drilling procedures are granular rather than fine dust particles, and thus, the process is being performed safely without the use of an immediate environmental enclosure. A 3-inch diameter flexible vacuum chip disposal tube, maintained within one tube diameter (3 inches) of the drill bit, carries the chips to the single master chip collection system which services all the chip producing equipment in the beryllium room.

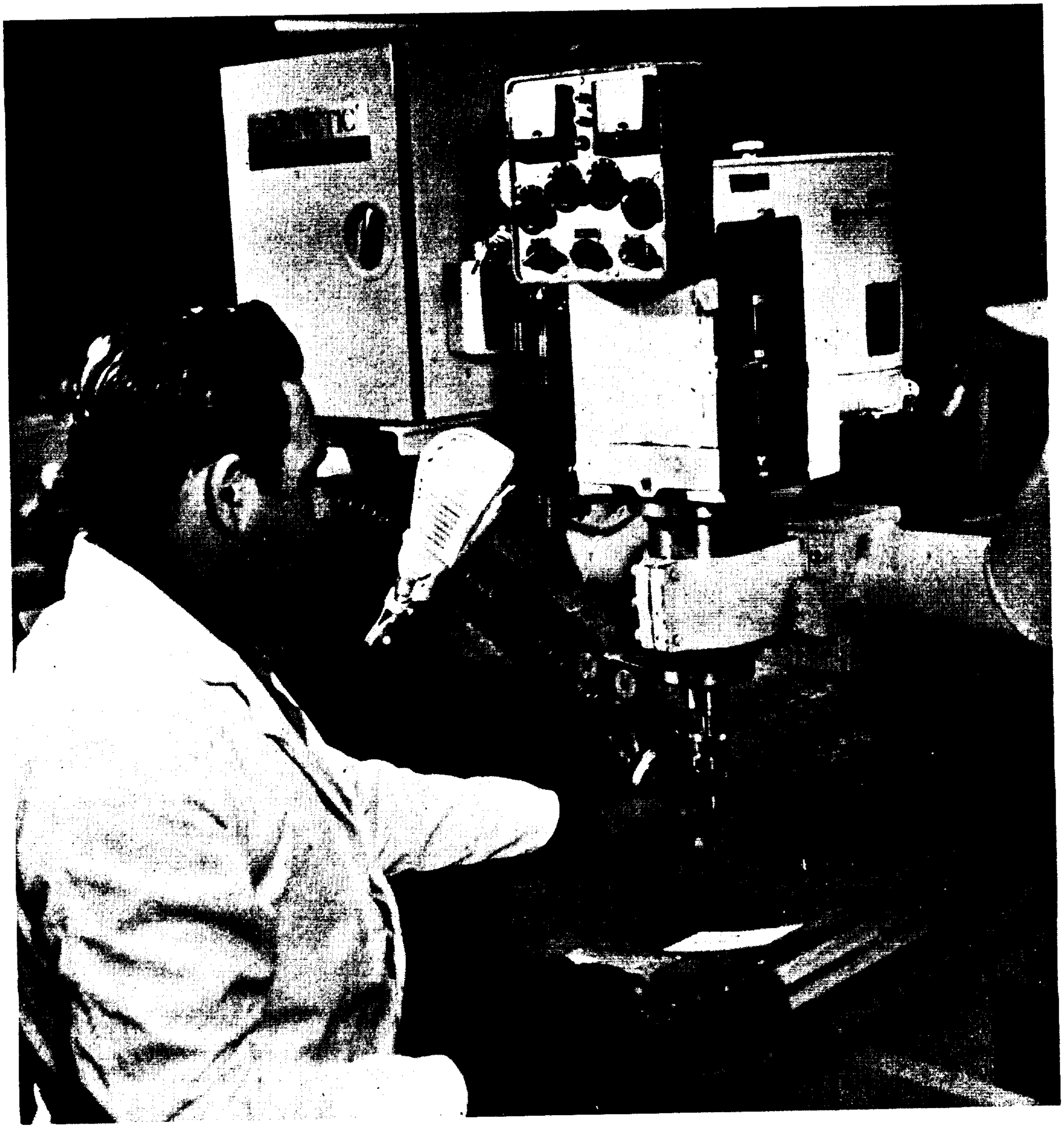


FIGURE 12. TYPICAL PANEL BEING DRILLED USING "TORNETIC" CONTROL HEAD. NOTE SUBSTANTIAL FIXTURING AND PROXIMITY OF HIGH VELOCITY VACUUM EXHAUST TUBE.

b. Equipment. Special equipment must be utilized, if the best results are to be achieved in the drilling of holes in beryllium sheet and plate material. The tornetic control system is the most important item of equipment. This sytem consists of an automatic torque sensing device which varies both the spindle speed and feed as necessary to maintain the cutting forces within the safe limits of both the drill and the material. This device is capable of compensating for, within limits, the machinability of the workpiece, the condition of the drill, and the break-through characteristic of the hole. This desirable system is manufactured by Dyna Systems, Incorporated, of Torrence, California

Another specific requirement for drilling equipment is that it must be as rigid as possible in order to maintain a constant chip-load for efficient cutting. Beryllium is very abrasive and cutting tools will dull rapidly if glazing, rather than cutting, occurs.

c. Machine Settings. The following standard shop procedure is used for setting the tornetic control device for drilling beryllium with a carbide "burr" type drill bit:

TABLE III

"TORNETIC" CONTROL SETTINGS

Material Gage	Regulator Pressure Lbs.	Over-ride	Torque	Speed	Feed
0.020 - 0.059	18	4	5	6	5
0.060 and Up	18	5	5	5	6

NOTE: These settings are valid for 0.125 to 0.250-inch diameter drills, and are recommended as initial settings only. Adjustments may be required to compensate for variations in material and/or machine conditions.

d. Drills. A special configuration carbide drill is used for drilling beryllium. A preferred grade is Carboloy 883, or equivalent. The major supplier of these drills is the Metal Removal Company of Chicago, Illinois.

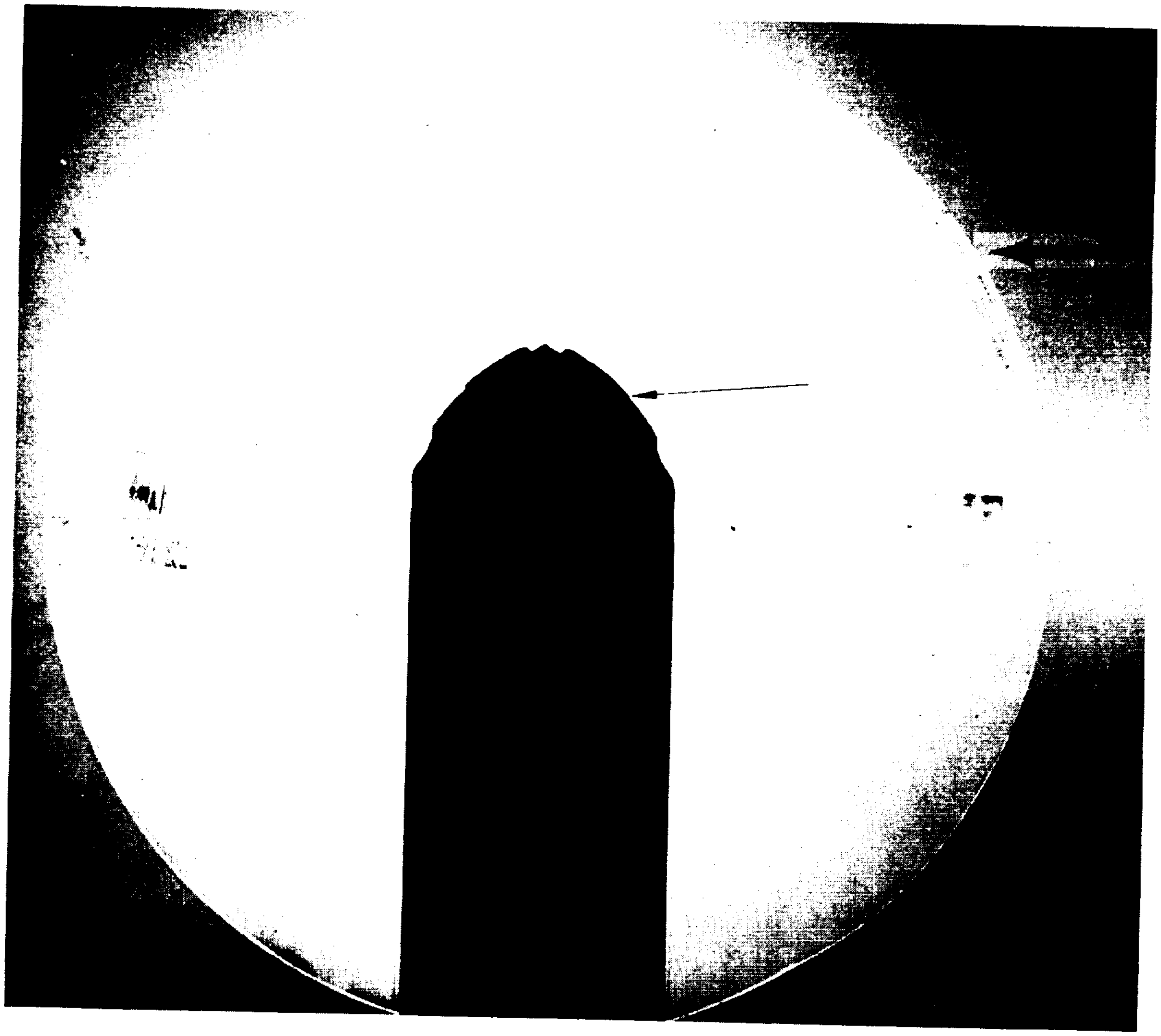
These drills are initially procured and later reconditioned (resharpened) with a "burr" configuration point. This point configuration is similar to that of the point of a ball end mill with two primary cutting lips or edges. In the back relief, secondary and tertiary edges are ground to serve two purposes: (1) To break up the larger chips; and (2) To provide a "safety" cutting edge in the event the primary cutting edge becomes chipped or broken.

Considerable specialized grinding equipment and skilled personnel are required to accurately grind and/or resharpen the "burr" configuration of the solid carbide drill bit. Since the required accuracy of the configuration is critical and the tolerances are very "tight," it is felt that the supplier should perform both the initial grind and the subsequent re-grinds of the drills.

e. Receiving Inspection. Critical receiving inspection procedures are required. Two methods of inspecting the drill geometry and verifying the tolerances are being used: (1) A plastic overlay on a comparator; and (2) A microscope incorporating a special rotary table.

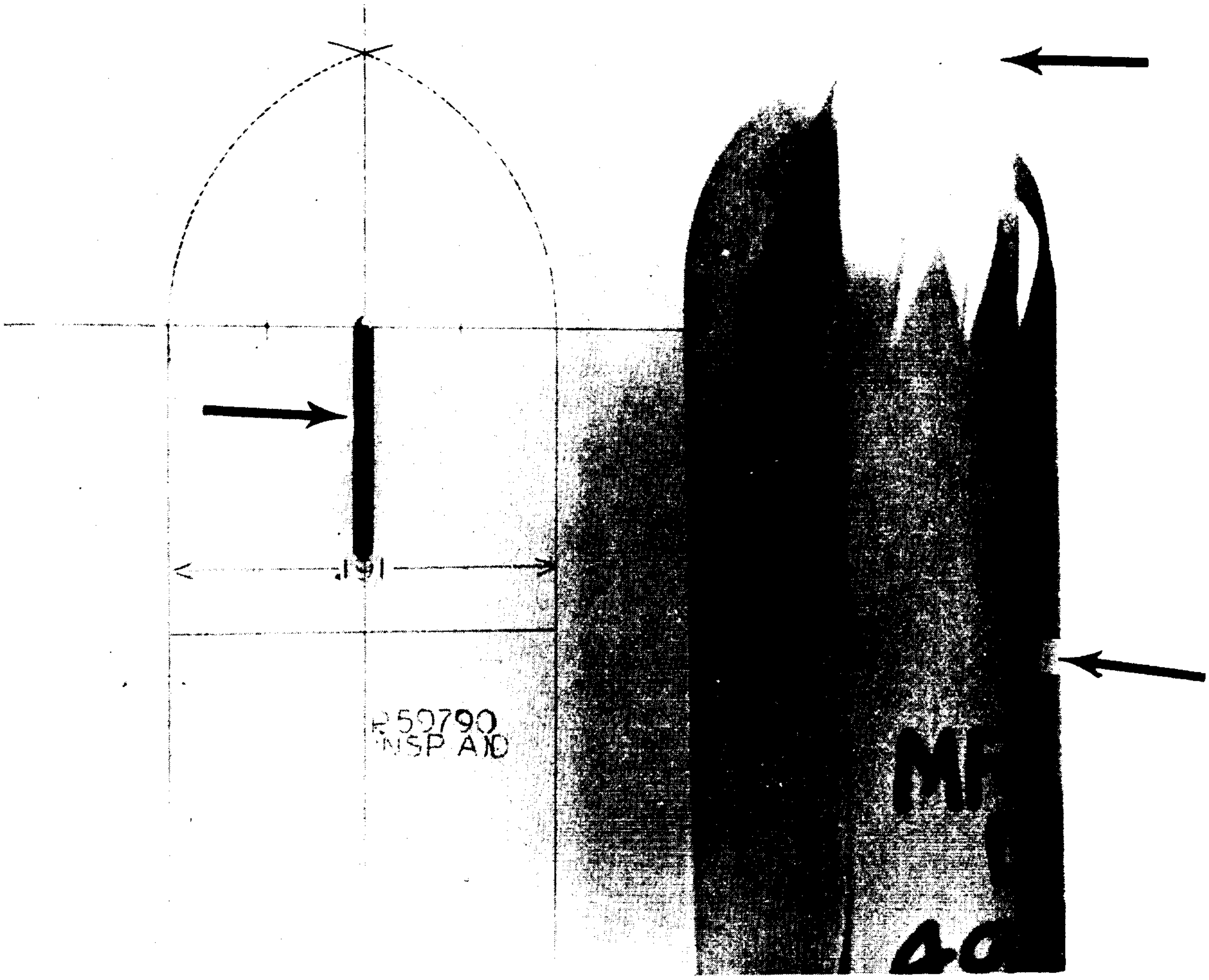
The clear plastic overlay, used with the comparator, is 20X size. If the drill shadow fits the overlay, the point, radius, and diameter are acceptable. The burr points are also inspected at this time; a maximum burr point height of 0.001 inch above the primary edge is permitted. (Figures 13 through 16.)

The drill web thickness, the chisel point angle and thickness, the point cross-over gash, the burr point angle of relief, the primary cutting edge, the land width and the angle of clearance are measured with a microscope (Figure 17) using a rotary table. Figures 18 through 26 illustrate the magnified views of the various reasons for the rejection of drills.



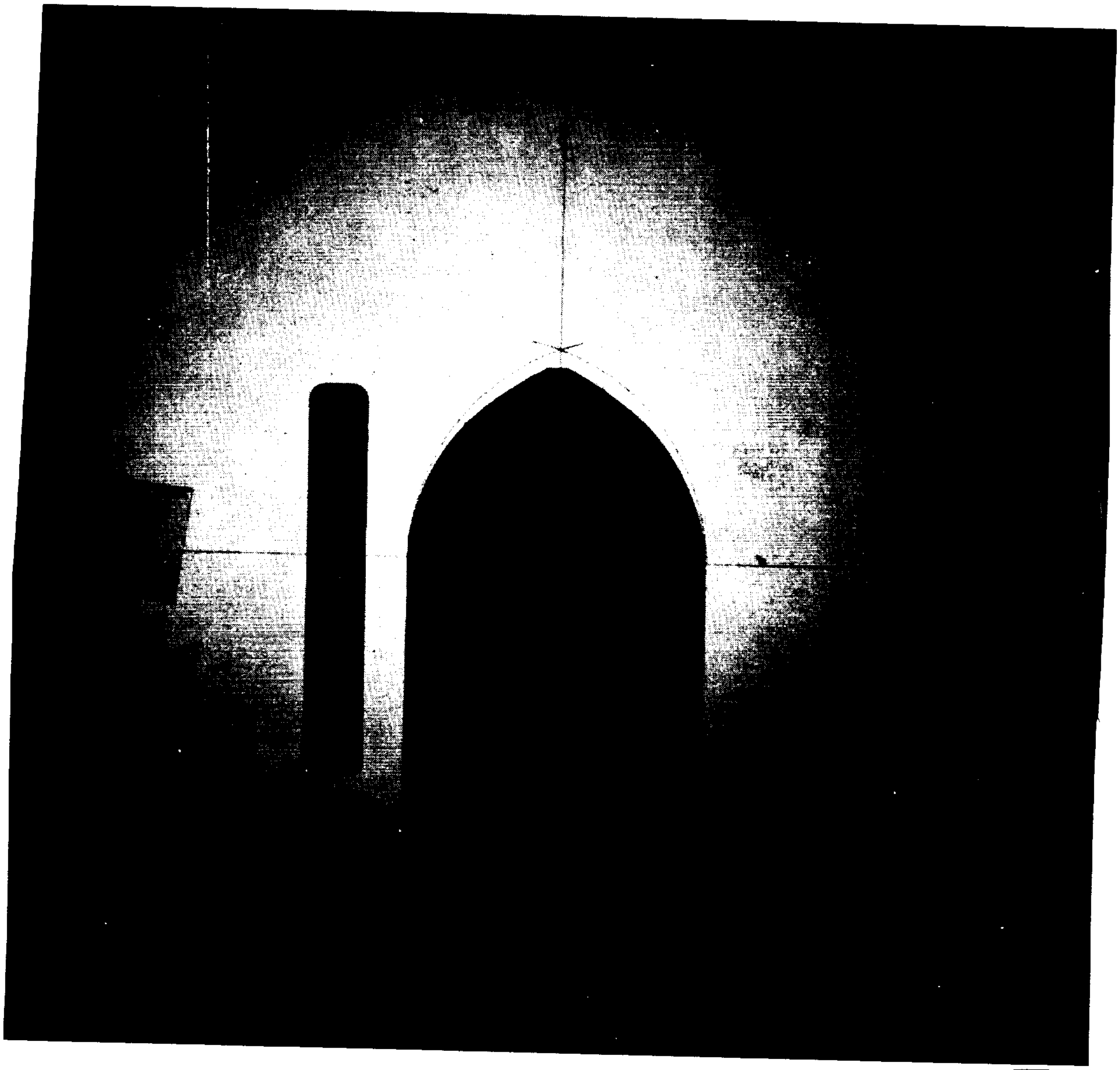
(20X)

FIGURE 13. BURR-POINT DRILL SHADOW FITTED INTO MASTER OVERLAY ON A COMPARATOR



(20X)

FIGURE 14. VIEW OF COMPARATOR MASTER OVERLAY, ACTUAL SIZE OF BURR-POINT DRILL AND ENLARGED WOODEN MODEL OF BURR-POINT DRILL USED AS VISUAL AID



(20X)

FIGURE 15. BURR-POINT DRILL TURNED TO CAST SHADOW OF BOTH PRIMARY CUTTING EDGES, SHADOW IS FITTED INTO MASTER OVERLAY MOUNTED ON A COMPARATOR TO READ RADIUS, CONCENTRICITY AND DIAMETER

FIGURE 16. BURR-POINT DRILL INSPECTED ON A COMPARATOR. CHECKING UNIFORMITY OF BURR GASHES, DEPTHS AND RADIUS OF POINT.(20X)

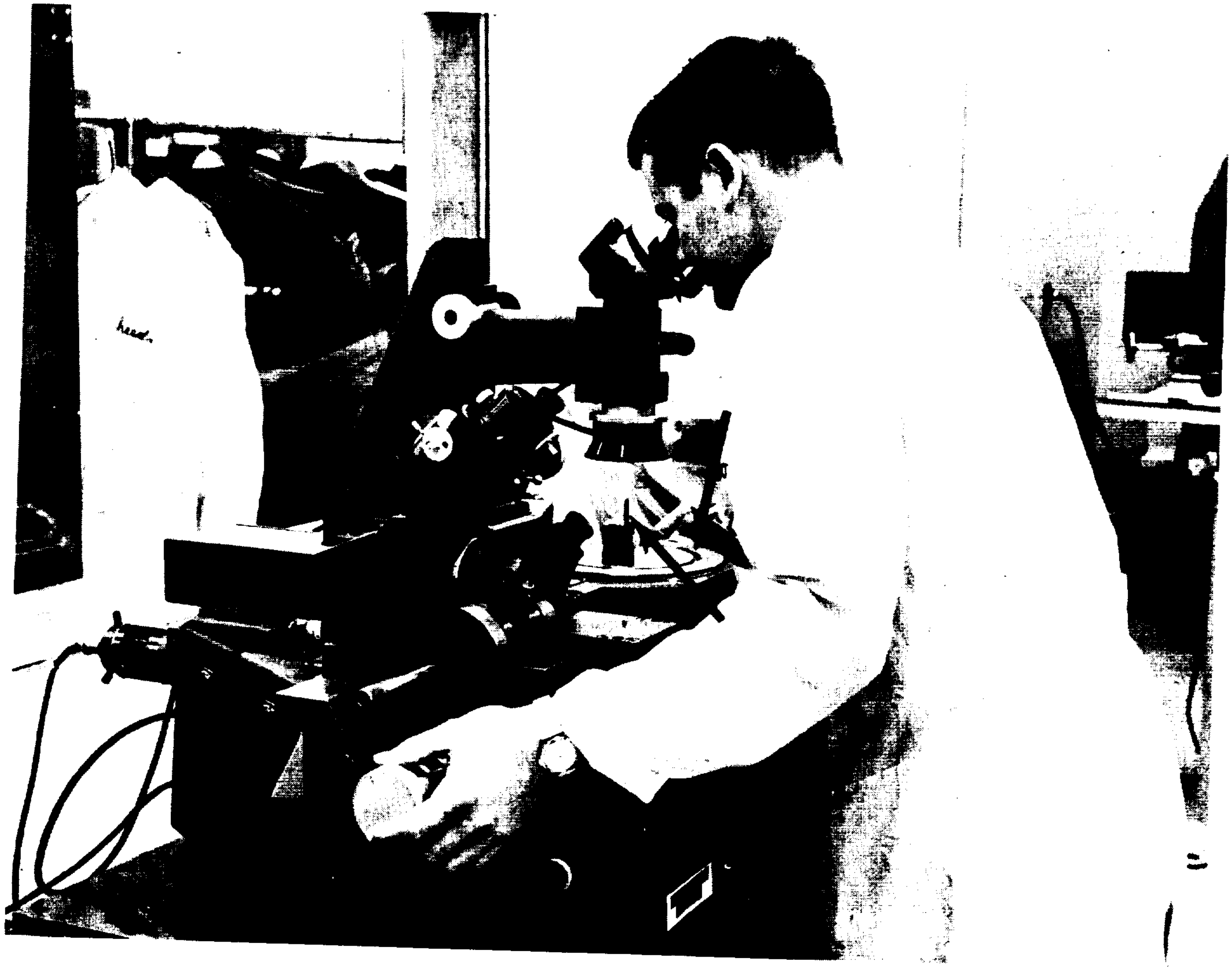


FIGURE 17. BURR-POINT DRILL BEING INSPECTED ON A MICROSCOPE WITH SPECIAL ROTARY TABLE

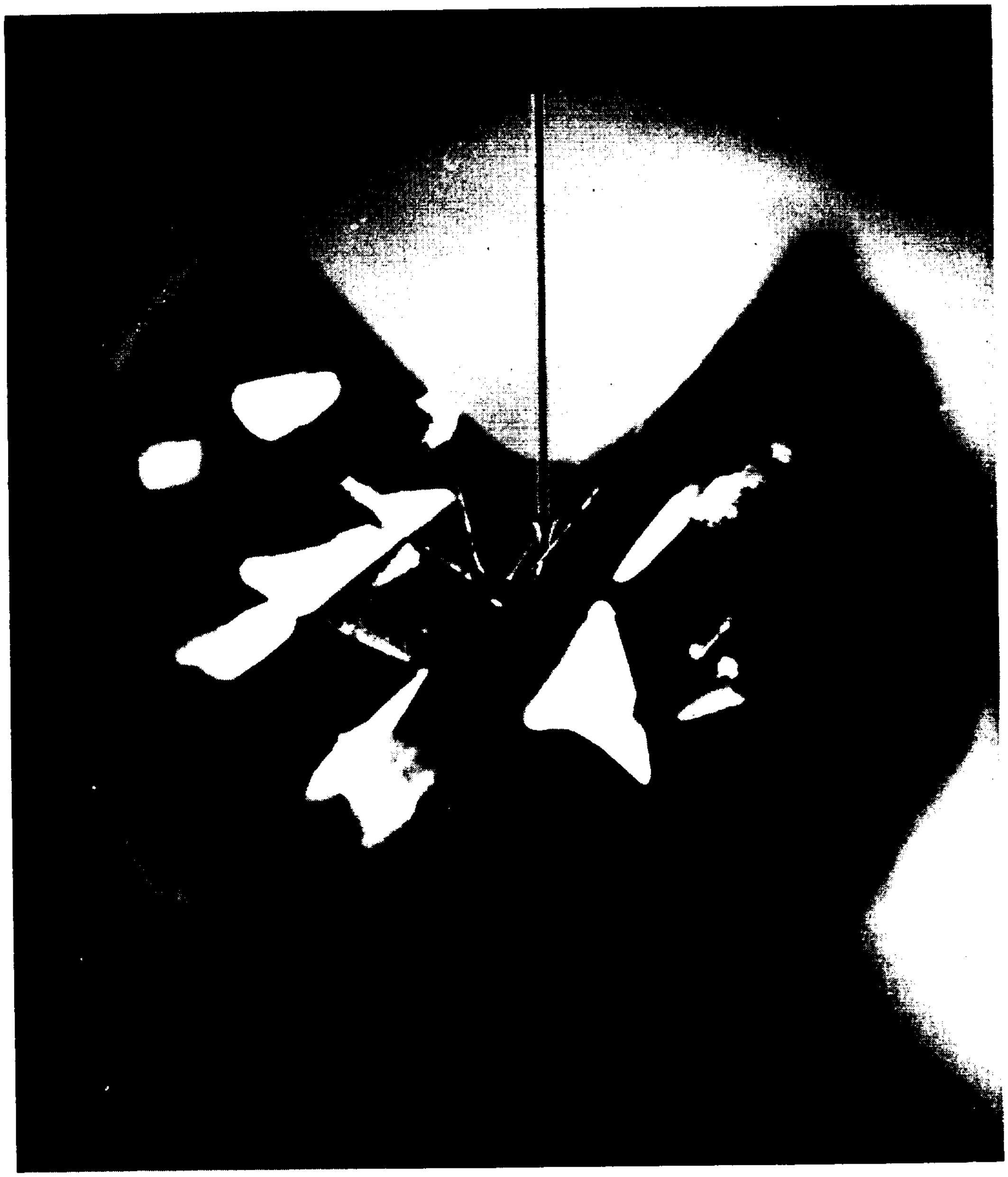


FIGURE 18. ENLARGED MICROSCOPIC VIEW OF BURR DRILL POINT SHOWING FLAT SPOT AT CHISEL POINT PROGRESSING ALONG RIGHT PRIMARY CUTTING EDGE

FIGURE 19. ENLARGED MICROSCOPIC VIEW OF BURR DRILL POINT SHOWING GASHES ALLOWED TO PROGRESS INTO PRIMARY LANDS AND THROUGH ONE (1) PRIMARY CUTTING EDGE

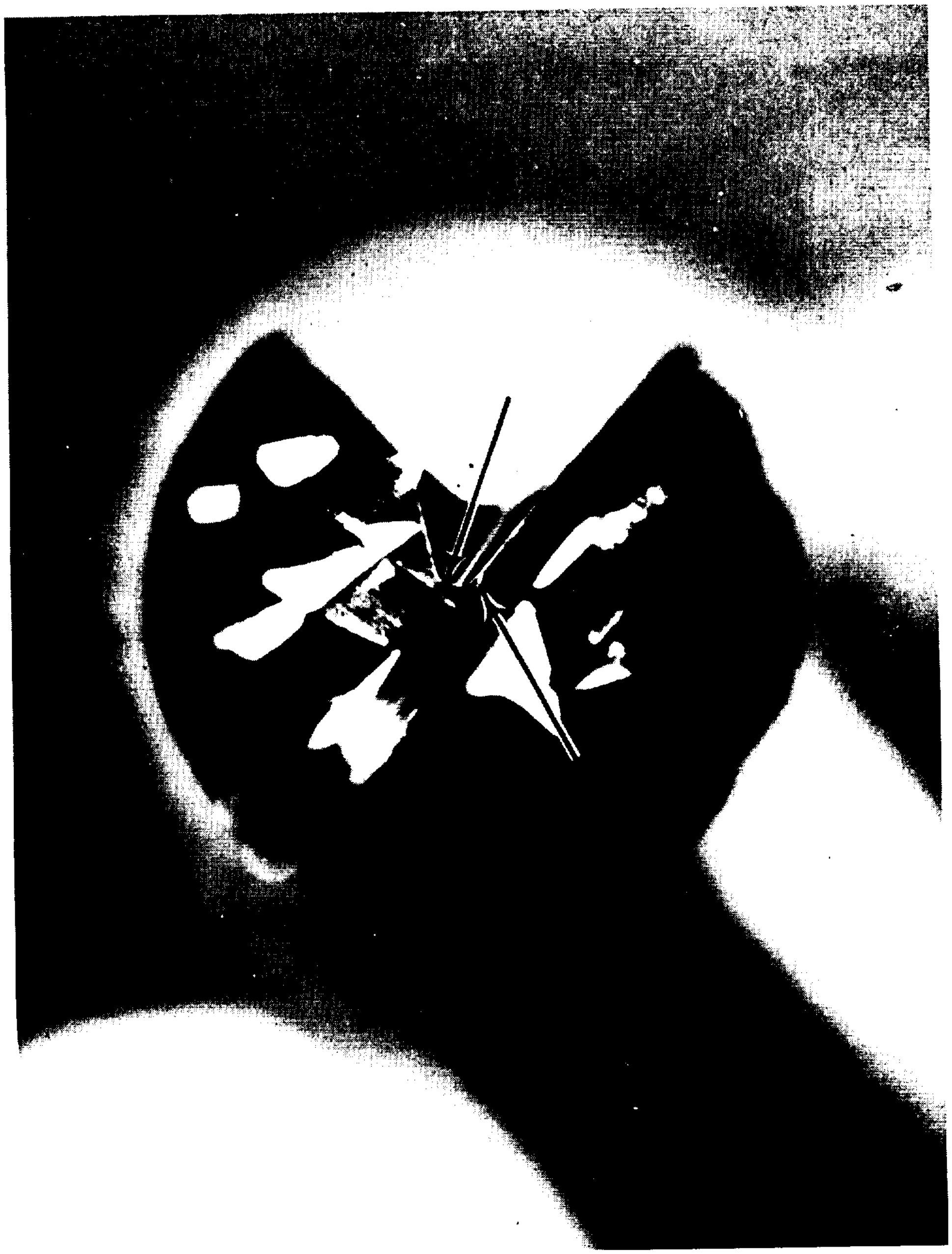


FIGURE 20. ENLARGED VIEW OF BURR DRILL POINT SHOWING FLAT SPOT AT CHISEL POINT OF PRIMARY CUTTING EDGE. WEAK BURR POINT AT CHISEL POINT, LEFT SIDE

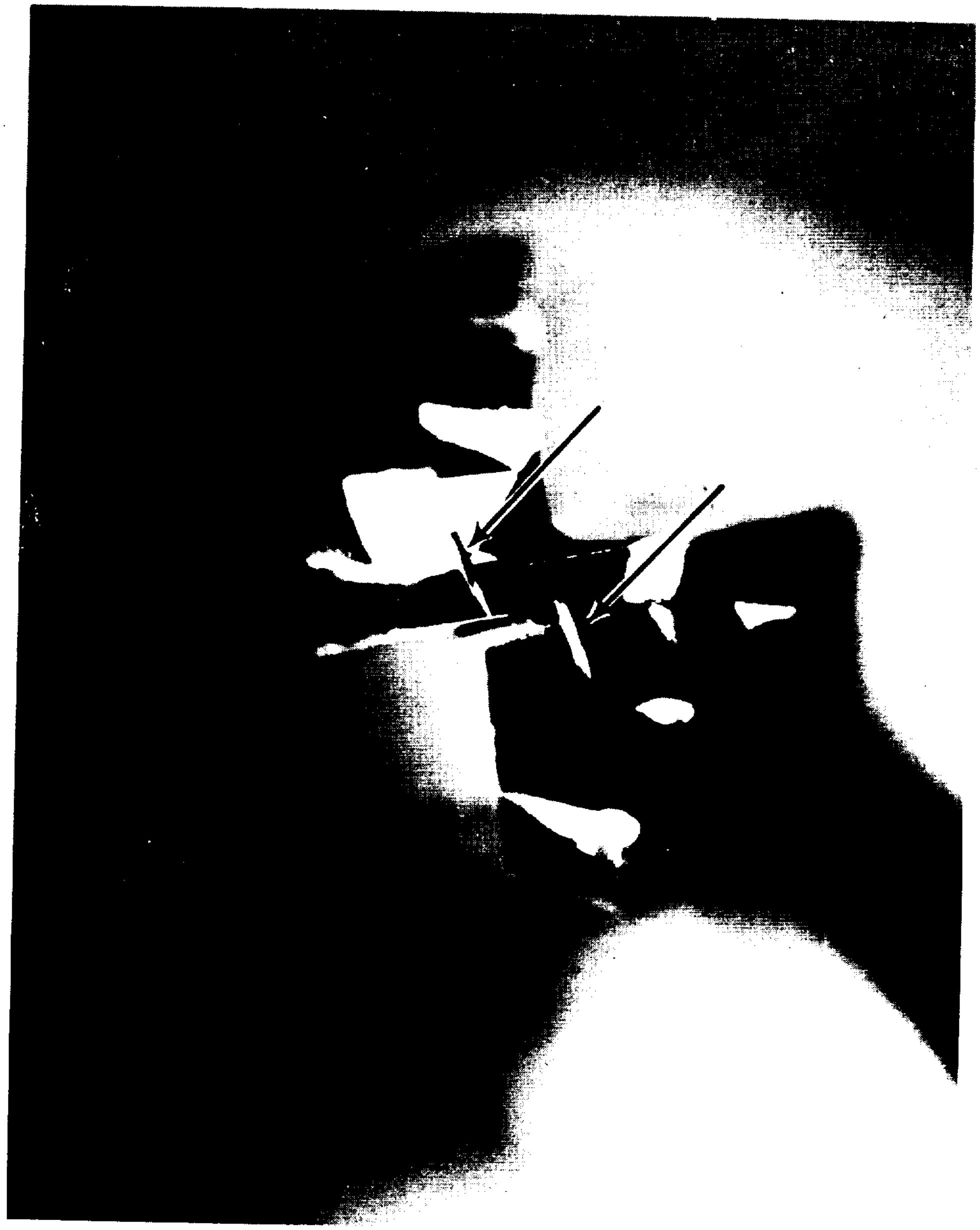


FIGURE 21. ENLARGED MICROSCOPIC VIEW OF BURR DRILL POINT SHOWING GASHES ALLOWED TO PROGRESS INTO BOTH PRIMARY LANDS

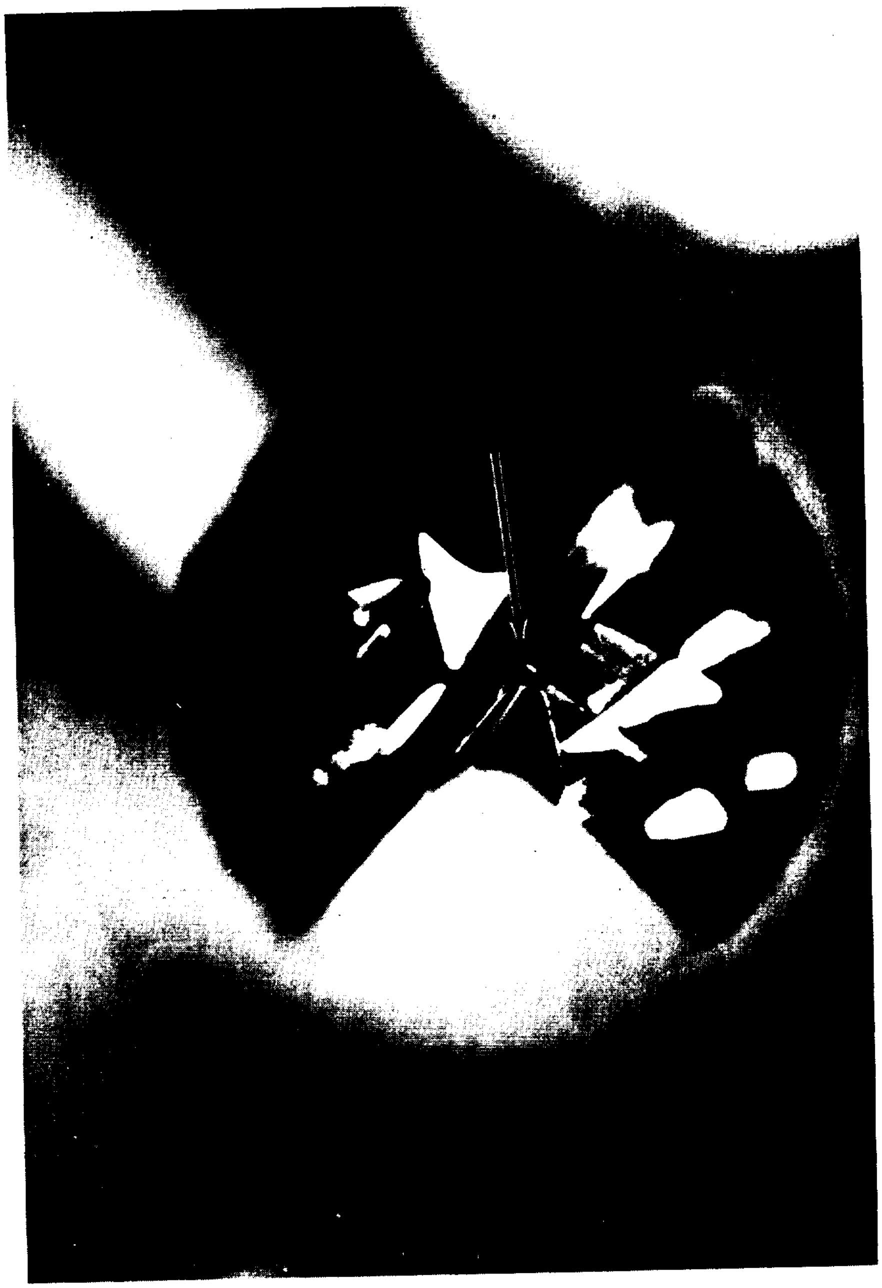


FIGURE 22. ENLARGED MICROSCOPIC VIEW OF BURR DRILL POINT SHOWING GASH PROGRESSED INTO PRIMARY LAND NEAR CHISEL POINT AND IN SUCH A MANNER AS TO WEAKEN TRAILING BURR TO CAUSE FRACTURE

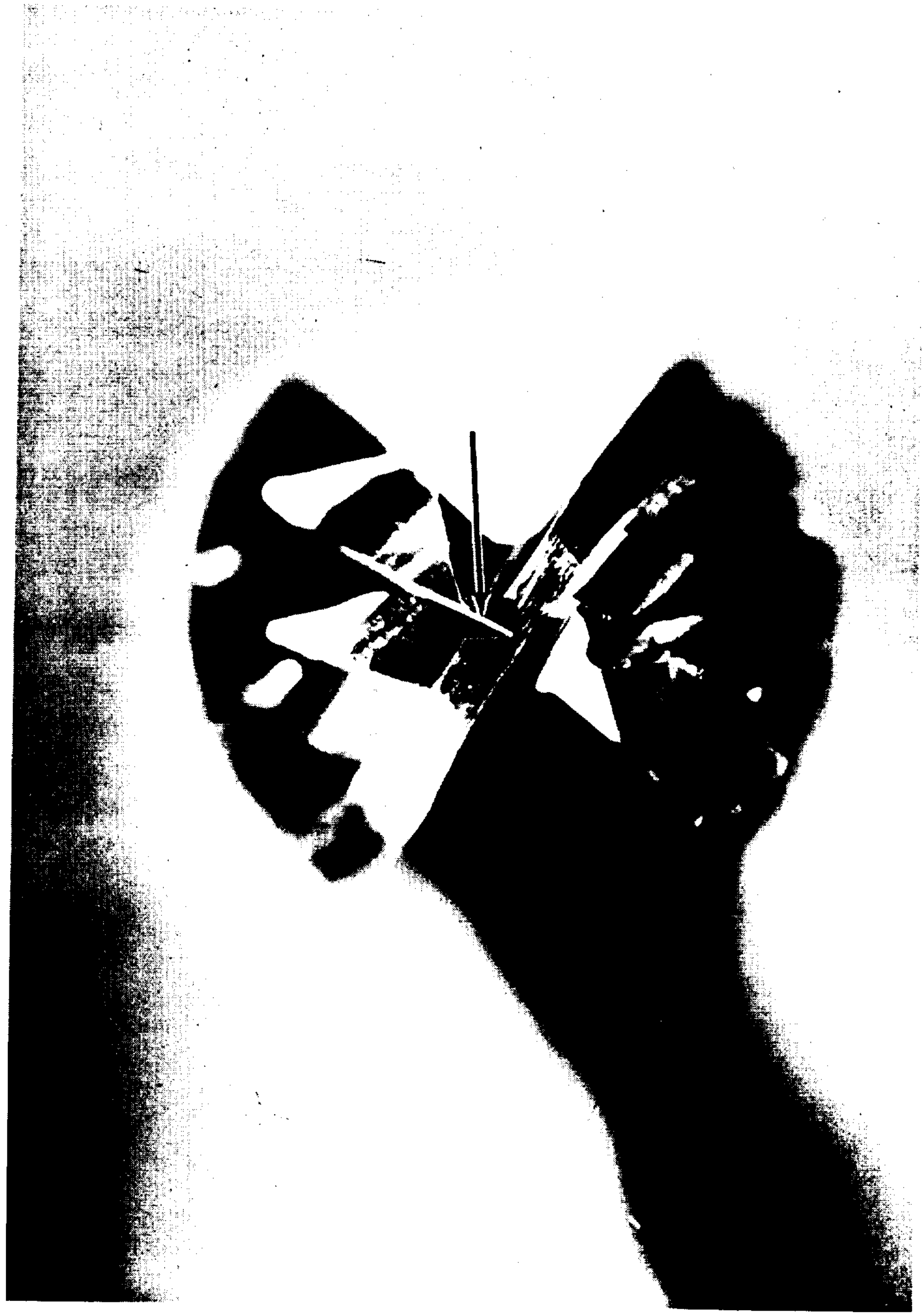


FIGURE 23. ENLARGED MICROSCOPIC VIEW OF BURR DRILL POINT SHOWING GASH WAS ALLOWED TO PROGRESS INTO PRIMARY LAND AT CHISEL POINT

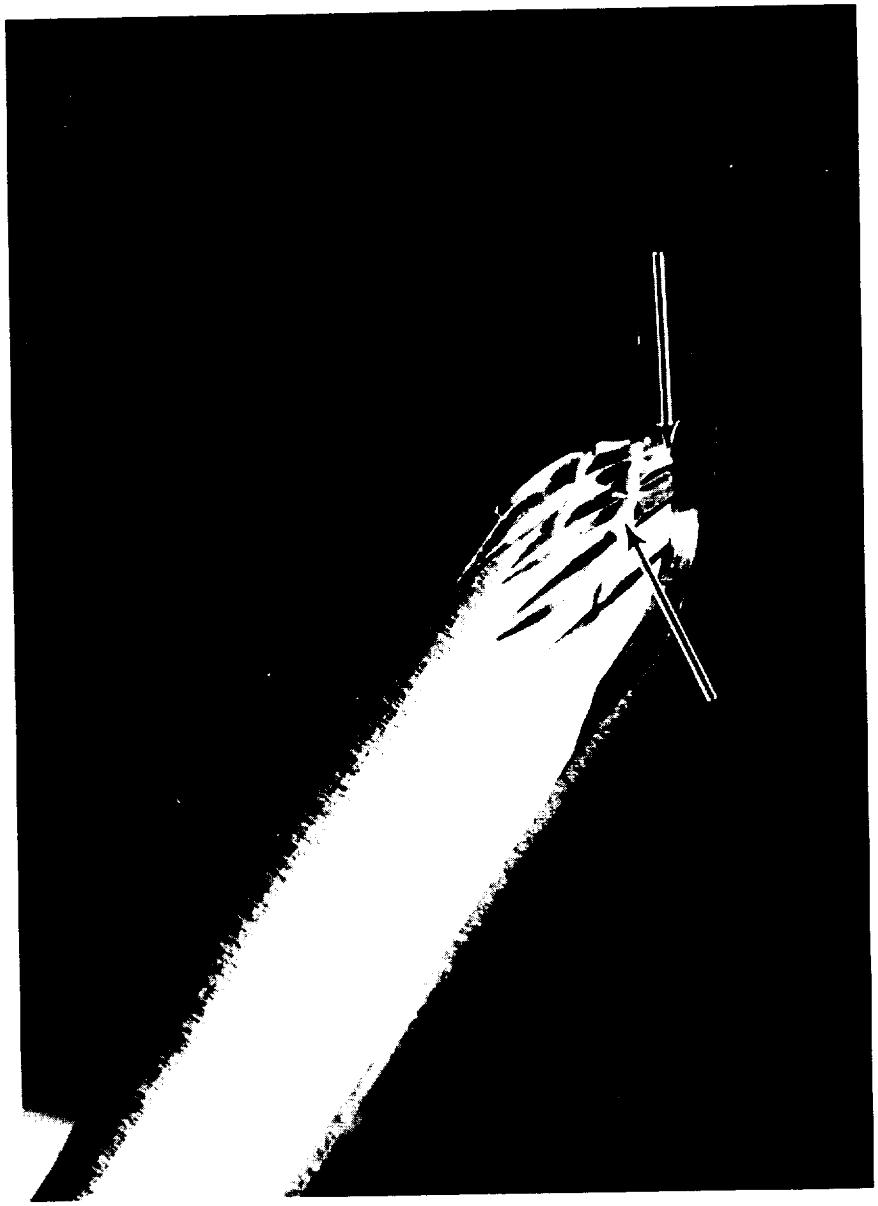


FIGURE 24. ENLARGED VIEW OF BURR POINTS AND RELIEF ANGLES

FIGURE 25. ENLARGED VIEW OF PRIMARY CUTTING EDGE AND LENGTH AND DEPTH OF GASH FOR CROSS-OVER OF POINT

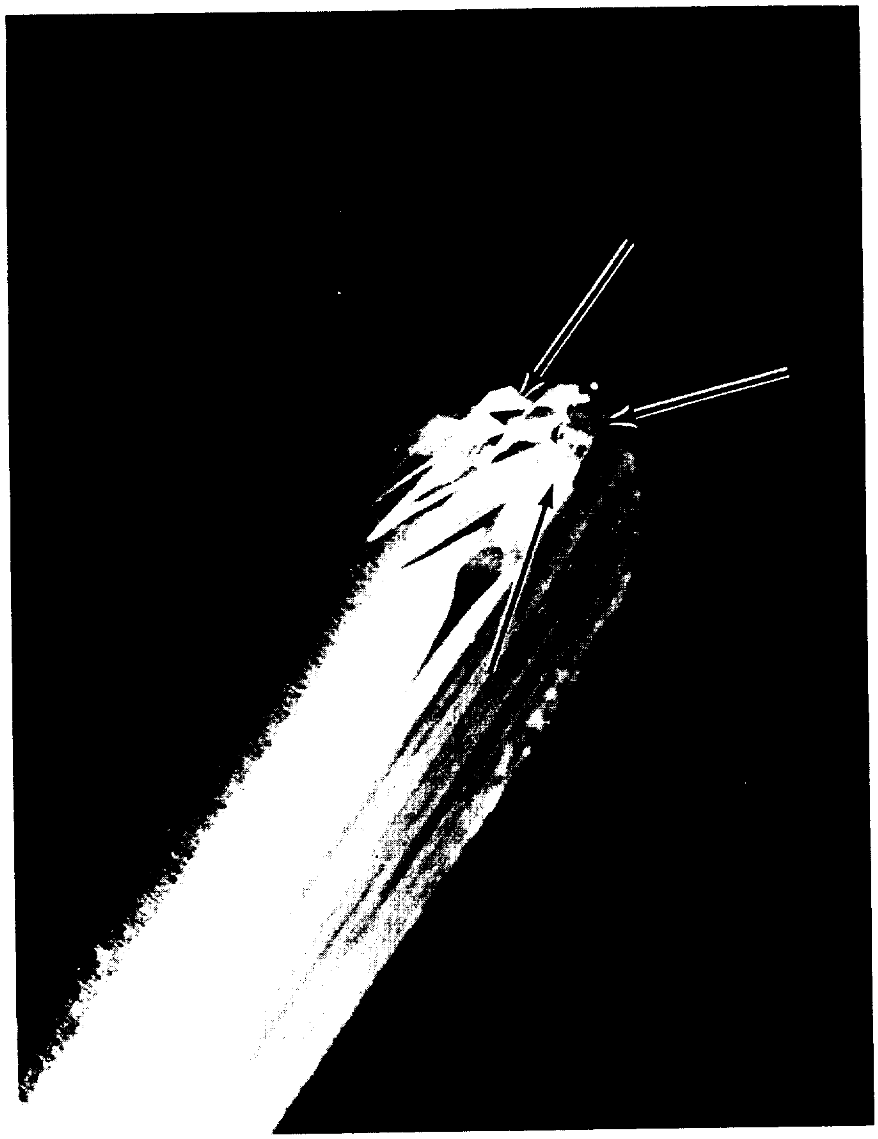


FIGURE 26. ENLARGED VIEW OF ANGLES OF BURR-DRILL POINTS, PRIMARY CUTTING EDGE AND ANGLE OF RELIEF OF PRIMARY LAND

The adoption of these inspection procedures has resulted in the elimination from production use of all drills having any tendency to fracture. Since these rigid inspection procedures were established, the production shop has been able to drill several hundred acceptable holes per drill before regrinding was necessary.

f. Shop Operation. The standard shop operating procedure for drilling holes is as follows:

(1) Handle carbide drills with care to avoid accidental dulling. Protect by storing in individual containers. Segregate dull drills from sharp ones. Avoid dropping drills on hardened surfaces.

(2) Select the drill diameter 0.002 inch under the required finished hole diameter to allow for the subsequent chemical etching.

(3) Install the drill in the spindle chuck, and set the micro depth stop to prevent accidentally drilling into the jig or table.

(4) Exercise care to avoid misaligning the drill in the hardened steel drill bushing when locating the hole under the spindle.

(5) Test drill five or more holes in scrap pieces of beryllium to check the drill grind, hole diameter, finish, etc., before drilling a production piece.

(6) Stop frequently and examine the drill for dulling and/or chipping on cutting edges.

(7) Start the drilling operation by pressing the "cycle" button. Hold the button depressed for rapid traverse. Release the button to stop the rapid traverse, and to automatically engage the spindle feed. (Exercise care to avoid the rapid traversing of the drill point into the work.)

(8) DO NOT use coolants in drilling operations.

(9) The spindle will retract automatically when it reaches the preset depth of cut and trips the microswitch. In case of any malfunction, press the red "Retract" button, and the drill will be withdrawn immediately from the work.

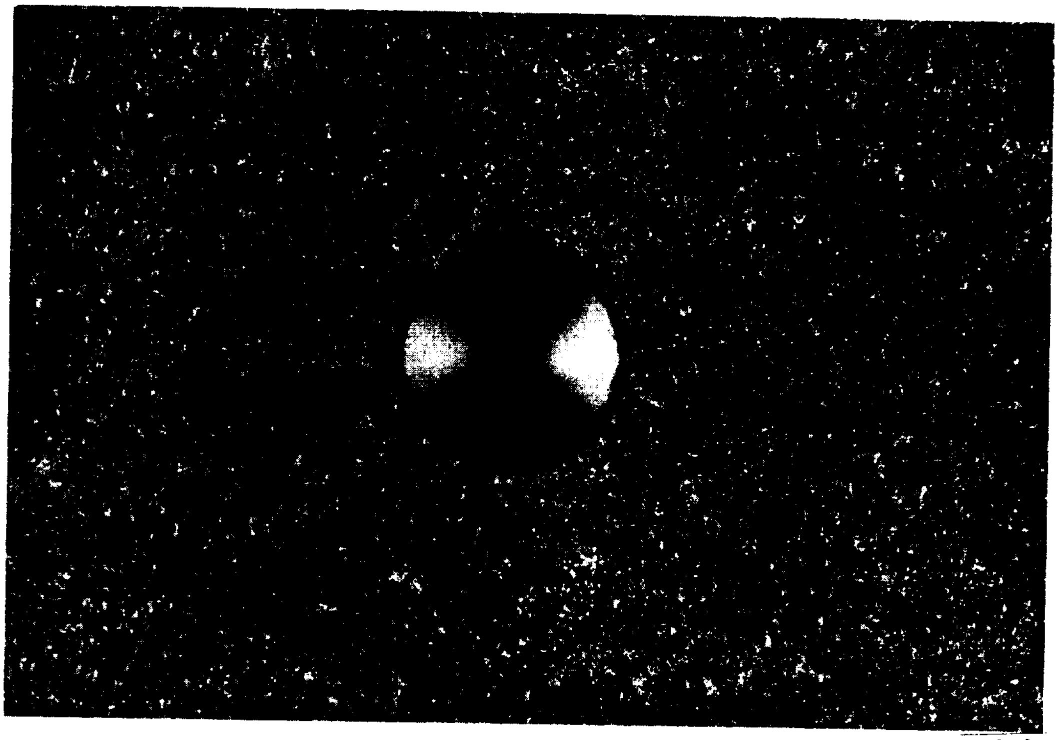
(10) After drilling, deburr the holes by wet or dry sanding, or by chamfering the hole with a carbide countersinking tool.

g. Hole Location and Bushings. In most drill jigs, the hole location is accomplished by means of pressed-in hardened steel inserts and slip bushings. The axis of rotation must be aligned perpendicular to the workpiece to avoid side stresses. Because of the abrasive character of beryllium, even hardened drill bushings are subject to wear and must be replaced periodically to maintain accurate hole location.

h. Tool Proving and Maintenance. Due to the abrasive characteristics of beryllium, the use of standard procedures for the initial proving and routine maintenance of tooling is mandatory. It is recommended that the fabrication of the first production pieces on a new tool be witnessed by the tool designer. The existence of any slight dimensional deviations, within the allowable tolerances, can be noted and recorded. Periodic inspections at regular intervals, based on past experience and wear records, should be made. Any dimensional changes should be recorded and any necessary repairs should be made. Rigid conformance with such procedures will preclude most, if not all, rejections due to tooling error.

4. Failure Analysis. In spite of the development of the previously described "burr" type drill and the rigid drilling and inspection procedures, drilling failures still may occur. Therefore, additional holes were drilled incorrectly to intentionally cause failure in one or more of the three basic modes which are: radial cracking, internal delamination, and spalling. For comparison, a correctly drilled hole is illustrated in Figures 27, 28, and 29.

The relative quality of the surface finish of the hole edge, and of the "as-received" material, is graphically shown in Figures 27 and 28. The absence of burring and the presence of only minute irregularities, which are removed during the subsequent etching operation, should be noted. A description



(10X)

FIGURE 27. CORRECTLY DRILLED HOLE USING RECOMMENDED PROCEDURES. EXIT SIDE (UNETCHED)

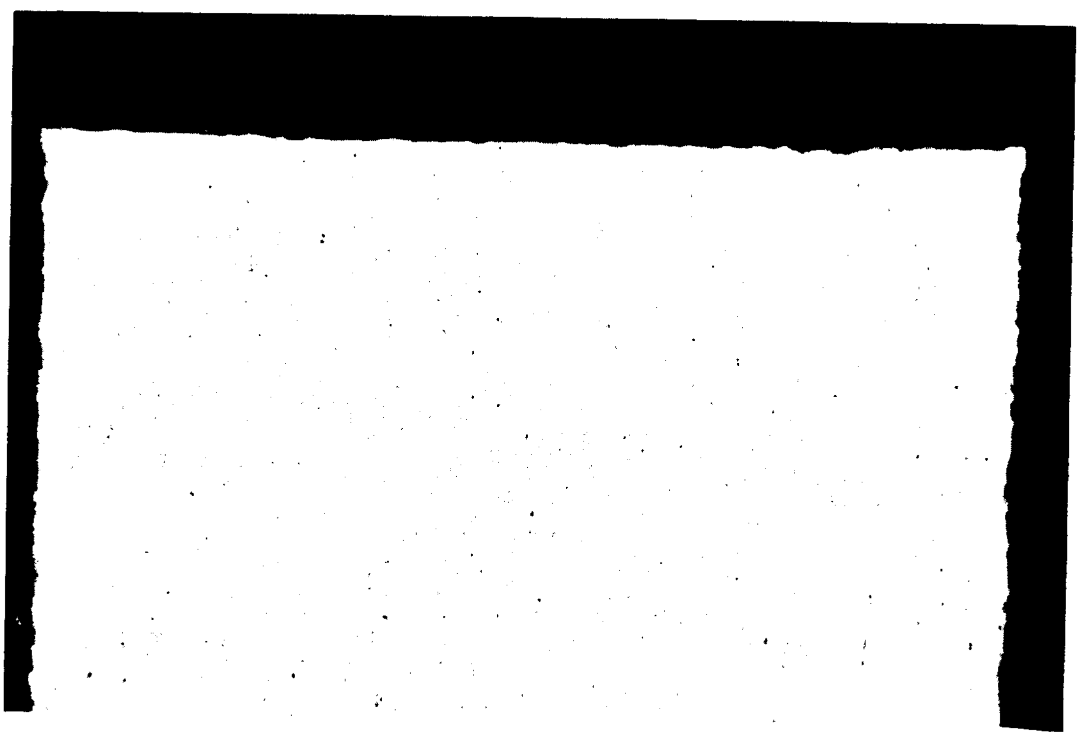


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FIGURE 28. CROSS-SECTION THROUGH GOOD HOLE USING RECOMMENDED PROCEDURES (UNETCHED)

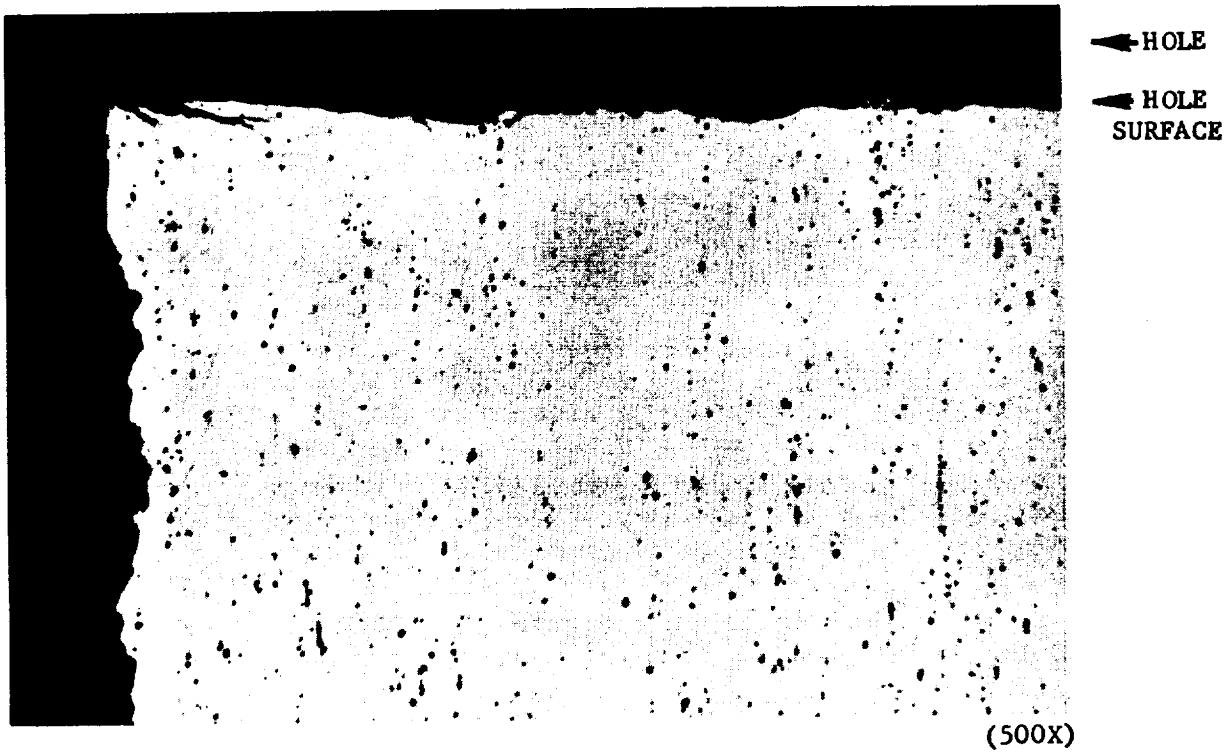


FIGURE 29. CROSS-SECTION THROUGH GOOD HOLE - MINOR TWINNING EVIDENT (UNETCHED)

of each type of defect, and its probable cause, is presented as follows:

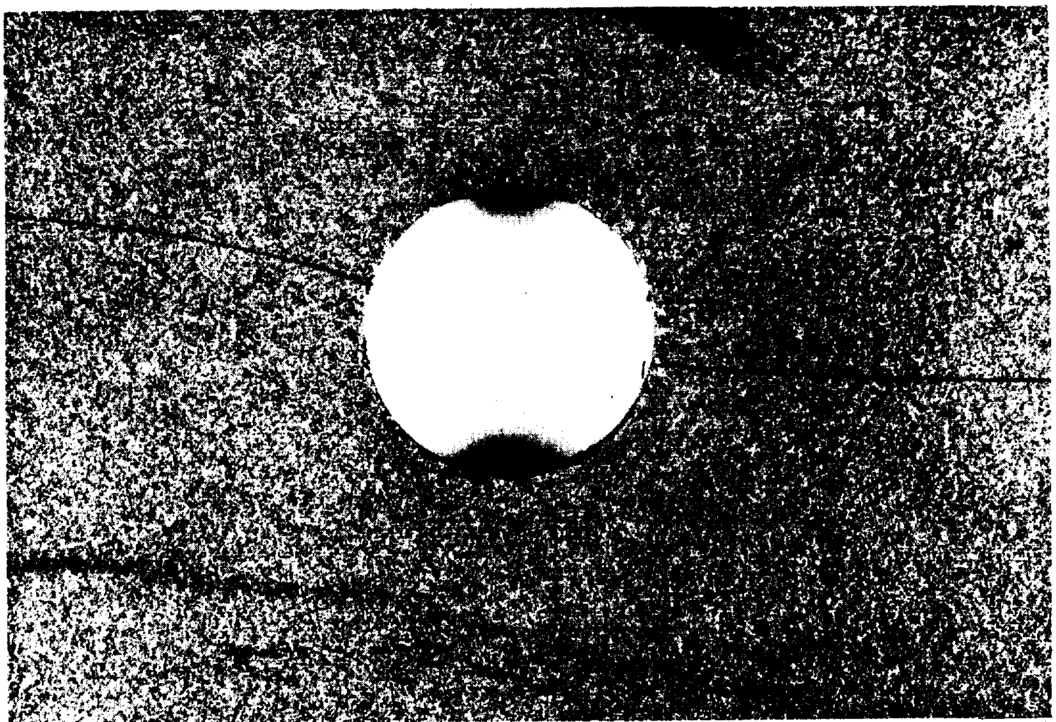
A radial crack is a surface crack which extends outward from the hole. Figures 30, 31, 32, and 33 illustrate this type of defect. This type of failure usually is located on the (exit) surface, opposite the drill feeding force, and is the result of the workpiece yielding to this force. In order to deliberately produce this defect, a dull drill and excessive feeding force were used. The surface condition of the resulting hole is illustrated in Figures 34, 35, and 36. Reducing the feed rate, increasing the drill speed (rpm), using a sharp drill, and providing the proper firm support for the workpiece usually will correct this condition.

Internal delamination is the designation for intergranular separation along basal planes, and, therefore, is in the plane of the material. Figures 6, 37, and 38 illustrate this type of defect. Such cracks usually are the result of using either an extremely dull drill or one with a broken cutting lip. Either type of drill generates side pressure through chip compaction. Repeated deflections of the workpiece also can result in this type of defect. Again, using sharp drills and providing the proper firm support for the workpiece will prevent this condition.

The term spalling refers to the flaking or cracking-out of the metal around the periphery of the hole on the exit surface of the workpiece. Figures 39, 40, and 41 illustrate this type of defect. When the drill "breaks through" the workpiece, the resistance to the drill feeding force is suddenly relieved and, unless the drilling force also is quickly decreased, the drill will surge through the workpiece and cause spalling of the hole. This defect can be avoided by the proper use of the tornetic control system.

E. ABRASIVE WHEEL CUTTING

1. Present Capability. The cutting of beryllium by means of an abrasive wheel is a relatively long-established and well-qualified production method. It is the preferred method for making straight-edge cuts whenever the workpiece configuration will permit the necessary approach and over-travel required for the circular wheel. A typical example of the newly acquired



(10X)

FIGURE 30. HOLE DRILLED WITH DULL DRILL SHOWING RADIAL CRACKING (UNETCHED)

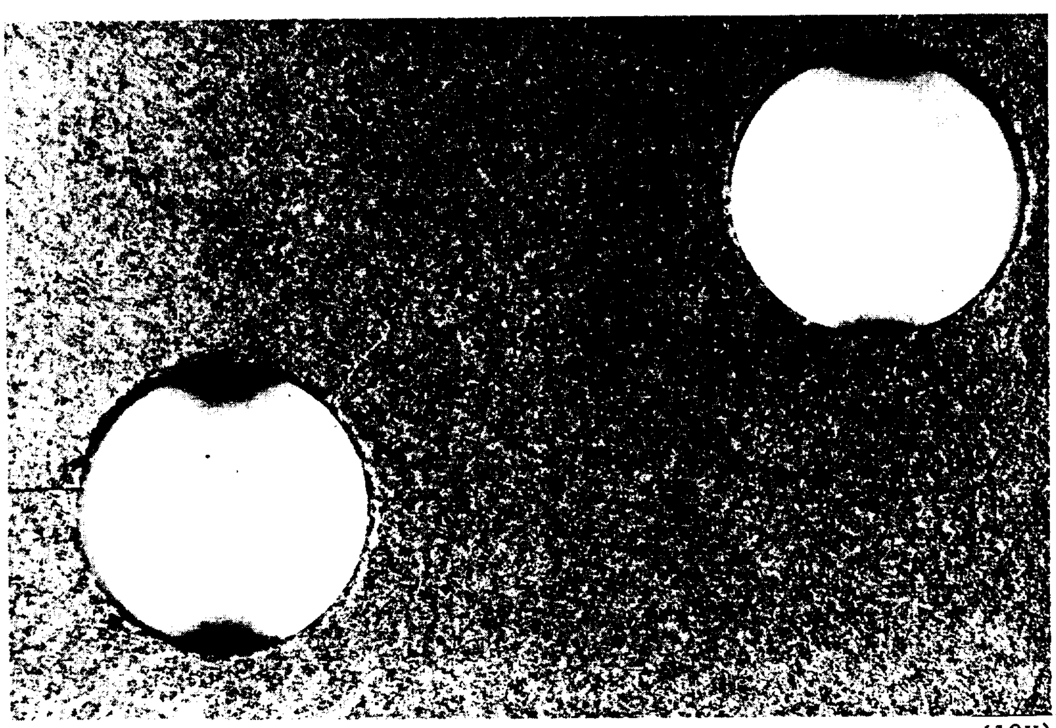


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FIGURE 31. HOLE DRILLED WITH DULL DRILL SHOWING RADIAL CRACKING AND BRIDGING FROM HOLE TO HOLE

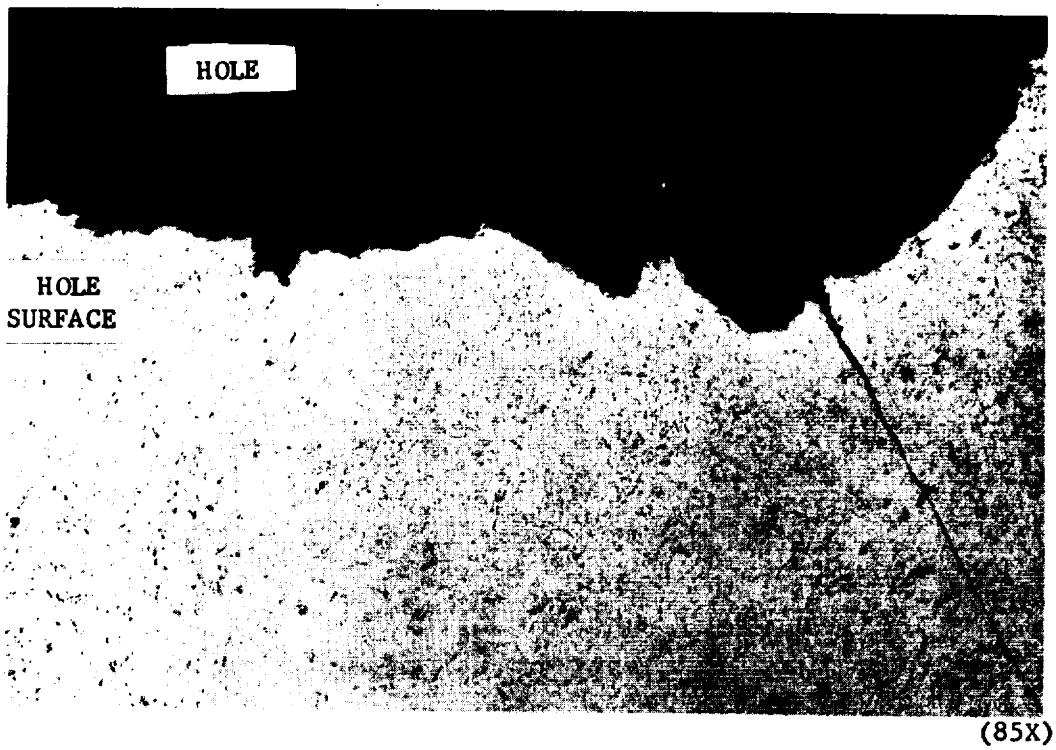


FIGURE 32. HOLE DRILLED WITH DULL DRILL, SURFACE OF SHEET SHOWING RADIAL CRACK EMINATING FROM ROUGH SURFACE OF HOLE - (UNETCHED)

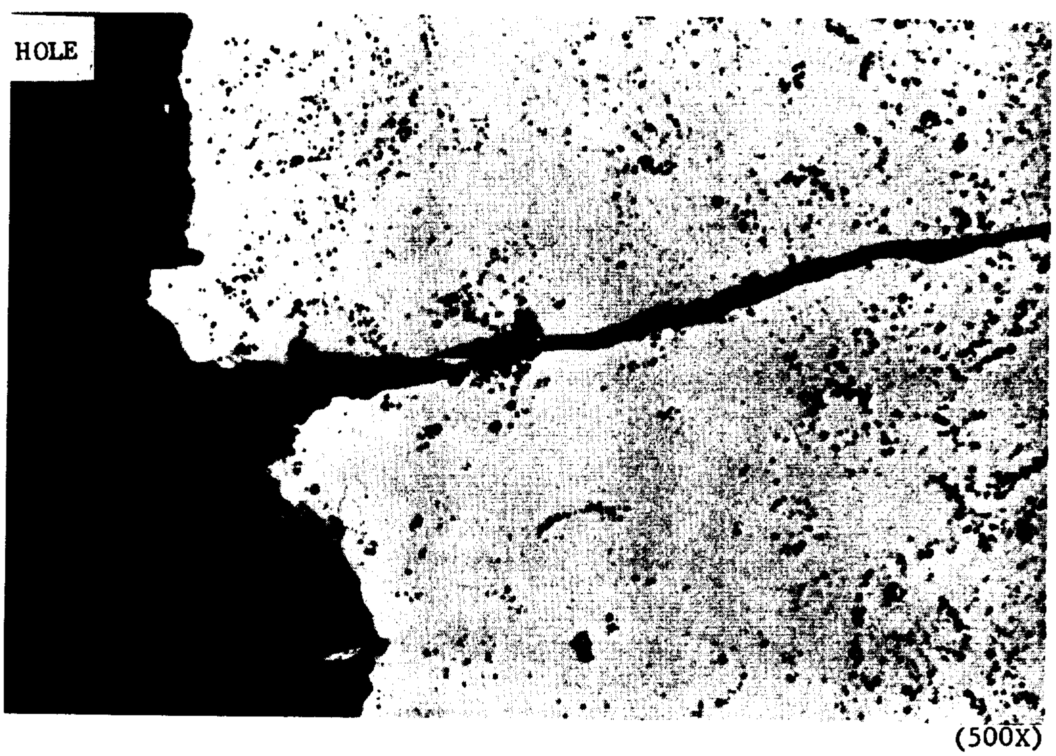


FIGURE 33. HIGH MAGNIFICATION OF RADIAL CRACK CAUSED BY DRILLING HOLE WITH DULL DRILL

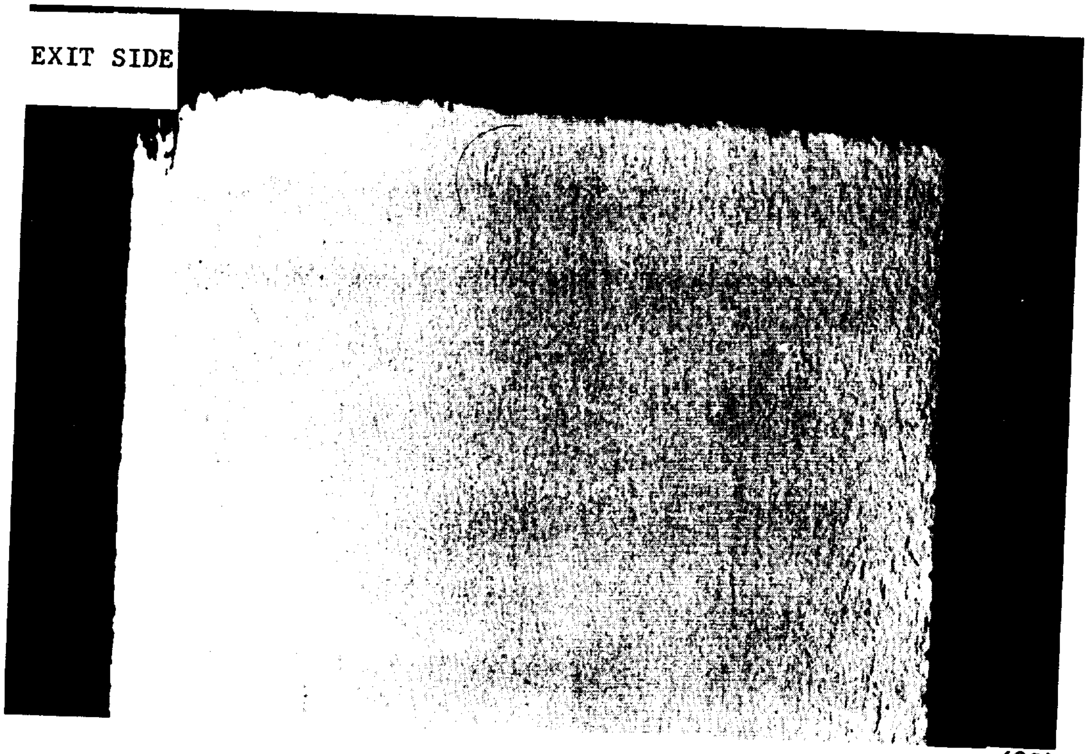


FIGURE 34. CROSS-SECTION OF HOLE DRILLED WITH DULL DRILL (UNETCHED)

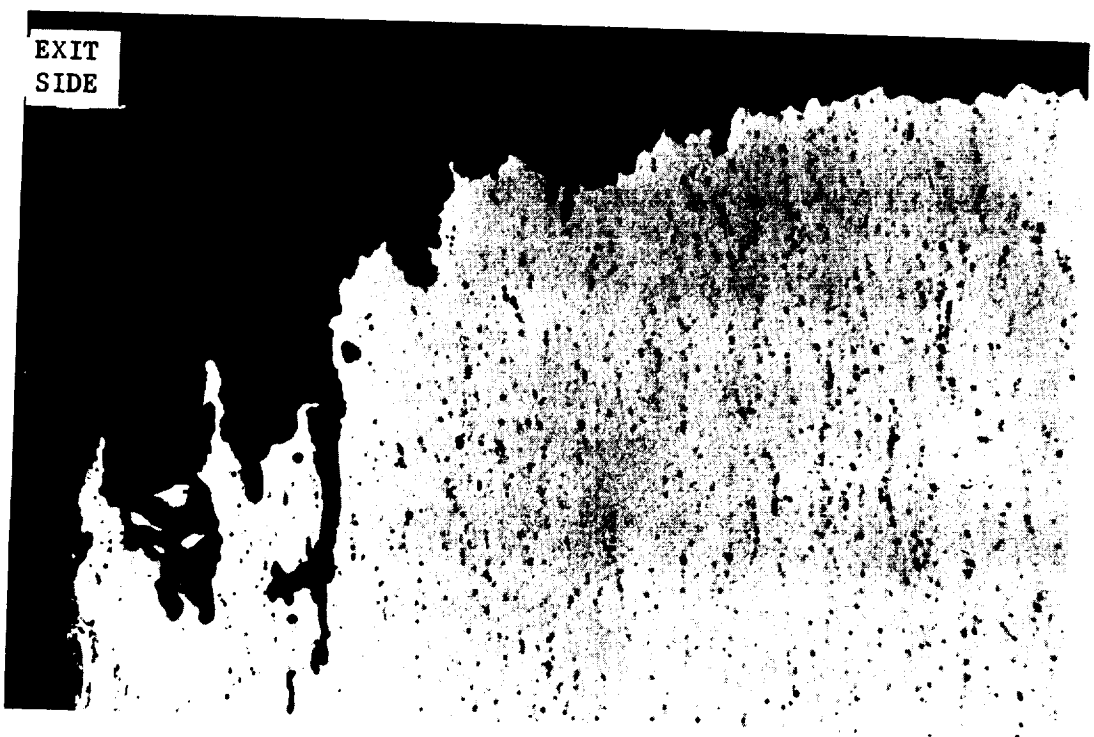


FIGURE 35. CROSS-SECTION OF HOLE DRILLED WITH DULL DRILL SHOWING SPALLED EDGE (UNETCHED)

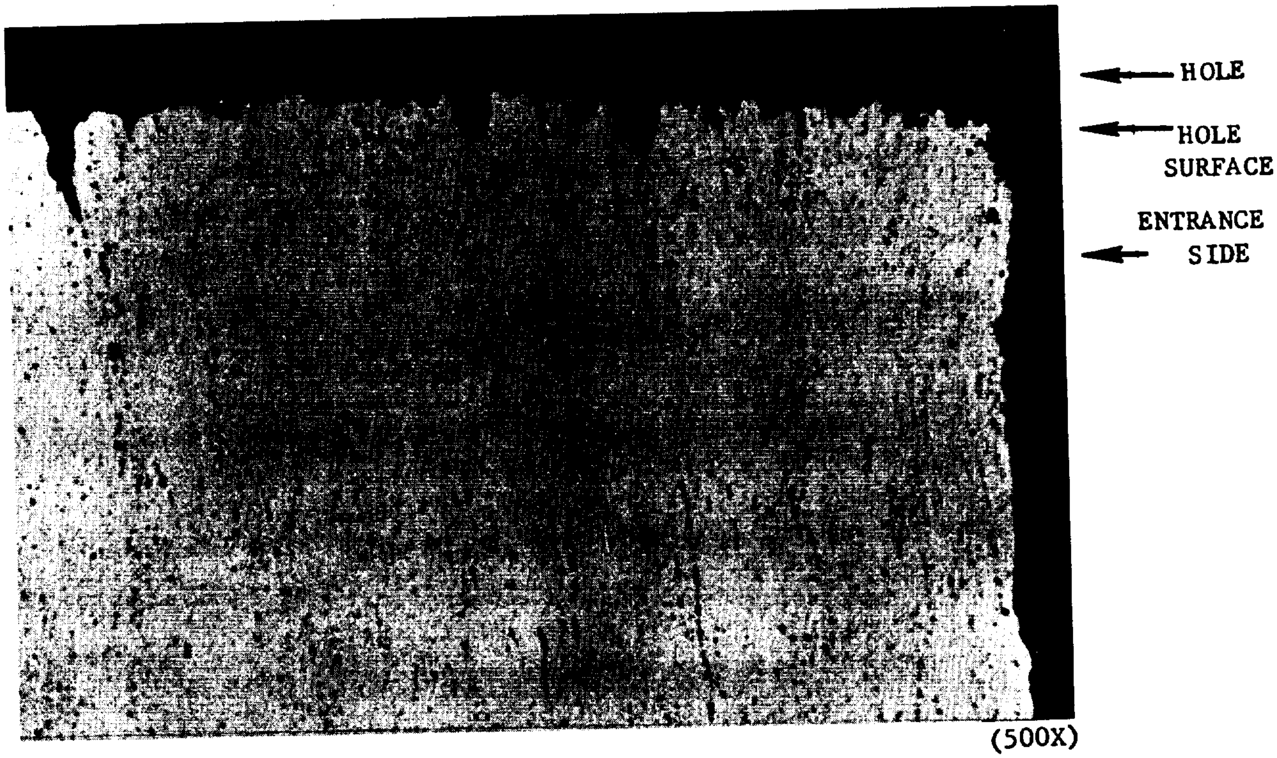
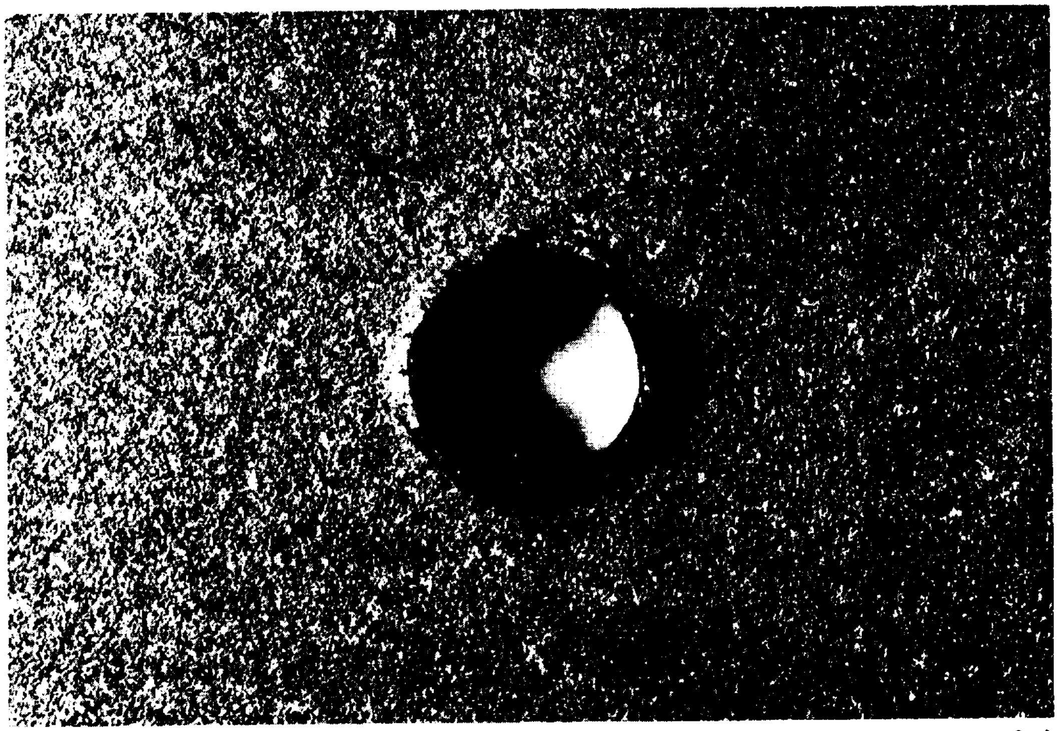
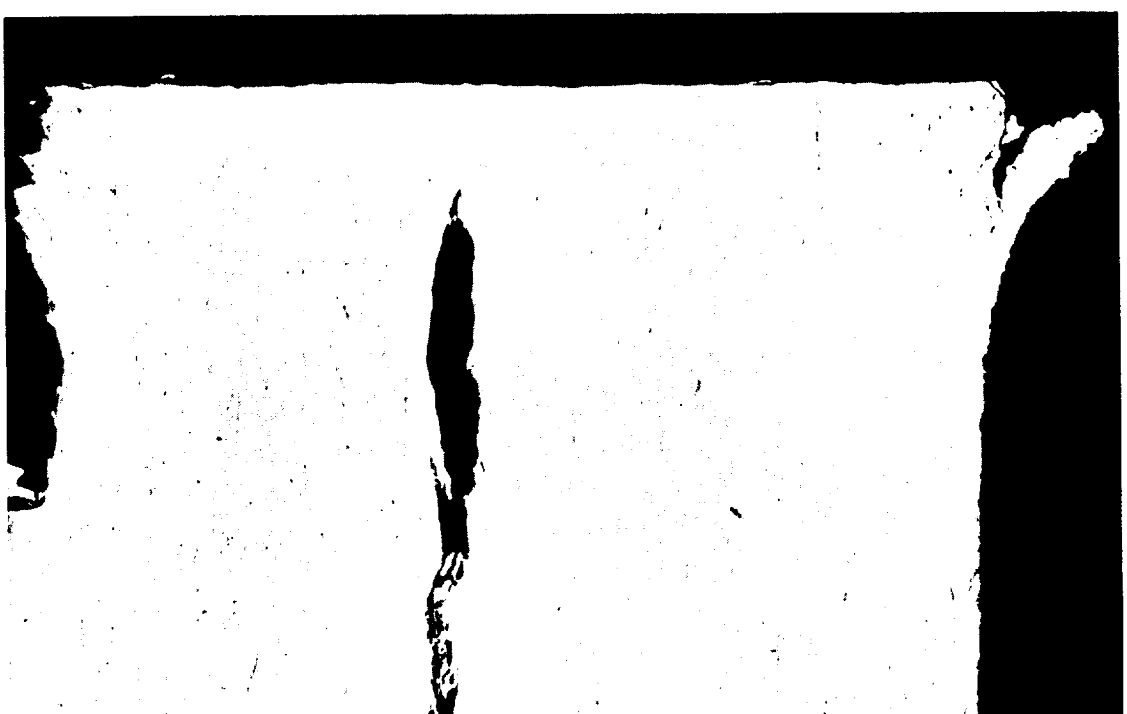


FIGURE 36. CROSS-SECTION OF HOLE DRILLED WITH DULL DRILL AT HIGH MAGNIFICATION (UNETCHED)



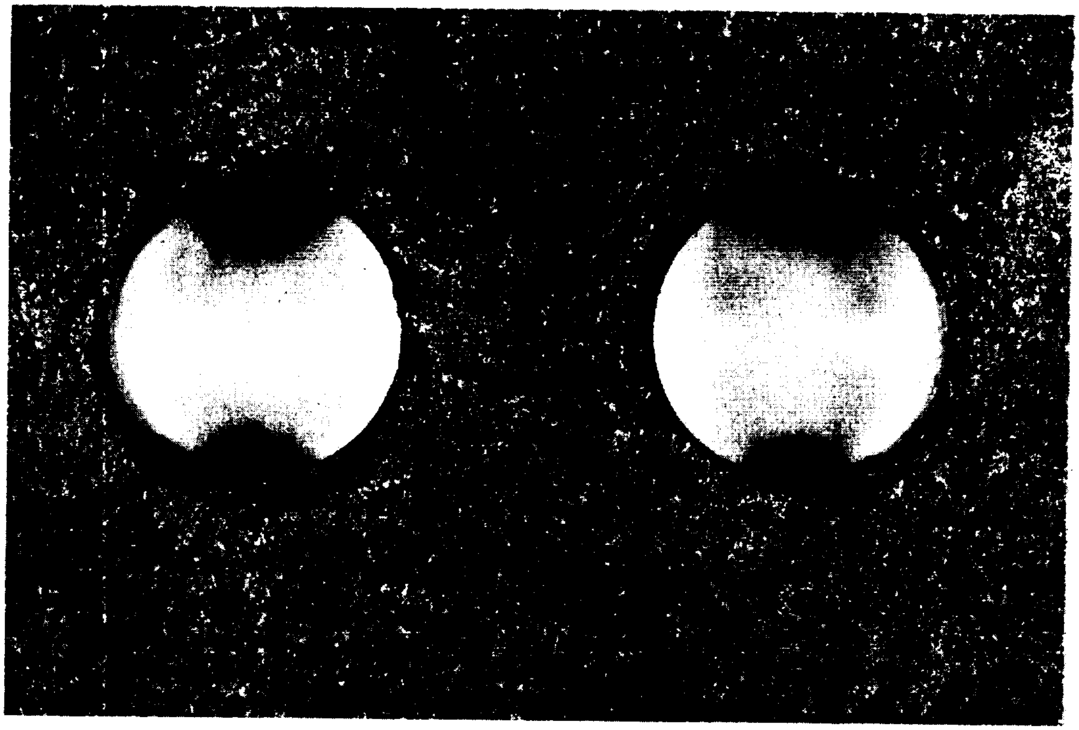
(10X)

FIGURE 37. HOLE DRILLED WITH IMPROPERLY SHARPENED DRILL. NOTE HEAVY BURR ON EXIT SIDE (UNETCHED)



(85X)

FIGURE 38. CROSS-SECTION THROUGH HOLE DRILLED WITH IMPROPERLY SHARPENED DRILL (UNETCHED)



(10X)

FIGURE 39. HOLES DRILLED USING EXCESSIVE FEED RATES.
NOTE SPALLING ON EXIT SIDE (UNETCHED)

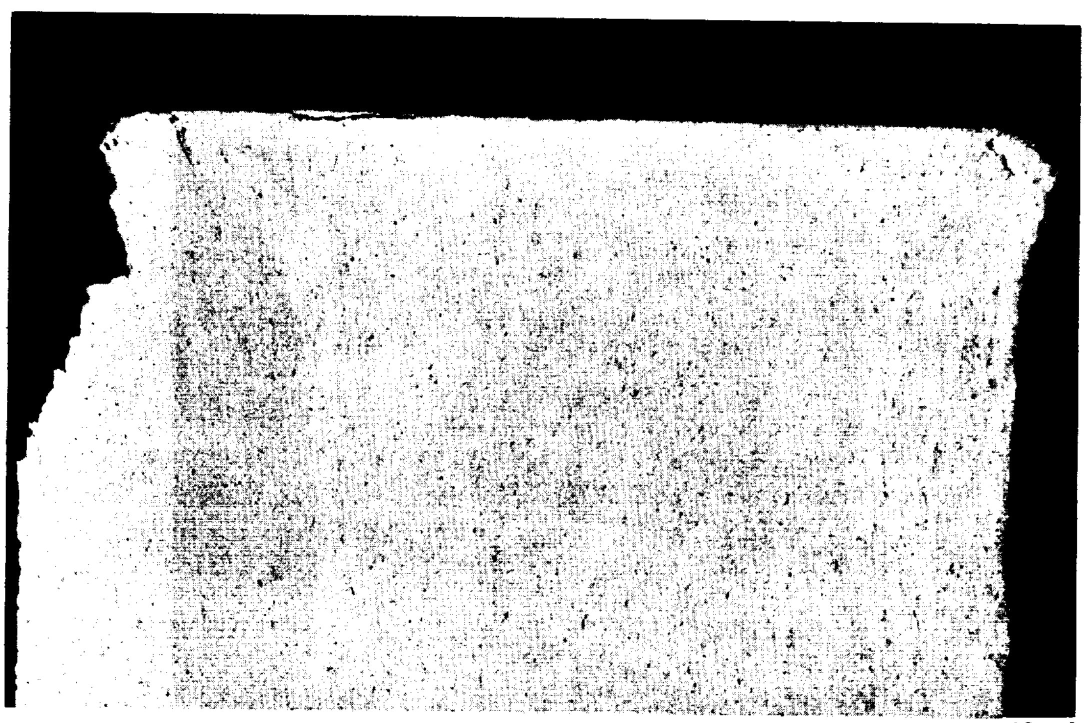


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FIGURE 40. CROSS-SECTION OF HOLE DRILLED USING EXCESSIVE FEED RATE.
NOTE SPALLED REGION (UNETCHED)

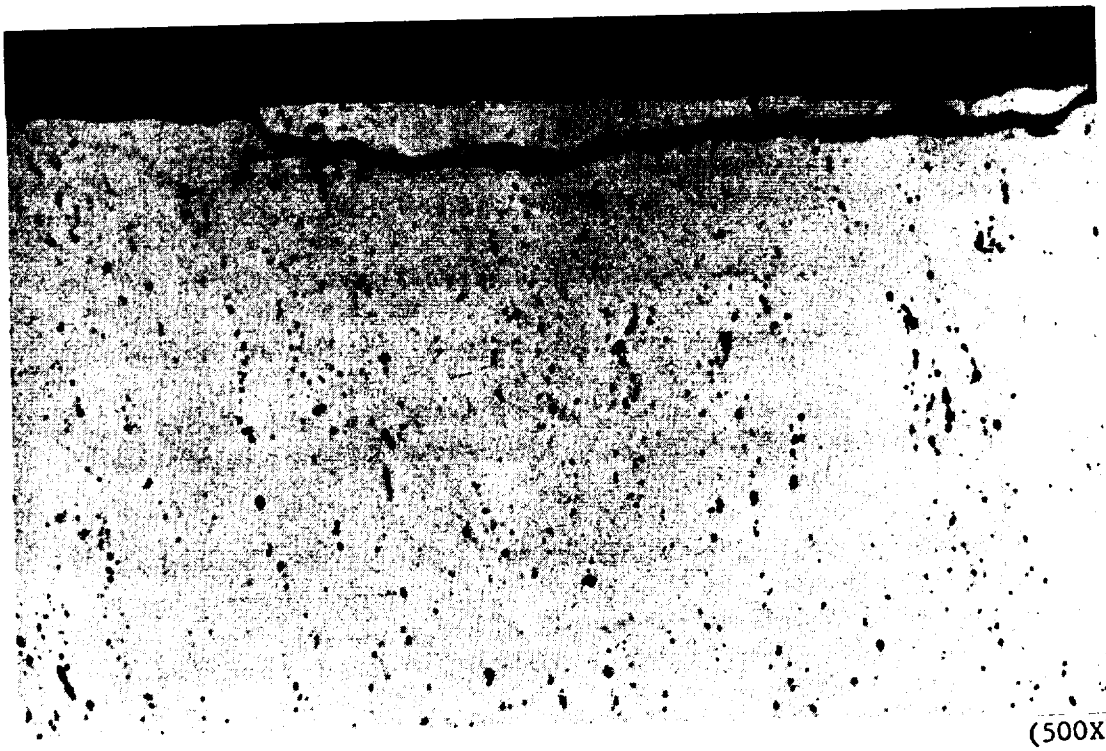


FIGURE 41. CROSS-SECTION OF HOLE DRILLED AT EXCESSIVE FEED RATE. NOTE CHIPPING ON FLAT PORTION OF HOLE SURFACE (UNETCHED)

equipment for the cutting of beryllium is the large capacity precision abrasive saw illustrated in Figure 42.

An examination of the following specifications reveals the extensive capabilities of this saw.

a. Capacity - Sheet and plate up to 2.0-inches thick; 96-inches wide and infinite length.

b. Traverse - Feed rate of 0.50 to 0.200-inches per minutes (ipm); rapid traverse of 150 ipm.

c. Vertical Adjustment - 4 inches

d. Coolant - 30 gallons per minute at 30 psi.

e. Spindle Speed - Infinitely variable from 2200 to 9000 surface feet per minute - based on 14-inch diameter wheel.

As is typical with abrasive cutting, the resulting surface finishes are superior to those produced from other processes. Figures 43 through 51 illustrate the typical surface conditions that can be achieved using a rubber bonded abrasive wheel manufactured by Allison; code Number C120-JRA. The wheel was operated at a constant speed of 8240 SFM with a varying feed rate and both with and without coolant.

It may be noted that as the feed rate is increased, the resulting edge burr is more pronounced although no actual metallurgical damage is apparent. Standard practice, however, is to use coolant during cutting to avoid the excessive localized build-up of heat, which could be cumulative during long cuts and might result in the development of edge cracks due to the thermal stresses. The use of coolant also prevents the dispersion of fine beryllium dust particles. Figures 49 and 50 illustrate the resulting edge. The abrasive wheel cutting method is used for trimming the edges of both formed and flat sheets. Elaborate and expensive holding devices are seldom required as the cutting pressures are very low.

2. Projected Areas of Development. The current procedures have proven to be entirely reliable and satisfactory;

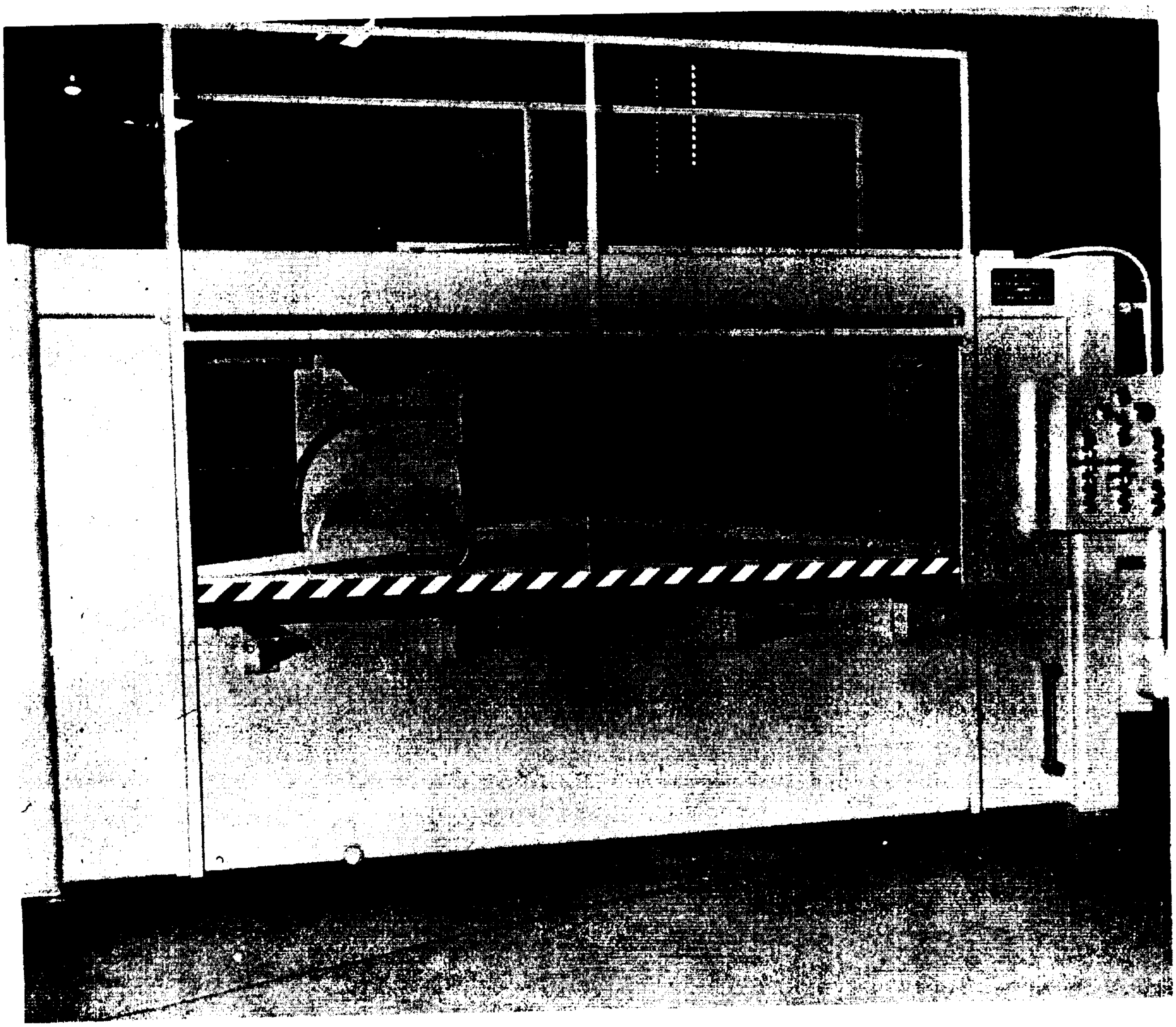
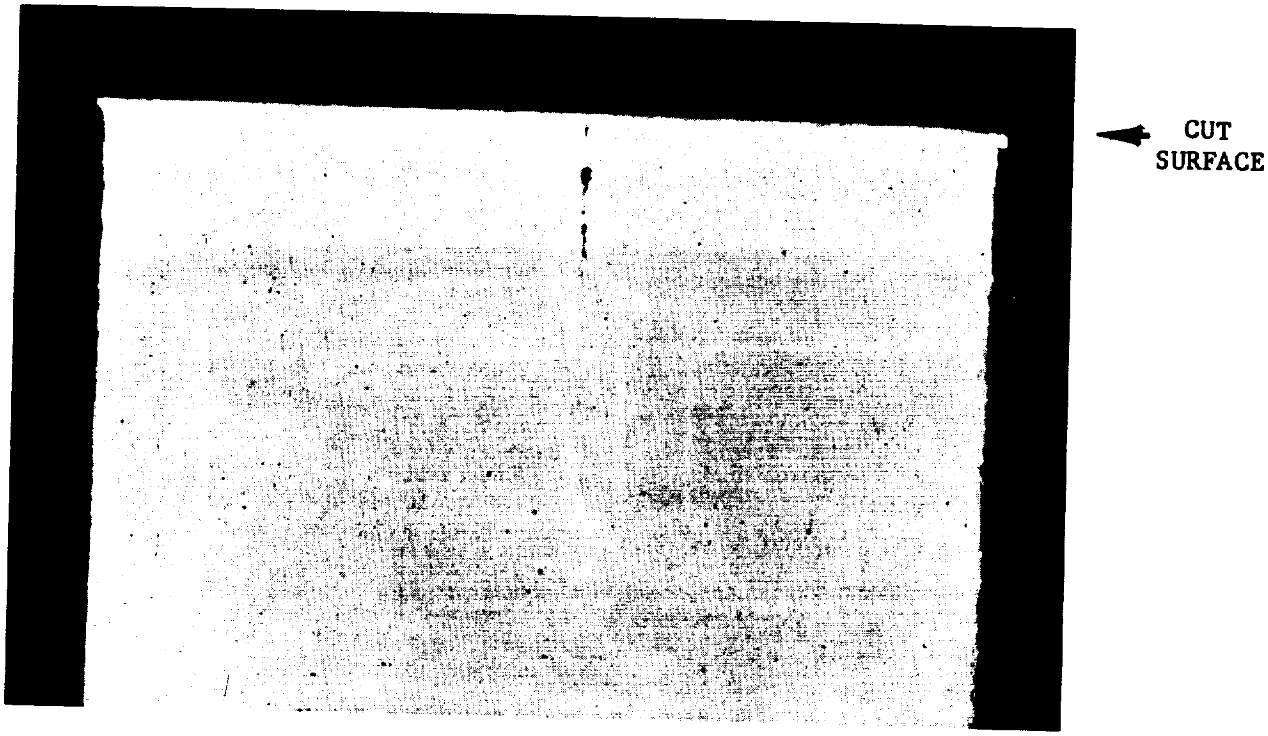


FIGURE 42. LARGE CAPACITY PRECISION ABRASIVE CUT-OFF SAW.



(85X)

FIGURE 43. CROSS-SECTION OF SURFACE CUT DRY ON ABRASIVE WHEEL. FEED RATE 4.0 IPM AT 8,240 SFM

(500X)

FIGURE 44. CROSS-SECTION OF SURFACE CUT DRY ON ABRASIVE WHEEL. FEED RATE 4.0 IPM AT 8,240 SFM. NOTE LARGE INCLUSION.

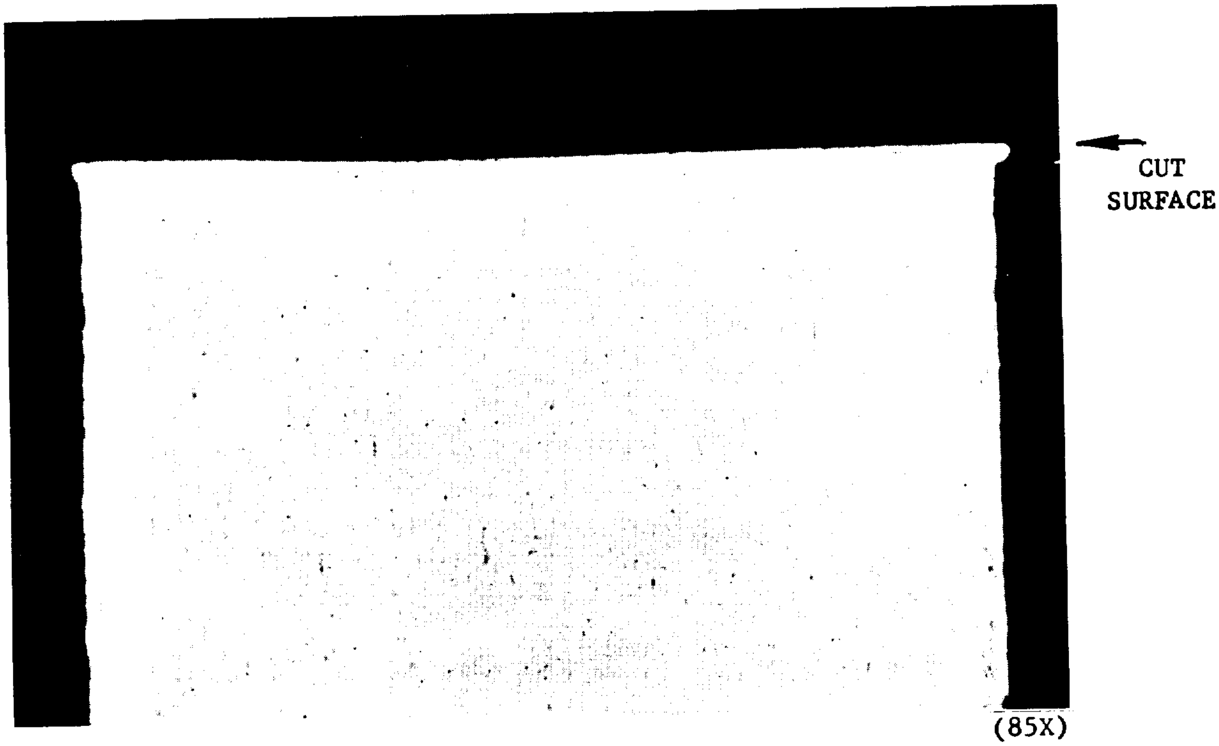


FIGURE 45. CROSS-SECTION OF SURFACE CUT DRY ON ABRASIVE WHEEL. FEED RATE 6.0 IPM AT 8,240 SFM.

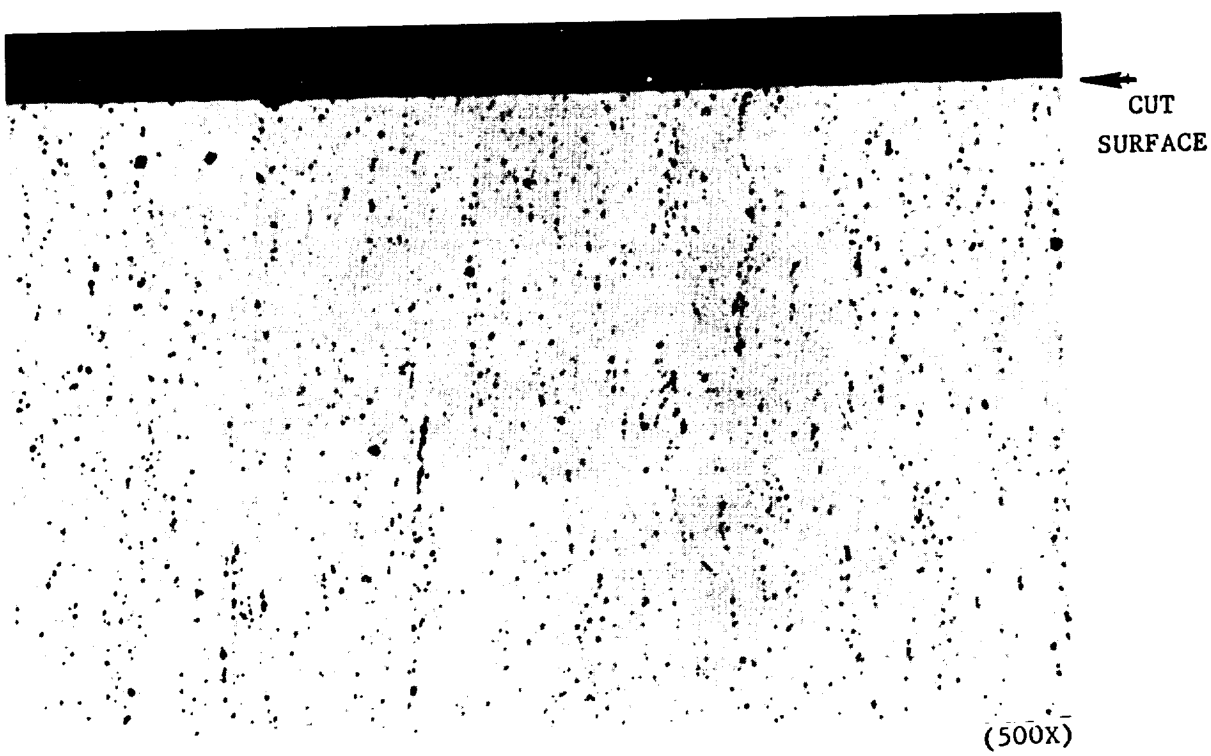


FIGURE 46. CROSS-SECTION OF SURFACE CUT DRY ON ABRASIVE WHEEL. FEED RATE 6.0 IPM AT 8,240 SFM.

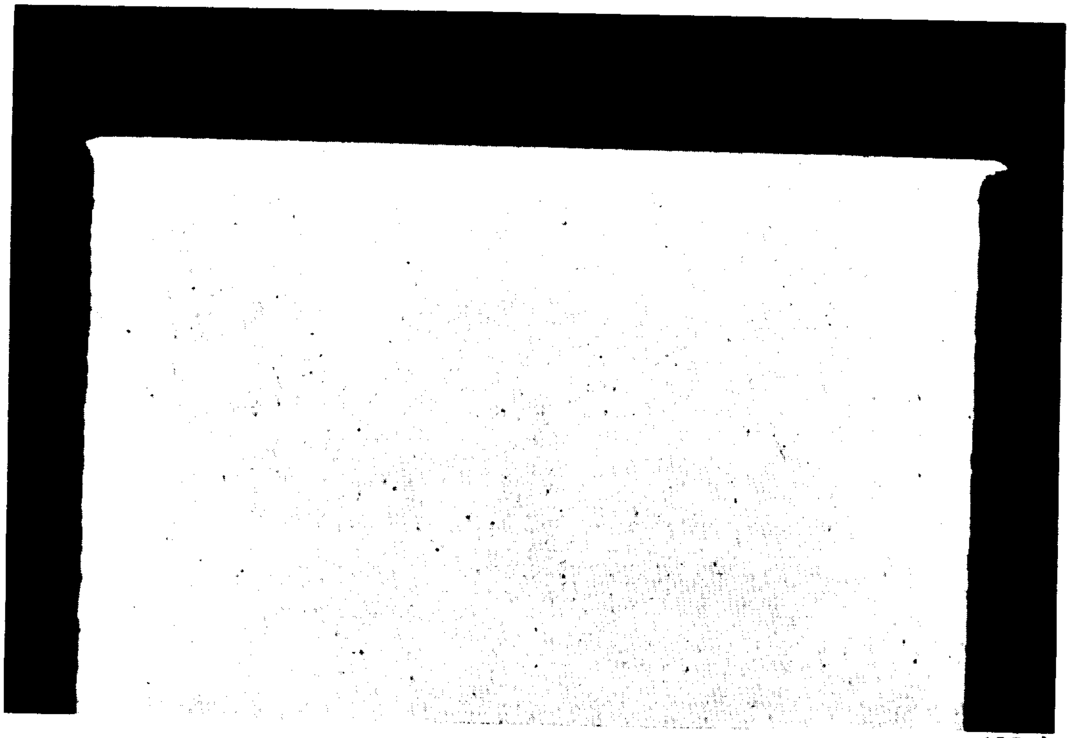


FIGURE 47. CROSS-SECTION OF SURFACE CUT DRY ON ABRASIVE WHEEL. FEED RATE 7.5 IPM AT 8,240 SFM.

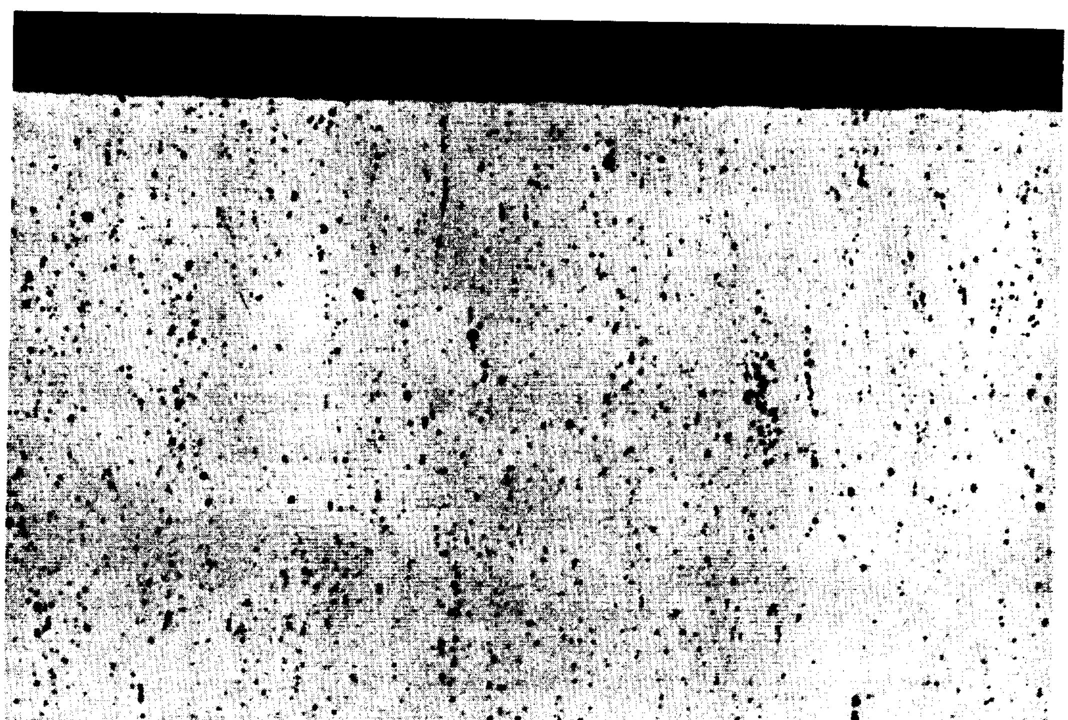


FIGURE 48. CROSS-SECTION OF SURFACE CUT DRY ON ABRASIVE WHEEL. FEED RATE 7.5 IPM at 8,240 SFM.

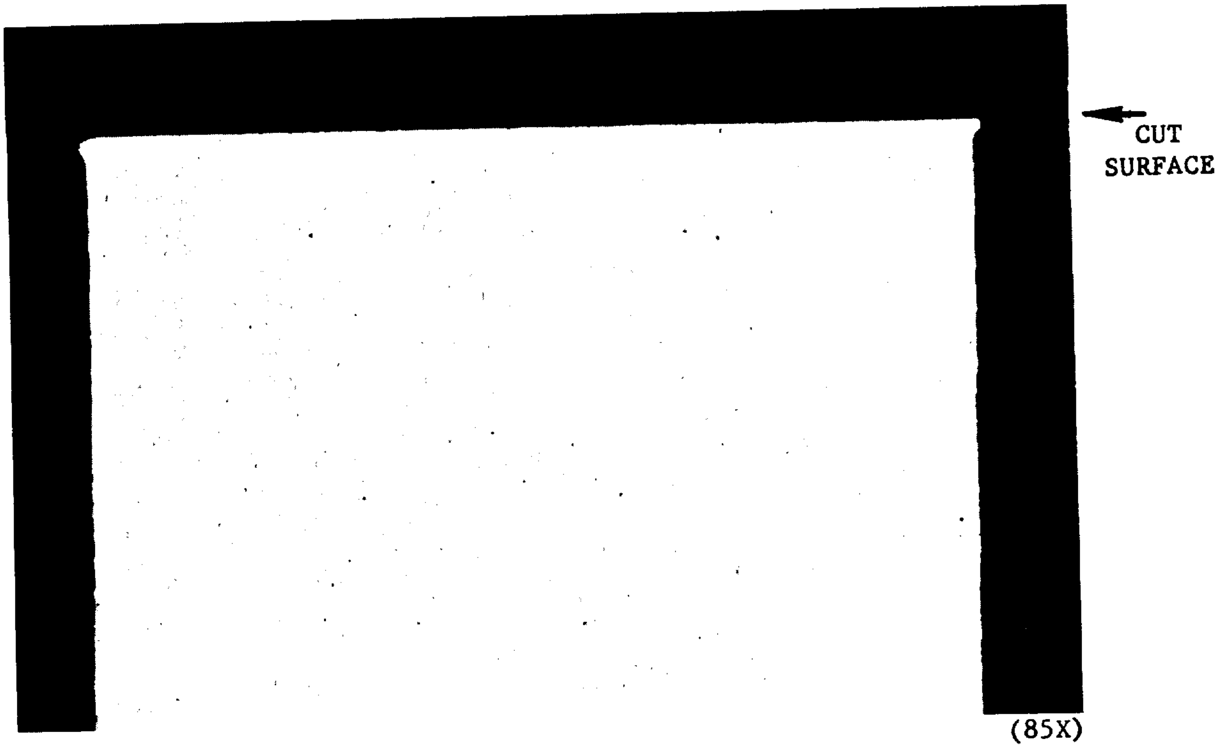


FIGURE 49. CROSS-SECTION OF SURFACE CUT ON ABRASIVE WHEEL USING COOLANT. FEED RATE 4.0 IPM AT 8,240 SFM.

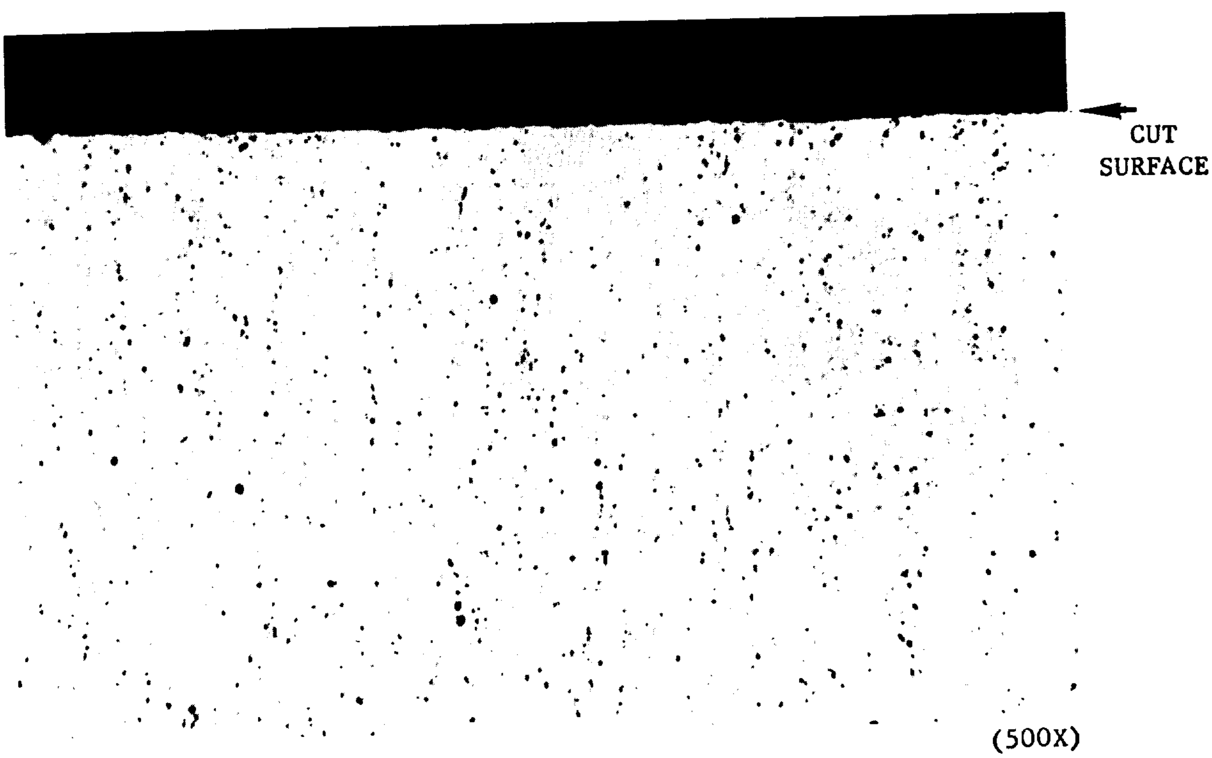
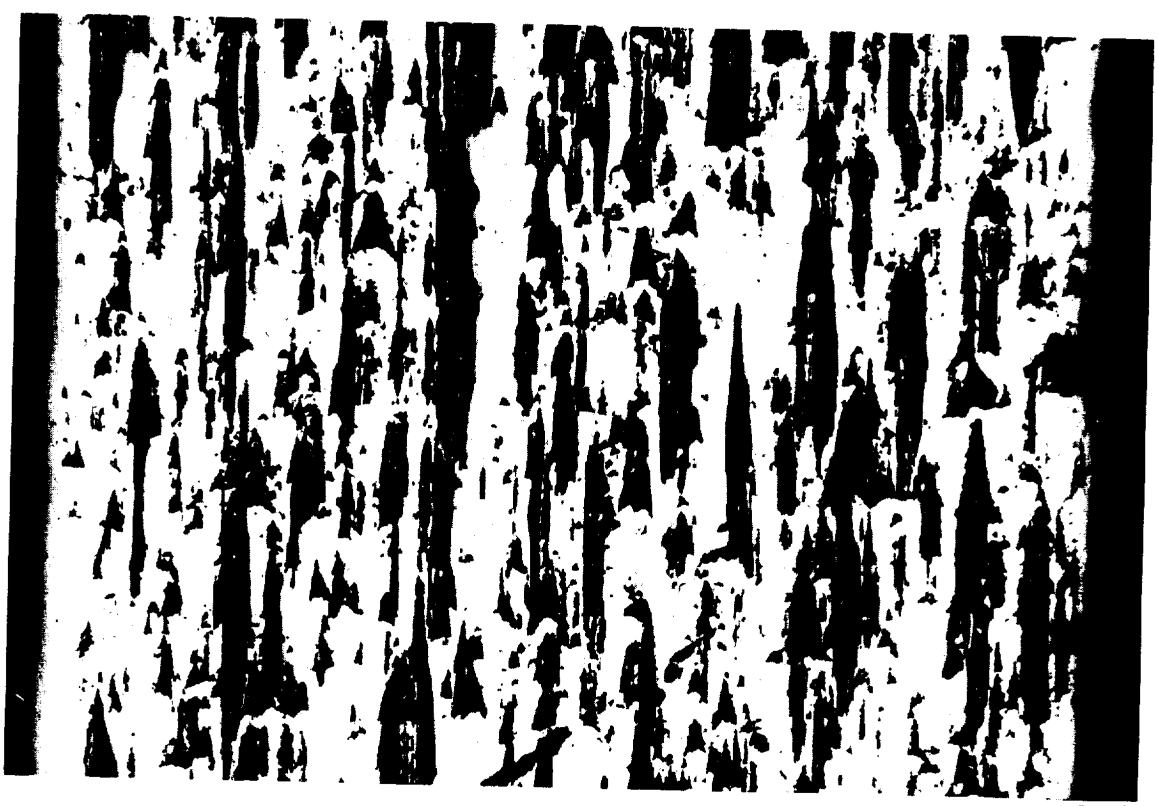


FIGURE 50. CROSS-SECTION OF SURFACE CUT ON ABRASIVE WHEEL USING COOLANT. FEED RATE 4.0 IPM AT 8,240 SFM.

(85X)

FIGURE 51. ABRASIVE WHEEL CUT SURFACE - LIGHTLY POLISHED.



(85X)

FIGURE 52. ROUTER CUT SURFACE - LIGHTLY POLISHED.

no major process advancement in abrasive wheel cutting is required or anticipated for the present or projected production needs.

3. <u>Current Procedure</u>.

a. Safety and Environmental Control. Because the action of abrasive cutting produces very fine beryllium particles which tend to become airborne, similar to those produced by grinding, the maintenance of rigid safety precautions is mandatory.

All abrasive cutting is accomplished in approved facilities located within the beryllium sheet metal fabrication shop. The machine is contained within a transparent enclosure equipped with high velocity vacuum hoses to capture any beryllium particles. In addition, the large capacity coolant system not only cools the work, but also flushes all cutting residue through a separator/filter system.

b. Shop Operation. Prior to starting any cutting operation, the abrasive wheel is always carefully inspected for indications of chipping, cracking, and edge wear. The workpiece then is placed in position, clamped in place, and the necessary height adjustment is made to insure the proper wheel penetration through the workpiece. The sliding transparent doors of the enclosure are closed, the vacuum and coolant systems and the wheel power are activated, and the abrasive wheel is advanced into the workpiece at a predetermined feed rate. All the controls are actuated from a central panel located outside the enclosure conveniently accessible to the operator.

F. ROUTING

1. <u>Present Capability</u>. Although routing is a long-established and well-qualified production method used for the machining of a wide variety of internal cutouts and edge profiles in many materials, the routing of beryllium sheet is a recently developed process which currently is being utilized for the production of skin panels and related parts of a space vehicle structure. Figure 54 illustrates both the special and standard cut carbide routed bits that have been developed for this purpose. The two basic types are the multi-fluted spiral cut and the standard diamond (burr)

pattern. Both types are available in either the ball or the flat nose configuration.

To insure successful routing, rigid and substantial fixtures must be used to reduce the impact loading to the minimum, and to provide constant loading of the beryllium during the routing operations.

Relatively inexpensive "router block" tooling is used to guide the workpiece relative to the stationary router spindle. Manual control of the cutter feed is being used at the present time as illustrated in Figure 53.

2. <u>Projected Areas of Development</u>. The availability of larger sheets and plates is anticipated and since it is easier to manipulate a small router head than a large workpiece, proposed designs for advanced routing equipment are taking the form of either bridge or gantry type machine tools utilizing either numerical or cam controls. In addition, longer tool life and improved cutting efficiency can be attained only by eliminating the variable feed resulting from manual manipulation of either the router head or the workpiece and router block.

3. <u>Current Procedures</u>. Cutouts and edge trimming are accomplished by routing. A firmly supported air-driven motor turning at a free-running speed of 900 - 1000 rpm is used for all routing operations. The feed rate is varied from 0.5 inch to 1 inch per minute, depending upon the gauge of the material. Internal cutouts are made by slowly plunging the ball nose type of cutter through the material, then progressing around the periphery of the cutout as guided by the tooling. The flat nose type of cutter is used for edge trimming or for making shallow cuts that do not penetrate completely through the material.

Figures 52 and 56 illustrate typical router cut edge conditions. It should be noted that the surface damage is very minor, and that twinning is limited to a very narrow band, approximately 0.0005-inch deep, which is easily removed during the required subsequent etching operation.

Routing has proven to be an efficient and economical method for producing internal cutouts of irregular shape, and for external trimming to net dimensional requirements.

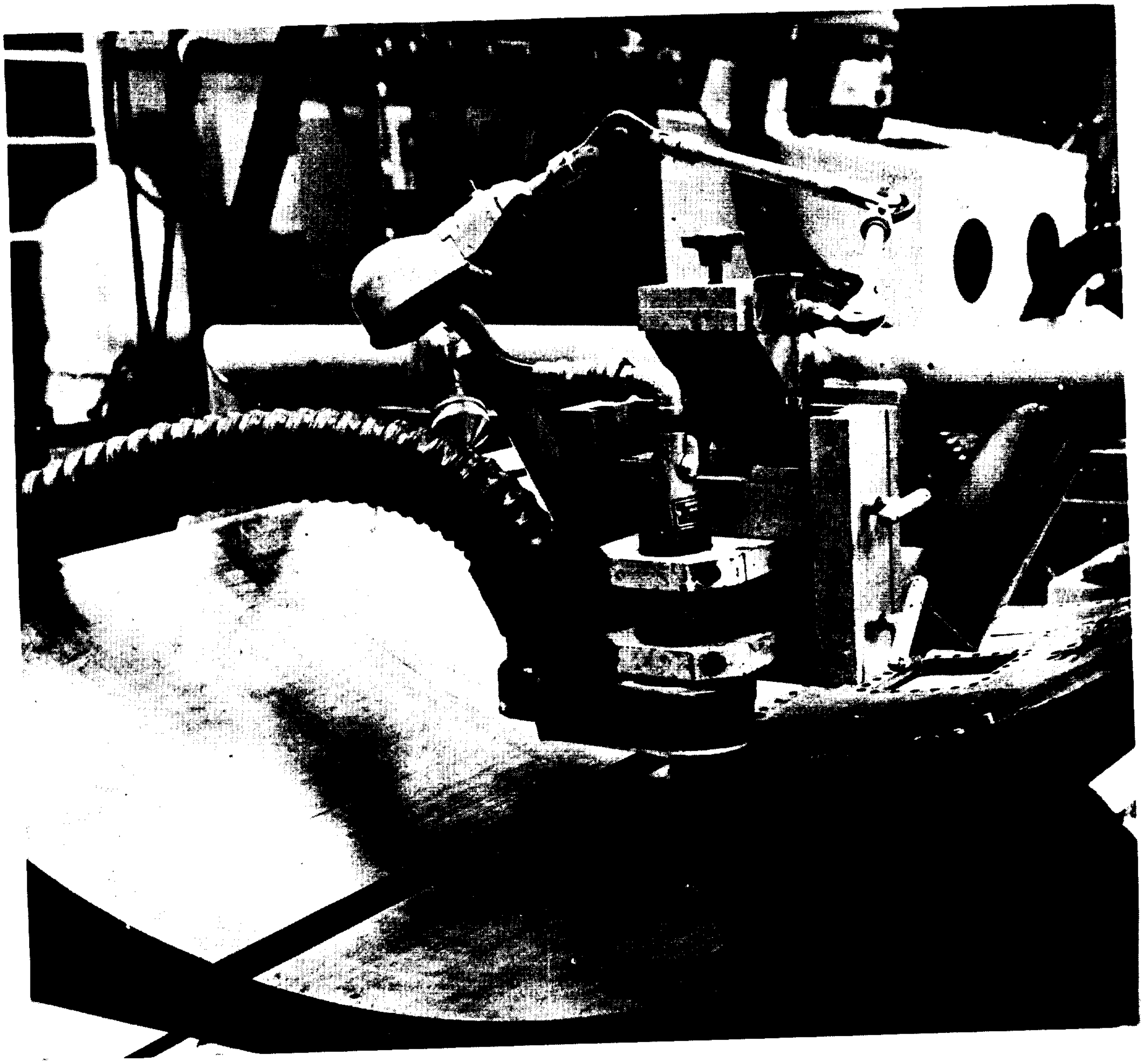
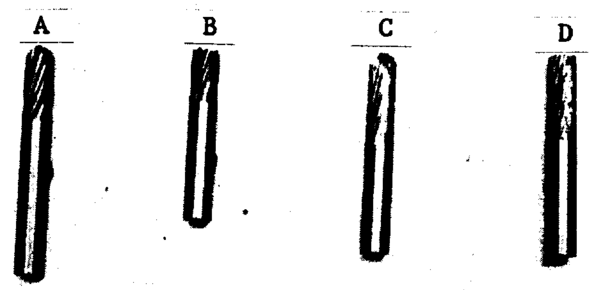


FIGURE 53. A TYPICAL PANEL IN ROUTER FIXTURE.
NOTE SUBSTANTIAL SUPPORT STRUCTURE AND PROXIMITY OF HIGH VELOCITY VACUUM EXHAUST TUBE.



A - SPECIAL SPIRAL MULTI-FLUTED BALL NOSE

B - SPECIAL SPIRAL MULTI-FLUTED FLAT NOSE

C - STANDARD CUT (BURR) BALL NOSE

D - STANDARD CUT (BURR) FLAT NOSE

FIGURE 54. TYPES OF CUTTERS USED IN ROUTING BERYLLIUM SHEET

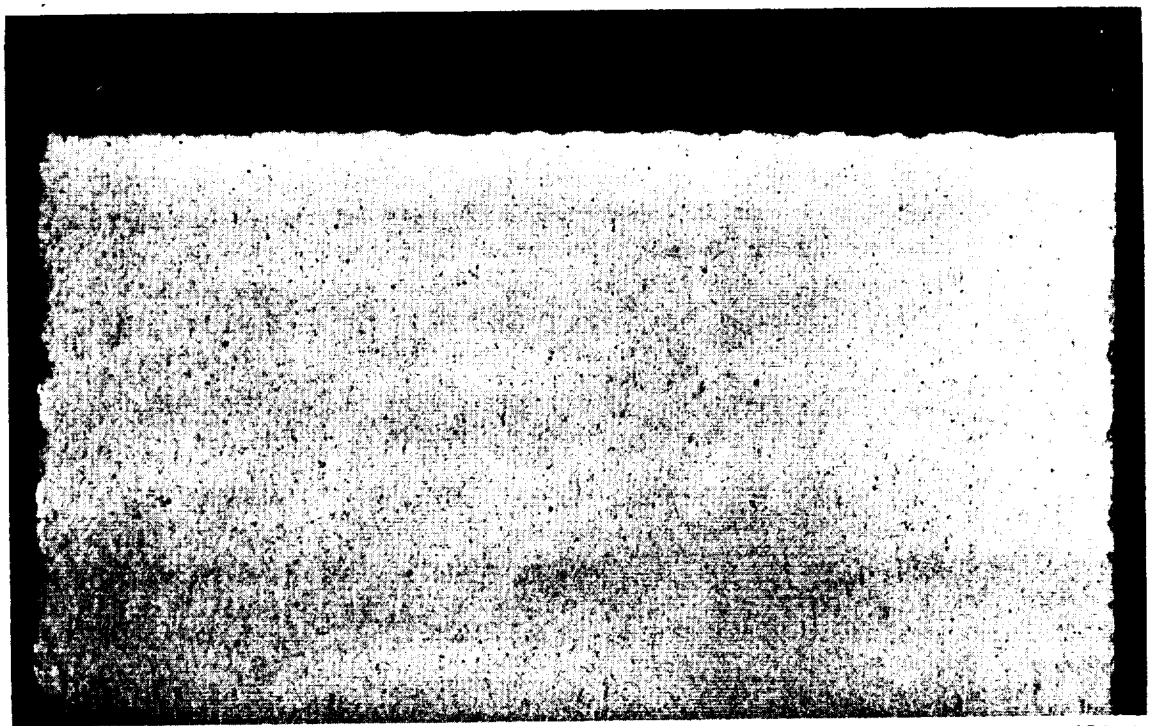


FIGURE 55. CROSS-SECTION OF ROUTER CUT SURFACE.

FIGURE 56. CROSS-SECTION OF ROUTER CUT SURFACE.

G. SHEARING

The shearing of beryllium, like piercing or punching, has been found to be a most impractical process at room temperature. Gross material damage and fracture invariably result. Shearing at elevated temperatures and shearing while encased in a protective metal envelope may be feasible. The disadvantages (time, specialized equipment, cost) of these added complications, however, appear to outweigh any possible advantage shearing might conceivably have over abrasive sawing or routing.

The primary advantage of the shearing process is the very low cost in production manhours per unit. The relatively high cost of beryllium material, however, makes the quality of product, and the reliability and repeatability of a production process, of far greater economic importance than a minor saving in manhours. Further investigation, therefore, is not anticipated.

SECTION IV. PRECISION MACHINING

A. GENERAL

This section describes beryllium metal removal operations as performed on conventional precision machine tools such as lathes and milling machines. The workpiece usually will be machined from vacuum hot-pressed block which possesses somewhat different properties from those possessed by wrought forms such as sheet, plate and extrusions.

Vacuum hot-pressed blocks are produced by compacting and sintering beryllium powder on a mold at a temperature of 1050°C and a pressure of 100 to 200 psi. The resulting grain structure is random (isotropic) and, therefore, has less tendency toward boundary separation or delamination during machining than the wrought forms which possess oriented (anisotropic) grain structures. Although the mechanical properties (Ftu and Fty) of the vacuum hot-pressed block are lower than those of the wrought forms, the machining characteristics are better, i.e., it is less subject to spalling, cracking, and/or delamination.

The relatively high cost of beryllium material has made the utilization of numerically controlled equipment particularly advantageous. The control tapes, fixtures, and cutting tools can be "tried out" and "proven" on the machine using inexpensive material for workpiece simulation. After the machine settings have been verified, the beryllium workpieces can be machined with confidence.

As more and more beryllium is used in ever-widening hardware applications, its cost undoubtedly will decrease. As this occurs, the manhour fabrication costs will become proportionally greater, and the development of ways and means for increasing the productivity of the precision machine tools will become increasingly important.

B. TURNING

1. Present Capability. The precision turning of beryllium on engine and turret lathes, and on vertical boring mills is an established and well-qualified fabrication method. Missile re-entry heat shields, frustums, and cones are machined by turning. A cutting speed of 250 surface feet per minute is used without coolant or an immediate enclosure. A close-capture, high-volume vacuum exhaust tube, located adjacent to the cutting tool, is used for the disposal of the chips. Excellent material removal rates are achieved using mechanically held carbide insert tool bits, and conventional work holding methods (chucking with soft formed jaws, etc.) frequently can be utilized to eliminate the need for expensive special tooling. Completely crack-free machined surfaces, with a 32 RMS finish, are consistently attainable in production operations. However, both the machine and the "setup" must be rigid, and the overhang of the workpiece and of the tool must be minimum.

2. Projected Development. The present machining (turning) procedures satisfy all current production

requirements. Approximately 400 surface feet per minute appears to be the best cutting speed for machining (turning) beryllium. However, at this speed, an enclosure must be used to contain the fine dust-like chips. Reasonable tool life has been attained with ceramic tool inserts used at speeds up to 800 surface feet per minute. Thus, high speed production turning methods have been proven feasible, and probably will be utilized in future facilities.

3. Current Procedures. At cutting speeds up to 250 surface feet per minute, a close-capture, high-volume, 3-inch diameter vacuum exhaust tube is entirely adequate for the safe control of the beryllium chips. However, at higher surface speeds, an enclosure must be used to contain the fine dust.

The cutting speed, feed, and depth of cut are interrelated with the cutting tool material and geometry. Slower cutting speeds, with coarser feeds and deeper cuts, normally are used for roughing cuts since more material can be removed per minute for a given tool life. This can be achieved only by using carbide or ceramic cutting edges. Carbide, expecially grade C-2 (Carboloy 883, Kennametal K-6, etc.), is the most satisfactory material for rough cutting. Because of their lower cost, availability, and dimensional repeatability, mechanically held indexible carbide inserts are preferred over brazed-on tips. (A new cutting insert can be indexed into position within 0.002 inch of the setting of the previous insert.) Positive side rake holders, with square and triangular inserts, are recommended for general cutting. A depth of cut up to 0.100 inch, with a feed up to 0.020 inch per revolution, can be used if the material is sufficiently thick to resist cracking.

Clamp-in type ceramic inserts (Carboloy, grade 0.30 cemented aluminum oxide), with negative rake, are superior to the carbides for finishing cuts or for light continuous cutting because they resist the formation of a built-up cutting edge. A side-edge cutting angle is satisfactory. The necessity for changing tools when changing from rough to finish cutting tends to deter their use. The cutting speed may vary from 150 to more than 400 surface feet per minute, with the depth of cut, and the fixed rate per revolution, ranging from 0.002 to 0.020 inch and from 0.004 to 0.012 inch, respectively. In general shop practice, an extremely light depth of cut and a fine feed are used as the required dimensions and surface finish are approached. Although care must be exercised in turning thin-walled or unsupported workpieces, surface cracks or workpiece breakage have not been serious production problems.

C. MILLING

1. Present Capability. Because of the low ductility of beryllium at room temperature, it was believed, initially, that the shock caused by the milling cutter teeth entering and leaving the workpiece might prevent milling from ever becoming an appropriate machining process for beryllium. However, experience in milling beryllium has shown that such is not the case, and today a wide variety of complex configurations are being successfully milled on conventional machines from all the forms of beryllium material: sheet, plate, extrusions, forgings, and hot-pressed block.

"Climb" or "down" milling is used for most machining operations as opposed to "conventional milling." Carbide cutting tools, usually without coolant, are used. Two to three hundred cubic inches of material can be removed before regrinding the cutter is necessary. Surface finishes of 125 RMS or better are readily attainable.

2. Projected Development. The present milling procedures are adequate for all forseeable production requirements; no significant developments are anticipated. However, it is anticipated that the application of numerical control may be particularly advantageous. The current success of milling operations is largely dependent upon the individual skill and care exercised by the machine operators, and therefore, is subject to human errors.

3. Current Procedures. Conventional milling machines are being used for machining beryllium. The machine and the set-up must be extremely rigid to avoid spalling. Because of the abrasive quality of beryllium, the machine ways and columns are subject to accelerated wear and, therefore, should be wet-wiped frequently. Most milling operations are performed without coolants using a close-capture, high-volume vacuum exhaust tube to dispose of the chips. When a cutting fluid is required, water-soluble oil may be used. Cutting fluids, which are used

for machining beryllium, should be stored in suitable containers, and should be disposed of only as approved by the appropriate safety personnel. Beryllium chips, which have been wet with cutting fluid, have a low salvage value and should be kept segregated from clean beryllium scrap.

"Climb" or "down" milling should be used whenever possible as this procedure will prevent spalling at the point the cutter leaves the work. When the conventional milling procedure must be used, a backup block should be used in the area where the cutter leaves the work. A piece of scrap beryllium is preferred to avoid the contamination of the chips. However, a piece of mild steel can be used as a backup; the mild steel chips can be readily separated from the beryllium chips by the use of a magnet.

Carbide cutting edges are recommended for all milling operations. Grade C-1 (Carboloy 44A or equivalent) is recommended for the rough cuts; grade C-2 (Carboloy 883 or equivalent) is recommended for the finishing cuts. Various types of milling cutters and bodies are being used successfully, e.g., inserted indexible carbide blades, brazed-on carbide tips, and solid carbide. In all cases, however, both the axial and the radial rake angles must be positive. Angles of 5 to 7 degrees are recommended, with primary and secondary clearances of 3 to 5 and 7 to 9 degrees respectively. The recommended cutter corner radius is one-fourth of an inch.

Beryllium has been milled satisfactorily at cutting speeds above 400 surface feet per minute. However, the problems and inconvenience involved in safely containing the fine chips and dust usually result in the use of slower cutting speeds - under 300 surface feet per minute.

A light feed per tooth of 0.002 inch per revolution, and a light depth of cut of less than 0.100 inch normally will result in the production of a surface finish of 100 RMS or better.

SECTION V. ELECTRICAL DISCHARGE MACHINING (EDM)

A. GENERAL

Under certain conditions, beryllium cross-rolled sheet is difficult to machine without incurring material damage because of its anisotropic grain structure. Therefore, the Electrical Discharge Machining process was included in this program in order to evaluate its applicability for machining cross-rolled sheet.

Electrical Discharge Machining may be defined as the process of removing metal by means of electrical discharges in the presence of a dielectric[1]. This is not a new or revolutionary process; it has been utilized by industry for many years. The principal advantages of the process are as follows:

1. The ease with which complex cavities or cuts can be made in otherwise difficult-to-machine materials.

2. The cutting tools (electrodes) can be fabricated from inexpensive materials, and will reproduce their configurations faithfully.

3. "Gang" drilling is applicable to many production operations, permitting the simultaneous cutting of holes and/or irregular shapes.

4. Freedom from defects and fine finishes are easily attainable, which can be duplicated only by other much more costly machining processes.

B. OPERATING PRINCIPLES

Electrical Discharge Machining (EDM) utilizes the eroding action of a short duration electric arc, or spark, in cutting or machining the workpiece. This arc is generated between the cutting tool (electrode) and the work; both items, therefore, must be electrically conductive.

The rate of material removal is dependent upon the electrical current flow (amperes). In order to control the cutting action of the spark, the spark duration is limited by the amount of energy delivered to the workpiece through the power supply.

The machine current flow consists of a series of sparks, each precisely controlled in energy content. The machining rate, then, is proportional to the average current through the spark gap. The lower frequency of the pulsating DC current, therefore, creates a larger portion of vaporized material at the point of impact. The crater thus created results in the production of a surface finish from 300 to 500 micro-inches. At low frequencies, a temperature approaching 7000°F is generated in the workpiece. The dielectric oil therefore, serves the dual purpose of cooling the work and preventing the shorting of the circuit by removing the material particles from the workpiece-electrode envelope.

The frequencies obtained at tap switch position 1 through 11 are included in Table III. It may be noted that each tap switch (except 9, 10, and 11) in ascending order provides a frequency approximately double that available at the previous setting. Thus, it would appear in each case, that an equivalent surface finish could be provided at twice the metal removal rate.

Figure 58 illustrates the effect of tap switch setting on surface finish. In example (A), one electrical discharge contains a certain amount of energy and will remove a given volume of material. Example (B) has the same average current flowing between the electrode and the work and the volume of material removed is the same in both cases. However, the number of discharges per second, or the frequency, has been doubled in example (B), i.e., the gap current has been divided into two discharges and the resulting surface finish will be improved. Examples (C) and (D) show the effect of increasing the frequency to four and eight discharges per second respectively. In each case, the total current was unchanged, and the total volume of material removed is the same. The surface finish, however, is improved with each increase in frequency.

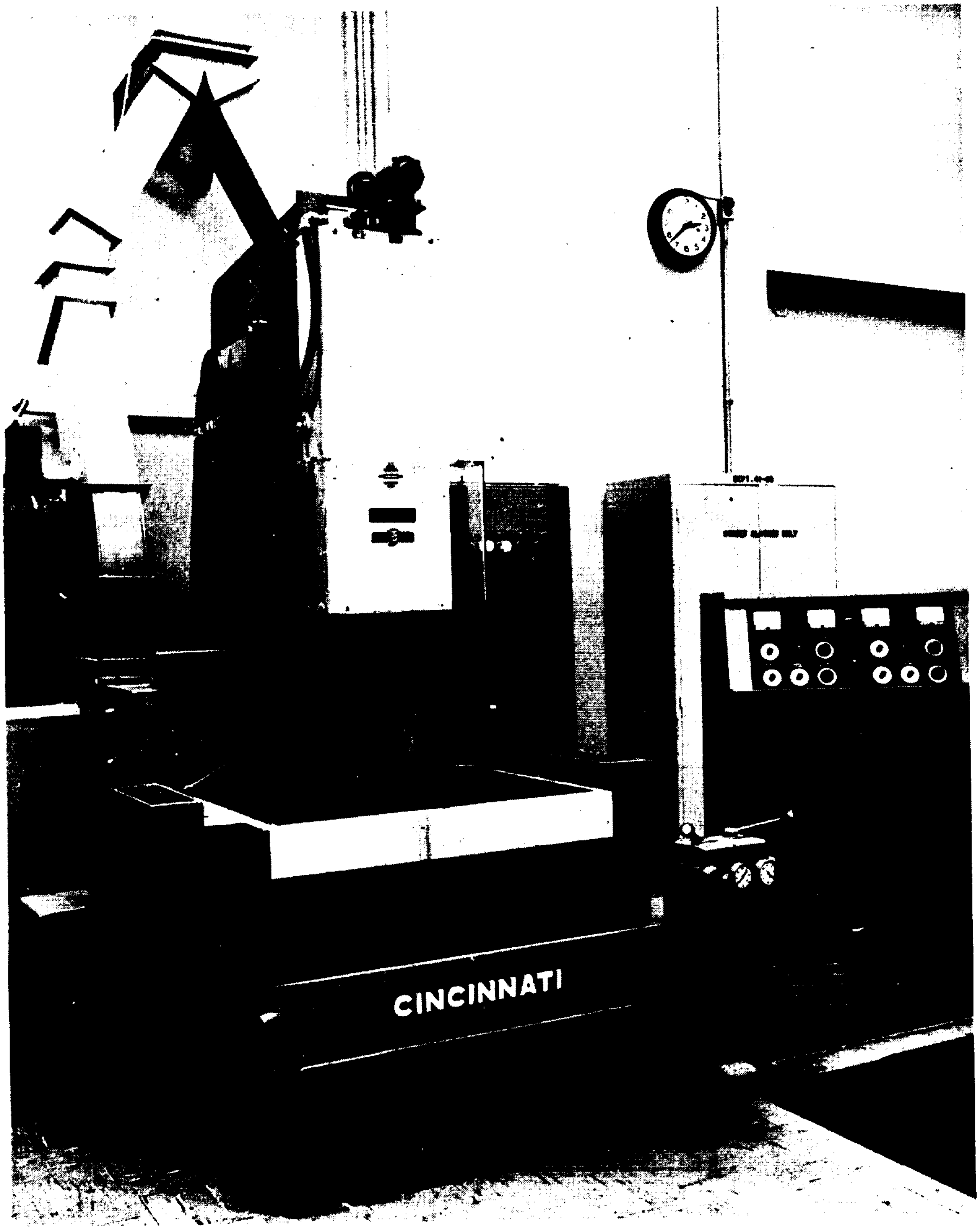


FIGURE 57. CINCINNATI MODEL 24A31 ELECTRICAL DISCHARGE MACHINE WITH ELOX NPS D-60 POWER SUPPLY

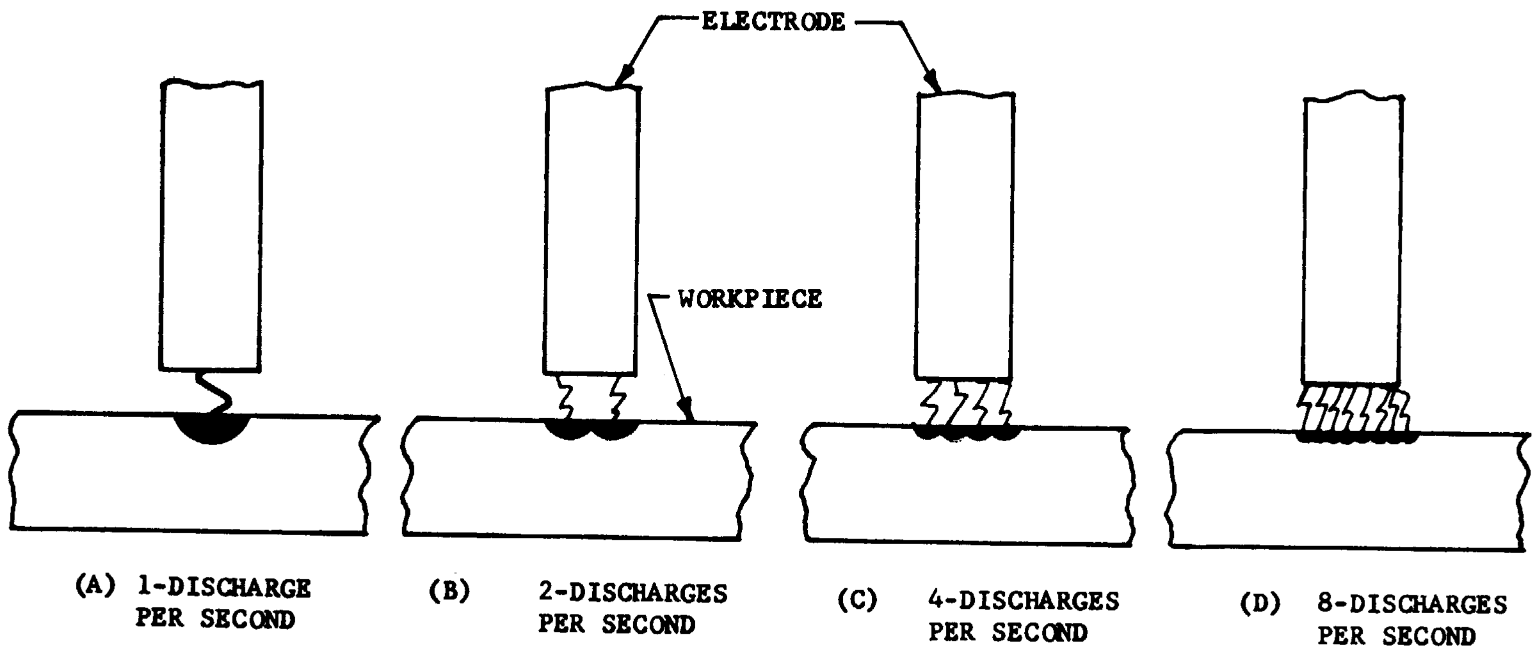


FIGURE 58. RELATIONSHIP BETWEEN SURFACE FINISH AND DISCHARGE FREQUENCY

C. PRESENT CAPABILITY

A typical machine, Cincinnati No. 2 Ram "Electro Jet," illustrated in Figure 57, is equipped with its own high-velocity vacuum system to remove vapors from the work area. The fine powder produced during the electrical erosion process is suspended and carried away in the dielectric fluid through a fine microfilter. This arrangement, in conjunction with the constant room monitoring, adequately meets all safety and hygiene requirements.

In addition, the machine is equipped with a rotating electrode capability for precision hole cutting. The ram platen is 12 inches by 18 inches and has a vertical travel limit of 12 inches. This machine has no provision for lateral and/or longitudinal table adjustments. Only vertical or plunge cutting can be accomplished without special tooling.

D. PROJECTED DEVELOPMENT

The Electrical Discharge Machining process has been used for miscellaneous "straight line" cutting and for drilling extremely fine holes. Tensile test specimens, being programmed for this machine (rather than the conventional "Tensilcut" router approach -- not described in this report) should provide more accurate and consistent test results. Additional development work is required to support any new specific applications.

E. PROCESS EVALUATION

In order to evaluate the Electrical Discharge Machining process, a series of holes was cut in a strip of 0.062-inch beryllium sheet material. The beryllium sheet, the test coupons, and the electrodes are illustrated in Figure 59. The electrodes were turned from brass tubing. The outside and inside diameters of the roughing and finishing electrodes were 1.330 inches OD and 1.280 inches ID; and 1.340 inches OD and 1.280 inches ID, respectively

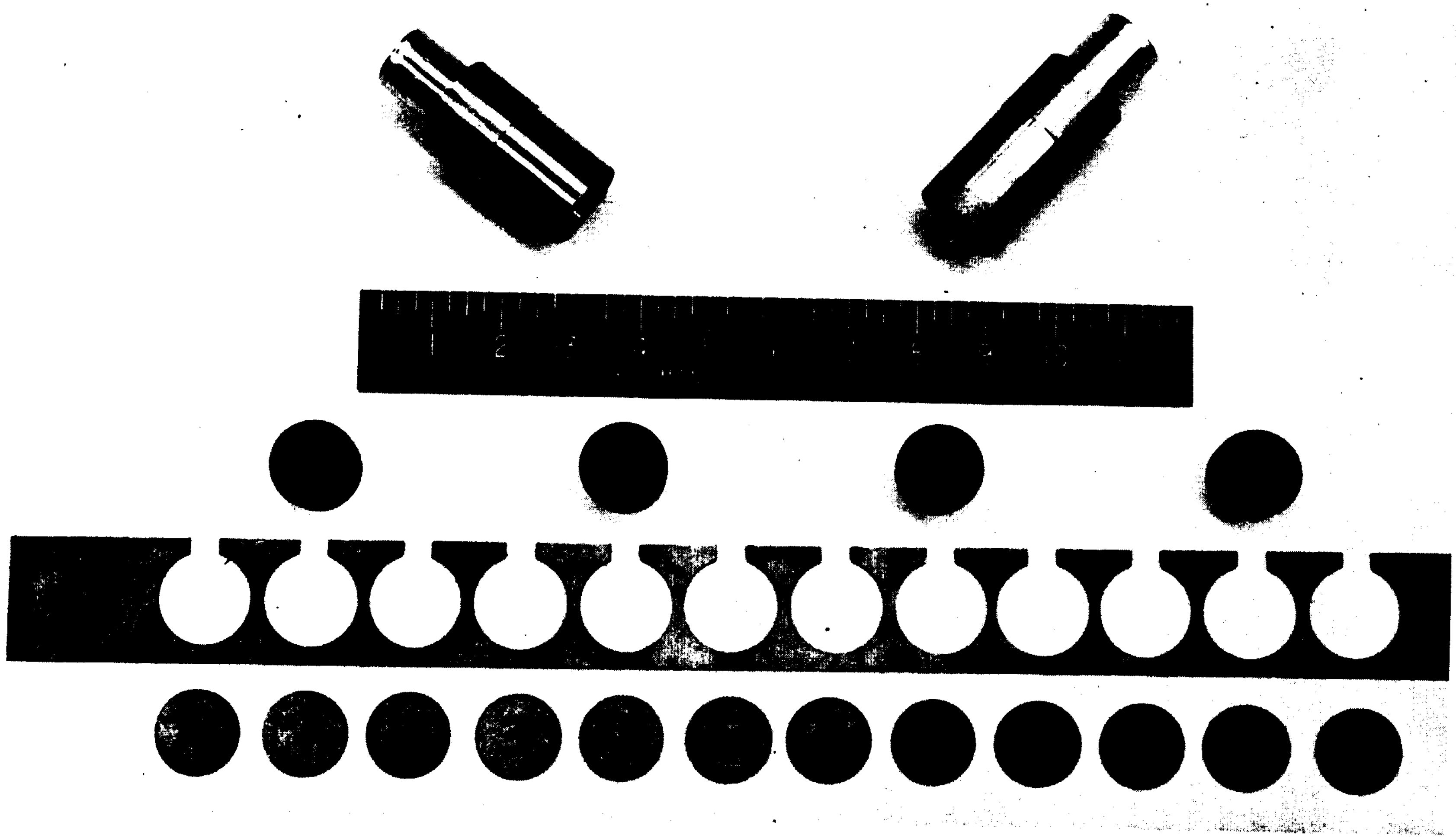
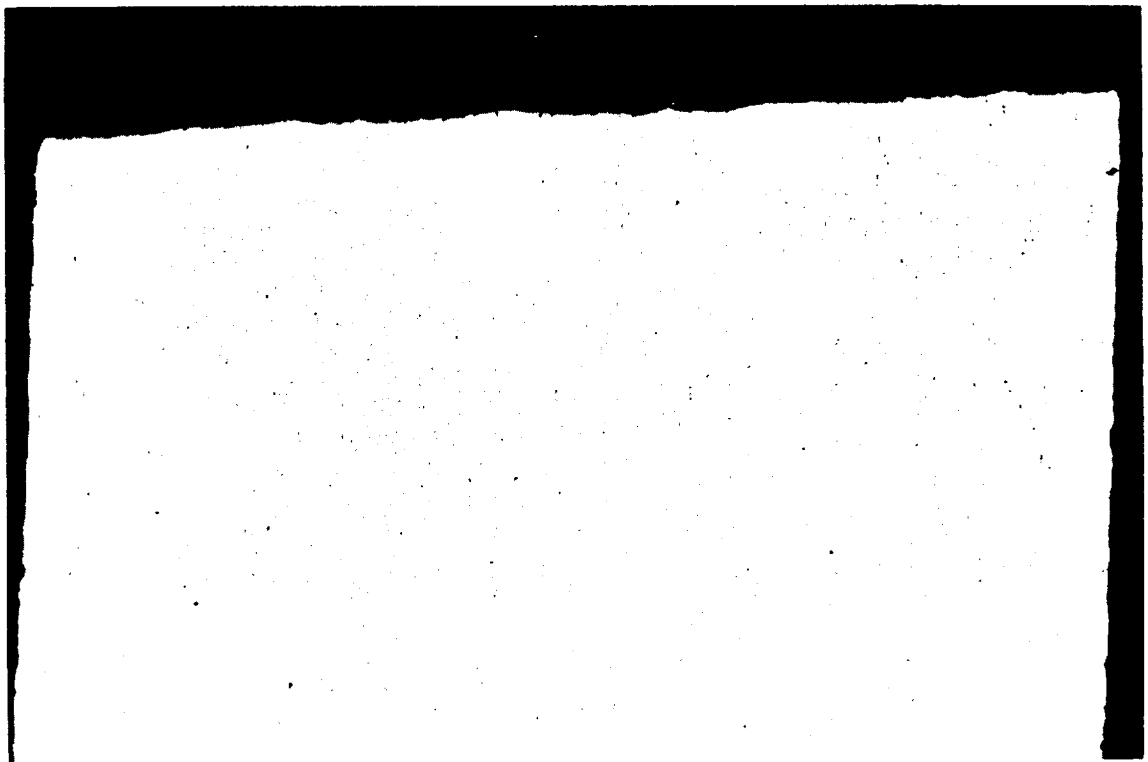
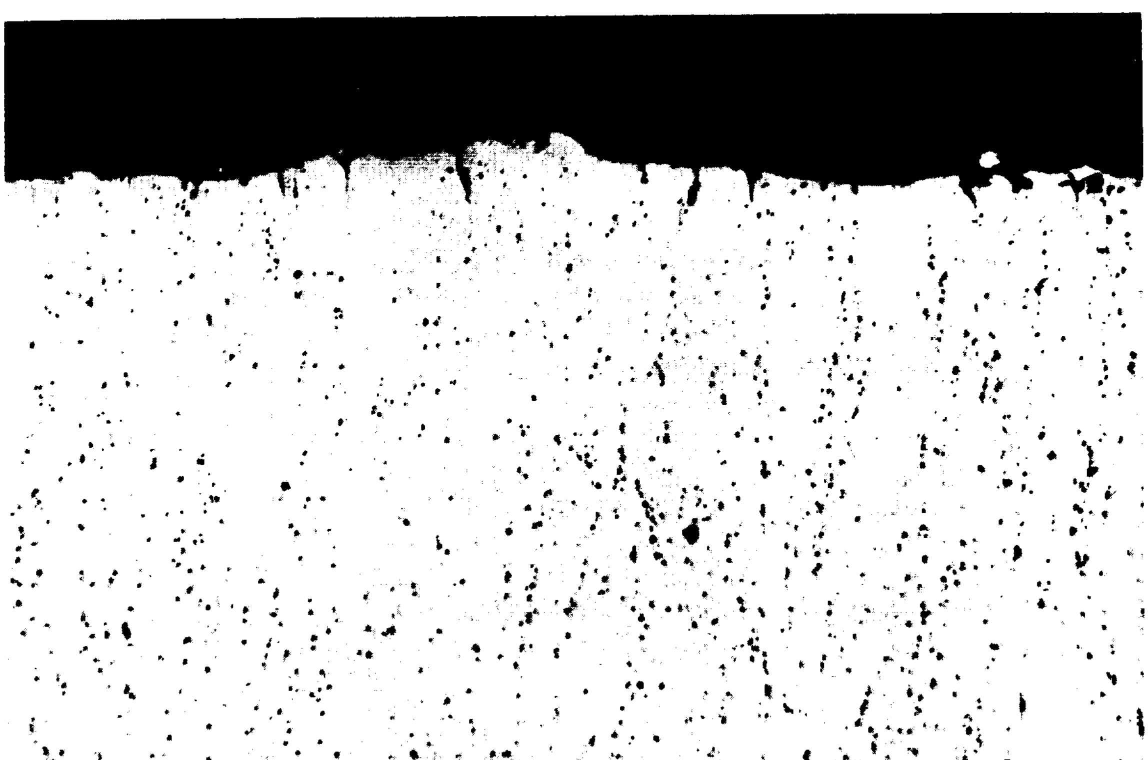


FIGURE 59. TEST COUPONS AND EDM ELECTRODES. ROUGHING ELECTRODE ON RIGHT AND FINISH ELECTRODE ON LEFT



(83X)

FIGURE 60. CROSS-SECTION OF EDM ROUGHING CUT



(500X)

FIGURE 61. CROSS-SECTION OF EDM ROUGHING CUT

The beryllium strip was clamped to an aluminum back-up block and the roughing electrode was mounted in the rotatable spindle. The tap switch was set on No. 5, which provided an operating frequency of 32,000 cycles per second at 4 Mfd, 7.0 amperes, and 74.0 volts.

All the holes were initially "roughed out" in 7 minutes at these settings at a metal removal rate of 1.82 cubic inches per hour. Figures 60 and 61 illustrate the resulting finish. The relatively uneven cut and the frequency of microcracks in the form of basal plane cleavage should be noted.

The roughing electrode was replaced by the finishing electrode and 11 of the 12 holes were "finish cut" at the tap switch settings shown in Table IV.

1. Specimen Preparation. A small wedge section was removed from each hole edge; mounted, ground and polished for microscopic examination in order to determine the effect of EDM machining at various rates on the material physical structure.

Specimen preparation provides a true cross-section of the hole and is therefore normal to the plane of the sheet intercepting the EDM cut surface. No etching was done prior to mounting for metallographic examination in order to preserve the true condition of the hole surface as cut.

All specimens were prepared in the following manner:

a. Mounting - The specimen was mounted in such a manner as to expose the above section surface with the EDM cut constituting one edge of the specimen. The specimen was mounted in green bakelite.

b. Grinding - The specimen was ground in beryllium contamination hoods on successively finer grit silicon carbide abrasive papers from 240 grit to 600 grit.

c. Coarse Polishing - The samples were coarse polished on a 1 micron diamond paste impregnated slipper satin covered polishing lap, using a multiple jig-dop device to eliminate excessive labor.

TABLE IV. EDM MACHING RATES/FINISHES

Tap Switch		Frequency CPS	Amps	Capacitance	Voltage	Work Piece Material	Metal Removal Rate Cu/In - Per Hr.	Surface Finish Micro/In.	Machine Time
11	X	8000	0.2	0.1	100	.062 Beryllium	0.006	10-12	3 hr 15 mi
10	X	32000	0.1	0.2	100		0.045	20	25 min
9	X	130000	0.5	0.05	100		0.125	25	9 min
8	X	260000	2.0	1.0	80		0.095	30	12 min
7	X	130000	2.5	2.0	66		0.285	60	4 min
6	X	65000	3.0	4.0	62		0.19	120	6 min
5	X	32000	4.0	6.0	70		0.388	160	3 min
4	X	16000	5.0	8.0	35		0.143	180	8 min
3	X	8000	6.0	14.0	25		0.380	200	3 min
2	X	4000	8.0	20.0	35		0.760	240	1-1/2 min
1	X	2000	20.0	28.0	40		1.140	280	1 min

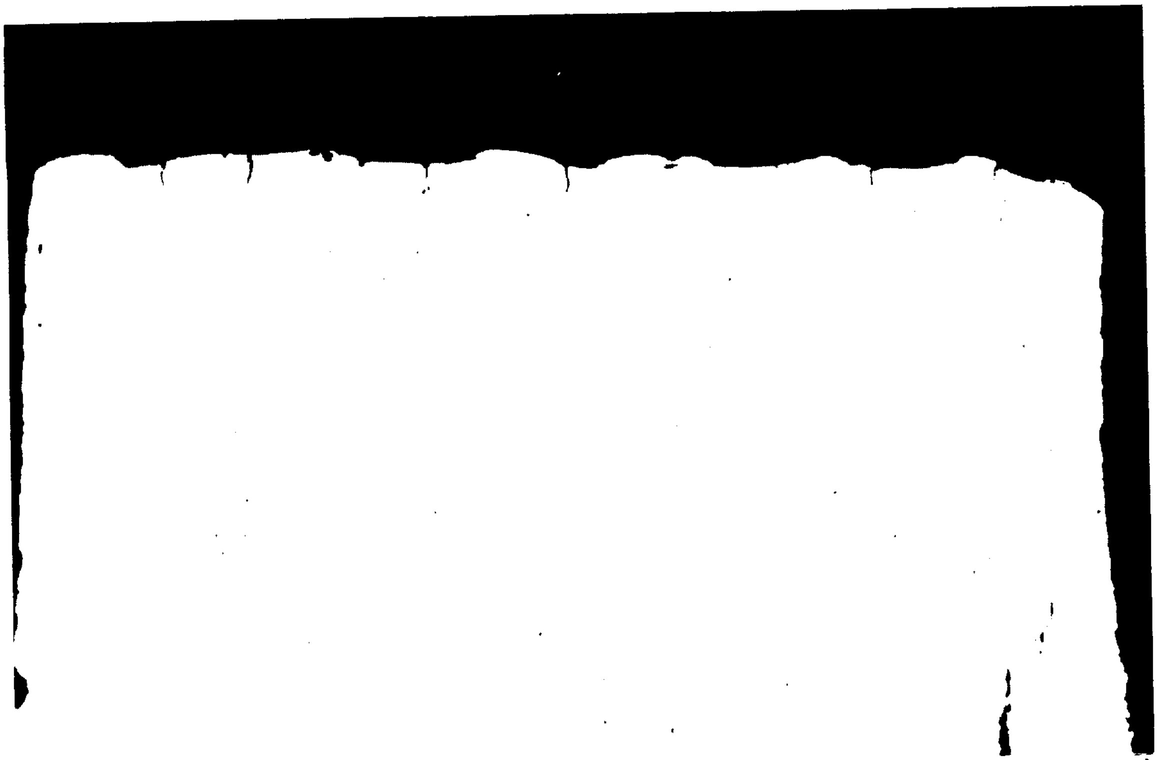
d. Final Polishing - Final polishing was performed on a proprietary automatic polisher of the rotational variety using a maximum load of 250 grams per sample for a minimum period of time (based upon inspection) to provide an adequate surface with a minimum amount of relief and rounding of the EDM cut edge. The polishing was performed in a contained slurrey of "Cer-Cer" metallographic polishing abrasive plus aqueous solutions of NaOH and CrO_3 added independently to produce an approximate pH of 9. This method produces a buffered basic solution to control corrosion of the beryllium. A "microcloth" was used in this operation and was isolated from the metallic polishing lap by a layer of lucite to prevent galvanic action.

e. Examination - No further preparation or etching was required. The specimens were photographed at magnifications low enough to include the entire EDM cut edge (i.e., the cross-sectional thickness of the sheet) and at a higher compromise magnification to show a representative edge and structural details. The magnifications chosen were 83X and 500X, respectively, for 5 by 7-inch plates. The type of illumination chosen was "bright field" reflected light since the examination involved the evaluation of surface contours and laminations produced by the cutting rather than crystalline deformation resulting in twinning etc., which would require polarized illumination.

2. Specimen Evaluation. Even a casual analysis of Table IV and Figures 62 through 71, inclusive, quickly reveals the direct relationship of the current density, discharge frequency, surface finish, and metal removal rate. A closer analysis reveals the severe intergranular cleavage resulting from the rapid cutting rates, which is unacceptable for beryllium, and the very minor damage incurred at the higher frequency, and slower cutting ranges. However, at the extremely high frequencies, the metal removal rates are unacceptably low for production operations.

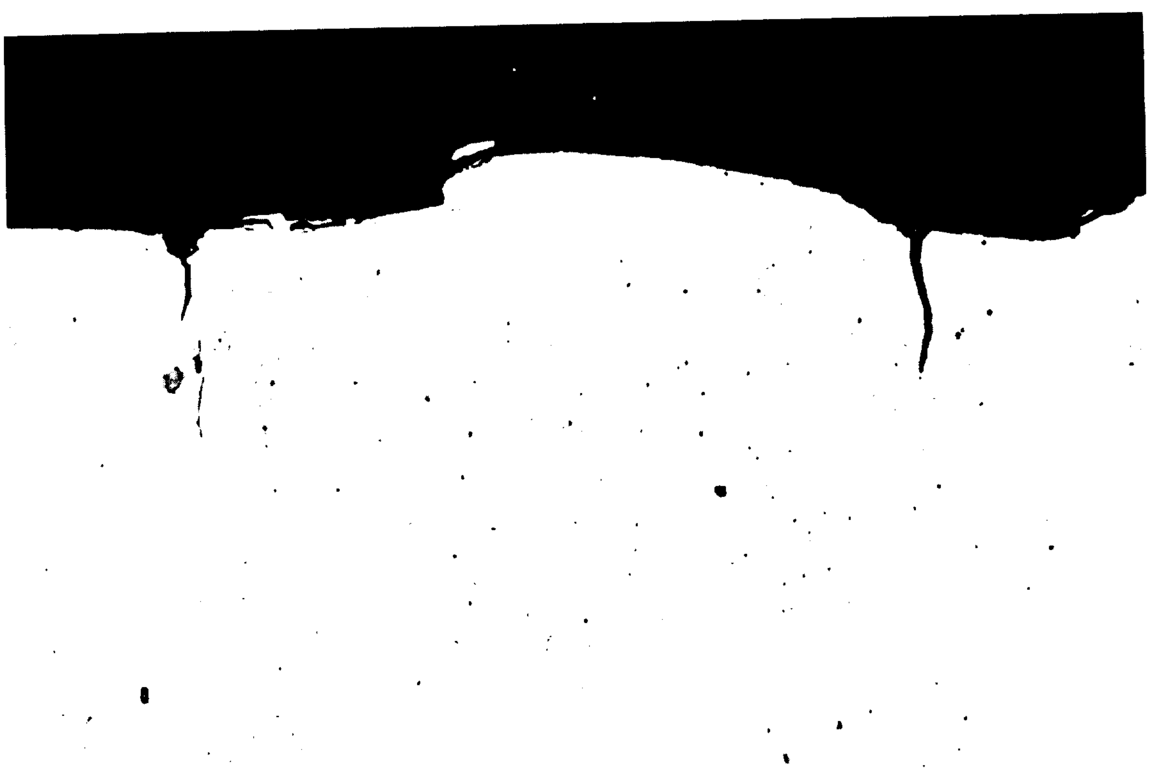
The results of this investigation then can be summarized as follows:

a. Tap switch settings 1 through 4, inclusive, should be used only for rough cuts, or when the tensile, bearing, or fatigue loads are low.



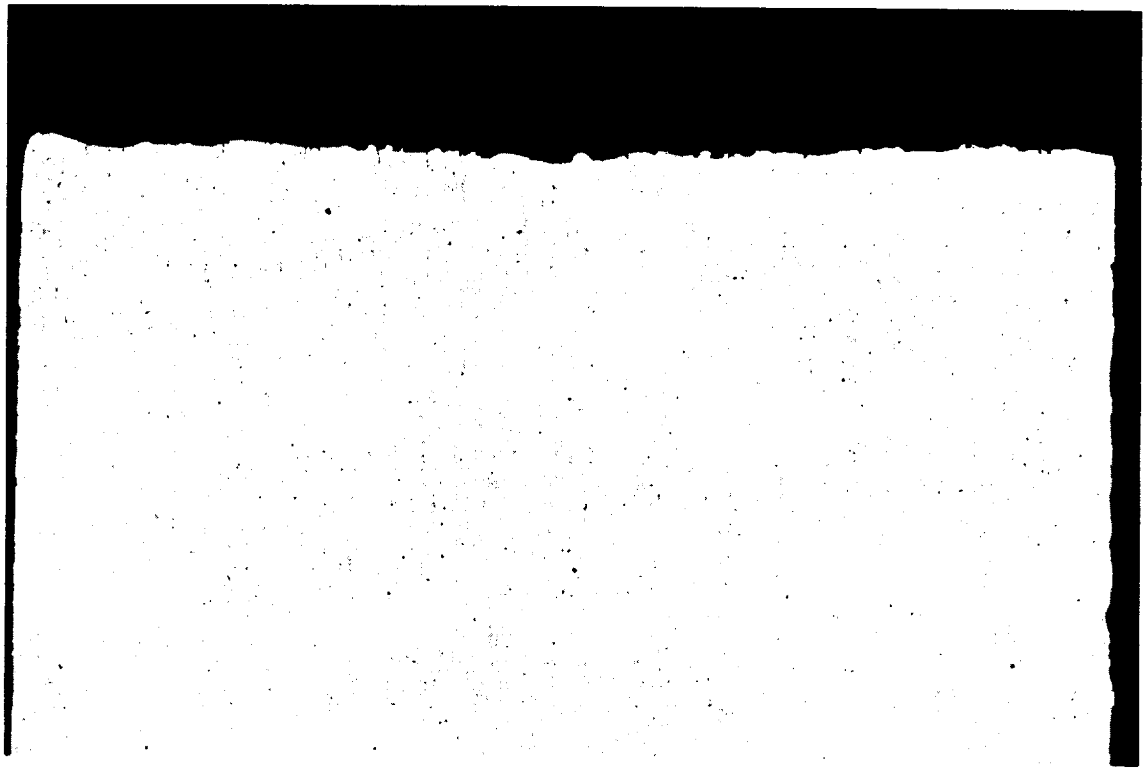
(83X)

FIGURE 62. CROSS-SECTION OF EDM FINISH CUT AT 2,000 CPS. METAL REMOVAL RATE 1.140 CU. IN./HR.



(500X)

FIGURE 63. CROSS-SECTION OF EDM FINISH CUT AT 2,000 CPS. METAL REMOVAL RATE 1.140 CU. IN./HR.

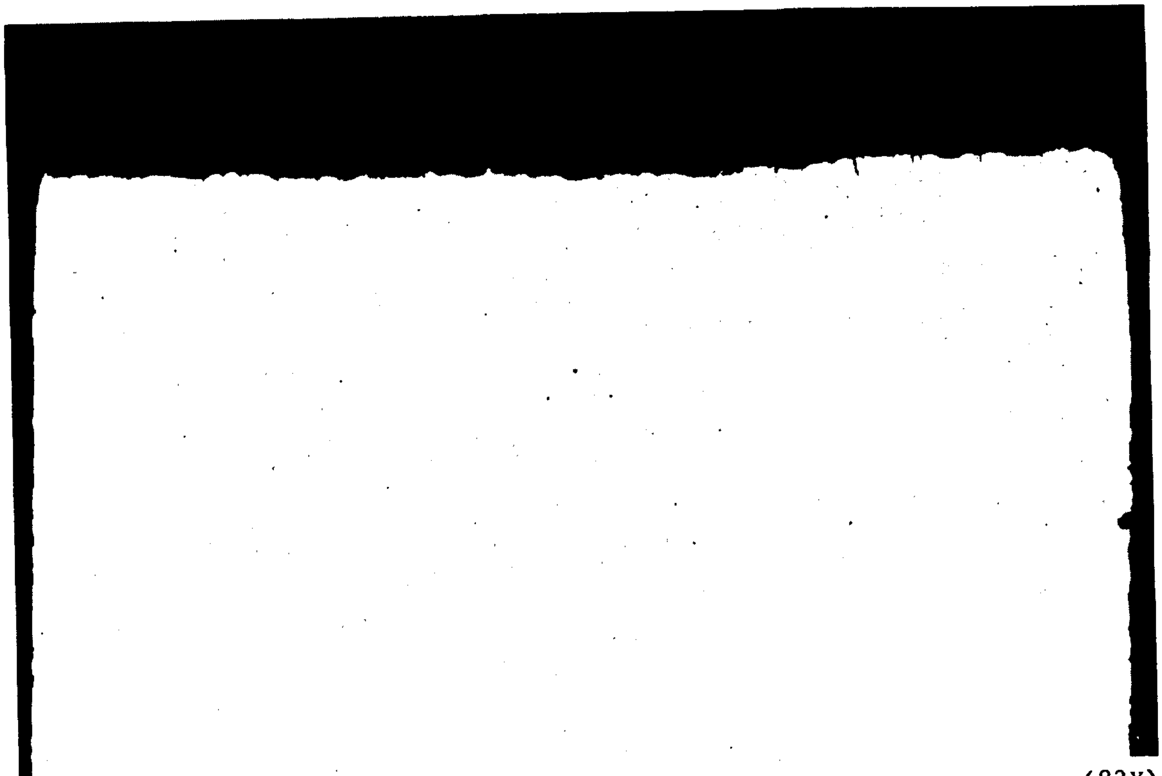


(83X)

FIGURE 64. CROSS-SECTION OF EDM FINISH CUT AT 8,000 CPS. METAL REMOVAL RATE 0.38 CU. IN./ HR.

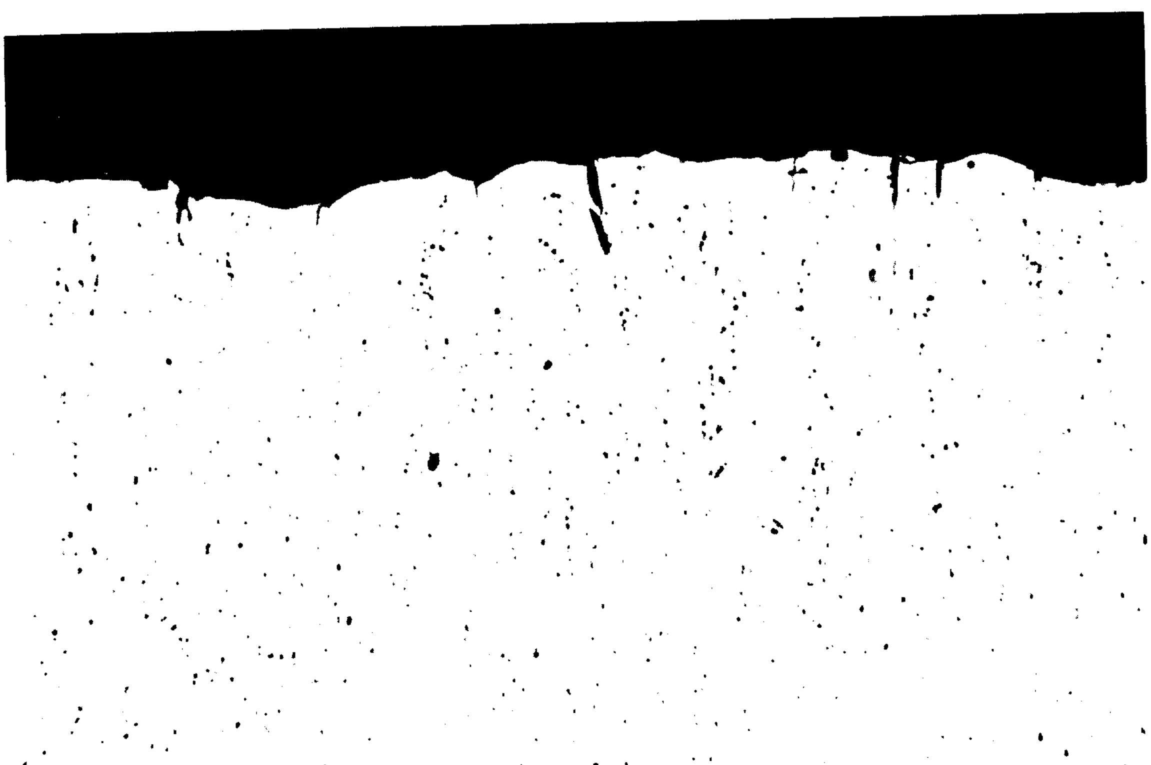
(500X)

FIGURE 65. CROSS-SECTION OF EDM FINISH CUT AT 8,000 CPS. METAL REMOVAL RATE 0.38 CU. IN./HR.



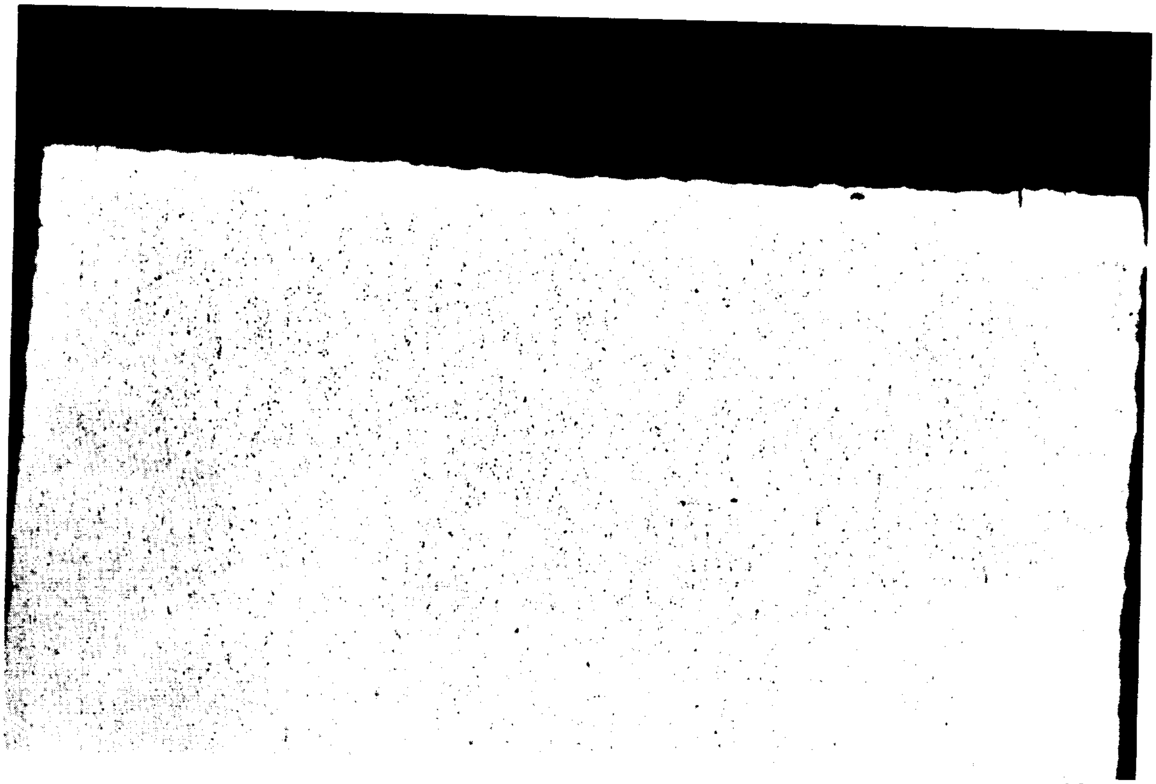
(83X)

FIGURE 66. CROSS-SECTION OF EDM FINISH CUT AT 130,000 CPS. METAL REMOVAL RATE 0.285 CU. IN./HR.



(500X)

FIGURE 67. CROSS-SECTION OF EDM FINISH CUT AT 130,000 CPS. METAL REMOVAL RATE 0.285 CU. IN/HR.

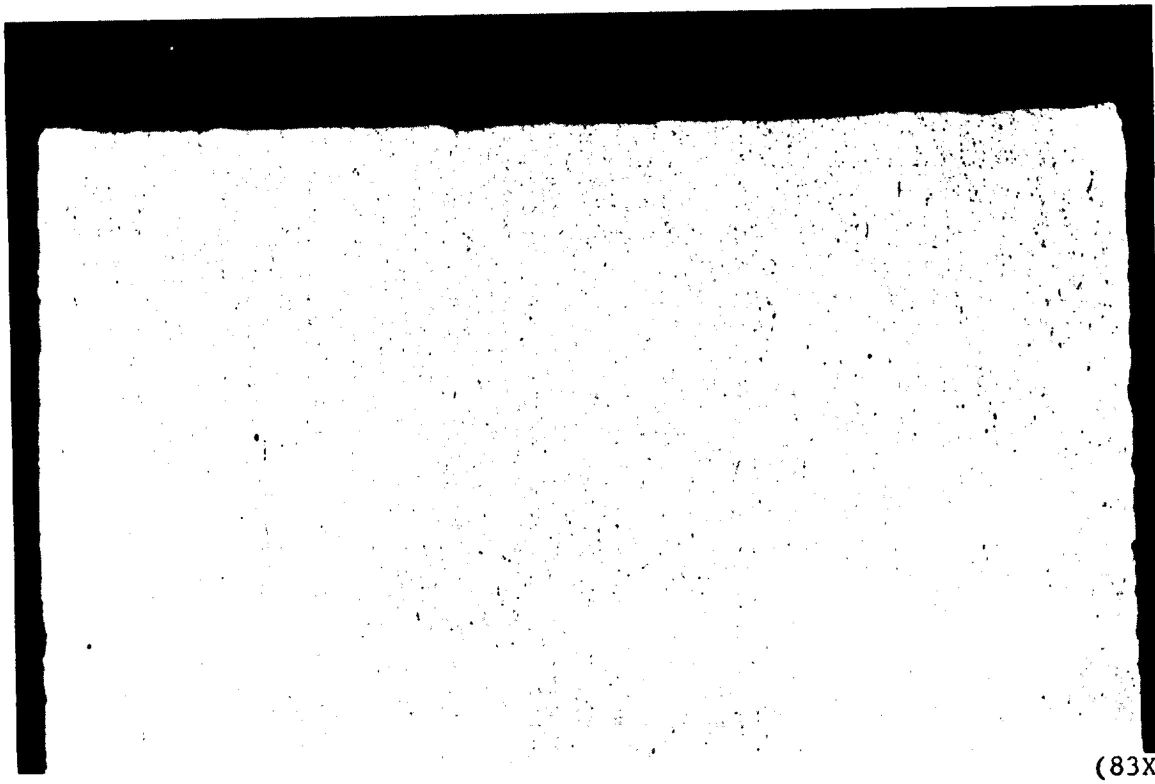


(83X)

FIGURE 68. CROSS-SECTION OF EDM FINISH CUT AT 130,000 CPS. METAL REMOVAL RATE 0.125 CU. IN./HR.

(500X)

FIGURE 69. CROSS-SECTION OF EDM FINISH CUT AT 130,000 CPS. METAL REMOVAL RATE 0.125 CU. IN./HR.



(83X)

FIGURE 70. CROSS-SECTION OF EDM FINISH CUT AT 32,000 CPS.
METAL REMOVAL RATE 0.045 CU. IN./HR.

(500X)

FIGURE 71. CROSS-SECTION OF EDM FINISH CUT AT 32,000 CPS.
METAL REMOVAL RATE 0.045 CU. IN/HR.

b. Tap switch settings 5 through 8, inclusive, are recommended for normal production operations.

c. Tap switch settings 9 through 11, inclusive, are special-purpose settings to be utilized when extremely fine finishes are required and extremely low metal removal rates can be tolerated.

It should be emphasized that the normal etching operation, mandatory subsequent to any machining, will remove all but the most gross defect indicated by the previous examples. It can be concluded, therefore, that the EDM machining of cross-rolled beryllium sheet is an efficient and satisfactory method for metal removal.

SECTION VI. CHEMICAL MILLING

A. GENERAL

Because of its anisotropic grain structure, the removal of relatively small amounts of material from the surface of cross-rolled beryllium sheet by conventional machining methods, without incurring material damage, is rather difficult. The accurate differential reduction in thickness of beryllium material, particularly in an intricate pattern, is proportionally more difficult as the intricacy of the pattern increases. Therefore the chemical milling process was included in this program.

Chemical milling may be defined as the process of removing metal by means of chemical action. This is not a new or revolutionary process; it has been utilized in industry for many years. The principal advantages of the process are as follows:

1. The ease with which complex patterns can be cut in otherwise difficult-to-machine materials.

2. The ease with which differential reductions in material thickness can be accomplished.

3. With accurate temperature and process controls, close tolerances can be attained.

4. Freedom from defects and good finishes are easily attainable.

B. PRESENT CAPABILITY

A typical facility for chemical milling and etching of beryllium consists of tanks and equipment as shown in Figure 72. A tolerance of 0.002 inch is routinely attained during production operations in this type of facility. A typical facility utilizing the chemical milling process is used in the production of "Agena" structural panels. Additional development is required to support a specific application.

C. PROCESS EVALUATION

In order to evaluate the chemical milling process and to increase the knowledge of the process as applied to beryllium, test specimens were chemically milled in four different etchants; Sulfuric Acid, Ammonium Bifluoride, Nitric Acid-Hydrofluoric Acid, and Sulfuric Acid-Phosphoric Acid.

In addition, a chemical polishing bath was used on specimens 20 and 22, following the chemical milling operation, to evaluate the "smoothing" effect on the chemically milled surface. The composition of this bath was as follows:

Chromic Acid	210	gm
Water	350	ml
Sulfuric Acid (95%)	82	ml
Phosphoric Acid (85%)	1500	ml

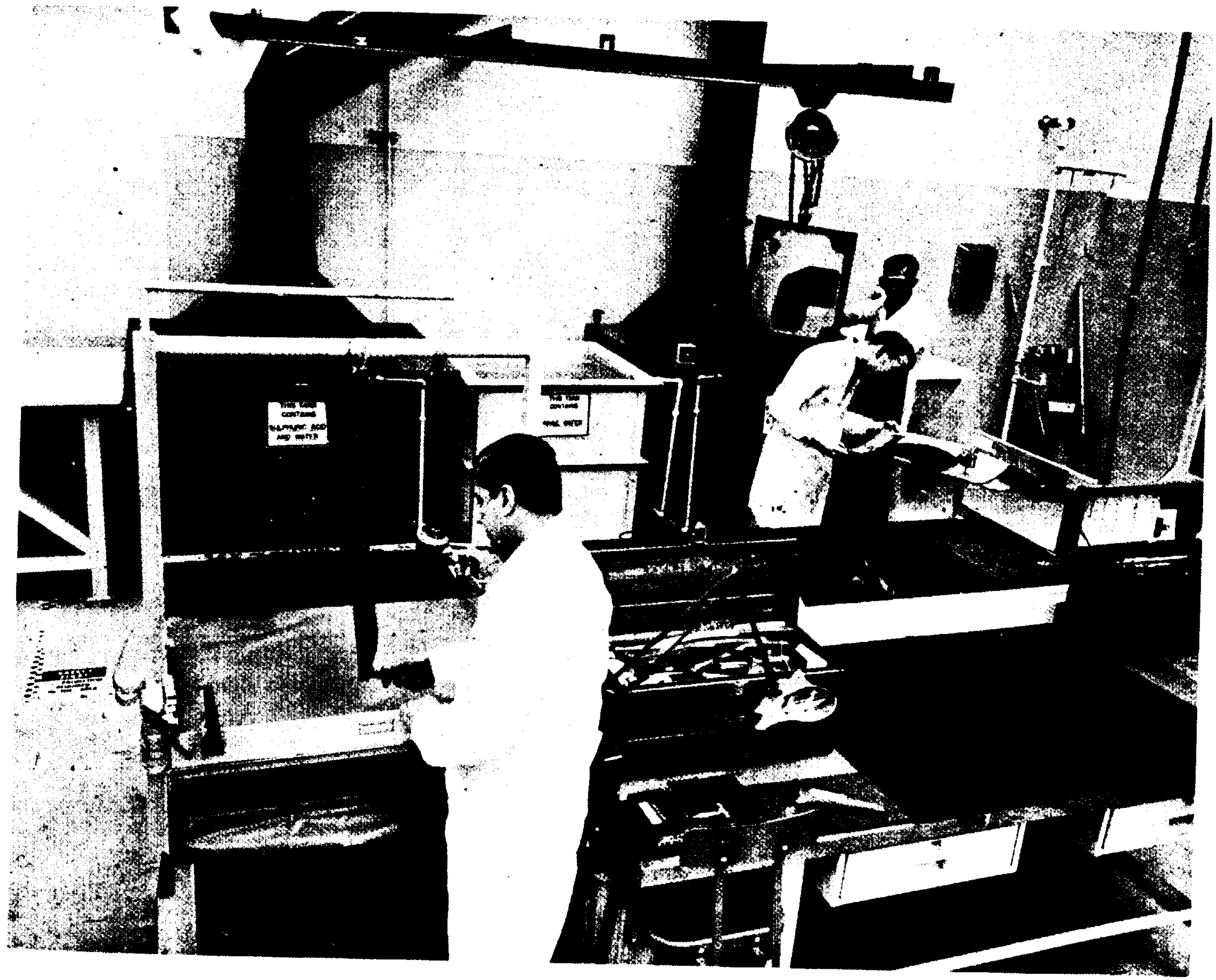


FIGURE 72. CHEMICAL MILLING AND ETCHING FACILITY

Test specimens, approximately 3 inches by 1.75 inches, were cut from the same sheet of 0.125-inch thick beryllium. The specimens were coated with approximately 0.008 inch of "Turcoform Maskant 7A," a neoprene base material, and a "window," approximately 1.8 inches by 1 inch, was made in the mask on one side of the specimens to expose the beryllium to the action of the etchant. A small "window," approximately 0.500 inch by 0.500 inch, was made in the mask on the other side of the specimen, opposite the center of the large "window," to facilitate the taking of accurate thickness measurements. During the chemical milling process, this small opening was covered with 0.005-inch thick vinyl tape to prevent chemical action by the reagent.

All the test specimens were chemically milled in four liter-glass or polypropylene beakers containing three liters of etchant. The ratio of bare beryllium surface to the volume of etchant is included in Table V. The specimens were placed on the bottom of the beaker with the "window side" up. When cooling was required to maintain the etchant temperature within the desired limits, the beaker was placed on a stand in a large water rinse tank. The thickness of each specimen was measured with a micrometer, before and after the chemical milling operation. Profiles of the surface of the "as received" material and of the chemically milled areas were obtained with a micro-inch "Proficorder" (Piloter Type RLC, Model 1; Amplicorder Type RAC, Model 4) manufactured by the Micrometrical Manufacturing Company of Ann Arbor, Michigan. In addition, RMS surface finish data were taken with a Model 3, Type OC Profilometer, also manufactured by the Micrometrical Company. To further aid in the evaluation of the resulting surface finishes, 18X macrophotographs were taken of the "as-received" and chemically milled surfaces.

It should be emphasized that any one item of data is misleading and should not be considered the "whole story." For example, the surface may be very wavy, i.e., completely unacceptable, and yet be quite smooth. The characteristics of the profile peaks and valleys, whether large or small, sharp or rounded, and their frequency and spacing all indicate measures of surface acceptability. The surface of specimen number 8 (Figures 98 and 100) is an excellent example of this combination; the wavy surface is clearly visible to the unaided eye, the macrophotograph and the profile record verify the waviness, and yet the surface smoothness is 100 RMS.

Representative macrophotographs and surface profiles are presented in Figures 73 through 100. The data, developed during the course of this investigation, are summarized in Table V, and are discussed briefly as follows:

1. Sulfuric Acid. Examination of all of the specimens chemically milled with sulfuric acid solutions revealed slightly wavy edges, due to the scribing method used in cutting through the maskant. In all cases, full radii were attained and smooth removal of material occurred at reasonable rates.

The rate of material removal was found to be proportional to both the concentration and the temperature of the sulfuric acid solution. In any case, the solution is highly exothermic and both heating and cooling must be provided to control the temperature of the bath and, thus the etching rate.

The degree of "cratering" appeared to be dependent upon the temperature of the solution. An examination of specimen number 12 (Figures 74 and 86), chemically milled at 80°F - 85°F, reveals extensive shallow cratering; specimen number 21 (Figures 77 and 79), chemically milled at 90°F - 95°F contains only vestiges of the craters visible on specimen number 12. Increasing the temperature of the solution to 90°F - 105°F very nearly eliminated the "cratering" but did induce some random pitting. Chemically polishing one of the specimens (No. 22) sufficiently to remove 0.001 inch of material brightened the surface but did not eradicate the slight pitting.

Because of this cratering effect at the lower temperatures, a minimum temperature of 100°F is recommended. As previously stated, and as shown in Table V, the metal removal rate is sensitive to both changes in concentration and temperature. These variables must be closely controlled to provide a predictable etching rate. Therefore, both heating and cooling capabilities with good thermostatic control, solution level control, and frequent solution analyses and replenishment are necessary to ensure accurate control of the chemical milling process. Otherwise, dimensional control can be maintained only by accomplishing the operation in short duration steps combined with frequent thickness measurements. Under such circumstances,

TABLE V. CHEMICAL MILLING

Specimen Number	Etchant	Temperature F Min	Temperature F Max	Sq. In. Be per Gal.	Time Minutes	Matl. Removed Inches/Side	Surface-RMS As Rec.	Surface-RMS Chem.Mill.	Cooled
1	5% H_2SO_4	76	78	2.3	60	0.014	25	150	No
5	10% H_2SO_4	86	110(1)	2.3	60	0.111	20	50	Yes
12	10% H_2SO_4	80	85	2.3	60	0.033	20	85	No
21(2)	10% H_2SO_4	90	95	3.9	60	0.050	20	95	Yes
22(2)	10% H_2SO_4	90	95	3.9	60	0.050			Yes
	Chemical Polish	74	81	3.4	30	0.51 (3)	18	65	No
14	10% H_2SO_4	98	105	2.3	60	0.063	17	125	Yes
16	7.5% H_2SO_4	98	102	2.3	60	0.047	15	95	No
18	12.5% H_2SO_4	95	105	2.3	60	0.077	19	40	Yes
2	5% NH_4HF_2	68	72	2.3	60	0.010	50	250	No
15	7.5% NH_4HF_2	83	86	2.3	60	0.024	16	150	No
6	10% NH_4HF_2	86	88	2.3	60	0.032	23	150	No
10	15% NH_4HF_2	80	85	2.3	60	0.035	19	250	No
13	20% NH_4HF_2	82	87	2.3	60	0.037	14	80	Yes
23	30% NH_4HF_2	82	88	2.3	60	0.056	20	280	Yes
17	15% NH_4HF_2	96	105	2.3	60	0.061	24	50	No
19(4)	15% NH_4HF_2	67	88	3.4	120	0.052	18	150	No
20(4)	15% NH_4HF_2	67	88	3.4	120	0.053			No
	Chemical Polish	70	78	3.4	30	0.054 (3)	18	90	No

TABLE V. CHEMICAL MILLING (CON'T.)

Specimen Number	Etchant	Temperature °F Min	Temperature °F Max	Sq. In. Be per Gal.	Time Minutes	Matl. Removed Inches/Side	Surface-RMS As Rec.	Surface-RMS Chem.Mill.	Cooled
3	45% HNO_3 + 1% HF	78	78	2.3	60	0.005	20	100	No
7	45% HNO_3 + 3% HF	78	80	2.3	60	0.010	21	110	No
9	50% HNO_3 + 25% HF	80	128(5)	2.3	45	0.073 (6)	19	90	Yes(1)
11	50% HNO_3 + 25% HF	76	78	2.3	60	0.028	25	100	Yes
4	50% H_3PO_4 + 20% H_2SO_4	70	73	2.3	60	0.004	18	100	No
8	5 (7) H_3PO_4 + 5 $H_2O+2H_2SO_4$	90	88	2.3	6	0.008	20	100	No

(1) Approximate peak temperature - cooled to 105°F when reaction became too violent
(2) Specimens 21 and 22 chemical milled together
(3) Total material removed - chemical milling plus chemical polishing
(4) Specimens 19 and 20 chemical milled together
(5) Runaway reaction after approximately 40 minutes
(6) Maximum removed - some chemical attack on protected side of specimen
(7) Parts by volume

the accomplishment of close tolerance work would be very difficult.

It should be noted that the metal removal rate becomes very high at temperatures slightly above the recommended operating range, and the heat produced during the reaction with the beryllium, if not controlled, can easily cause a runaway reaction.

Although sulfuric acid is a satisfactory reagent for the chemical milling of beryllium, a residue remains on the surface which must be removed by a subsequent operation. This residue can be removed by vigorous washing, scrubbing, or, more easily, by briefly immersing the beryllium in a Nitric acid-hydrofluoric acid bath and rinsing with water.

2. Ammonium Bifluoride. The radii and edges of the specimens chemically milled with ammonium bifluoride were very similar to those attained with the sulfuric acid solutions.

The chemically milled surfaces were textured in appearance and somewhat rougher than the surfaces chemically milled with sulfuric acid. There was, however, no evidence of deep pitting. The chemical polishing of one of the specimens did brighten the surface, but did not remove its textured appearance. The lower concentrations, 5 percent and 7.5 percent of ammonium bifluoride produced some shallow cratering. Figures 82 and 84 show this effect.

However, unlike sulfuric acid, the etching rate of ammonium bifluoride is not highly sensitive to the solution concentration. The rate, at solution concentrations varying from 10 percent to 20 percent, and within a temperature range of 80°F - 90°F, is quite constant; between 15 percent and 20 percent, it is relatively insensitive. Under these conditions, the resulting metal removal rate will be approximately 0.0005 inch per minute on the exposed material. The rate, however, is very sensitive to variations in solution temperature; an increase in the nominal operating temperature from 85°F to 100°F very nearly doubles the etching rate.

Because of the large amount of heat produced during the reaction, thermostatically controlled heating and cooling equipment are required to provide a predictable rate of metal removal.

3. Nitric Acid-Hydrofluoric Acid. The radii and edges of the specimens chemically milled with the nitric acid-hydrofluoric acid solution were uneven and evidence of double radii was visible to the unaided eye. The solution containing a low percentage of hydrofluoric acid tended to produce deep pits; the solution containing a high concentration of hydrofluoric acid produced a "wavy" surface. Figures 93 through 96 clearly illustrate these conditions. This combination of acids either reacted very slowly or with uncontrollable violence.

4. Sulfuric Acid-Phosphoric Acid. The radii were uneven and extremely undercut. The 50 percent phosphoric acid 20 percent sulfuric acid solution caused widespread cratering as shown in Figures 97 and 99. The high water content solution, used to chemically mill specimen number 8, caused a hill-and-valley effect combined with numerous nodules. Figures 99 and 100 clearly illustrate this condition.

D. RESULTS

Both the sulfuric acid and the ammonium bifluoride solutions etched the metal smoothly at reasonable rates, although the rate of metal removal was found to be very dependent upon the temperature of the solutions. Due to its relative insensitivity to variations in concentration, compared with sulfuric acid, the etching rate was much more easily controlled, and more predictable with ammonium bifluoride.

The nitric-hydrofluoric acid solution either reacted very slowly or with uncontrollable violence. Because of this condition, it is recommended that the use of this reagent be limited to light etching, the removal of machine induced surface damage, and the removal of the surface residue remaining after a sulfuric acid chemical milling operation. No further work is recommended.

The phosphoric acid-sulfuric acid solution not only reacted very slowly, but also had a destructive effect on the surface quality. No further work is recommended.

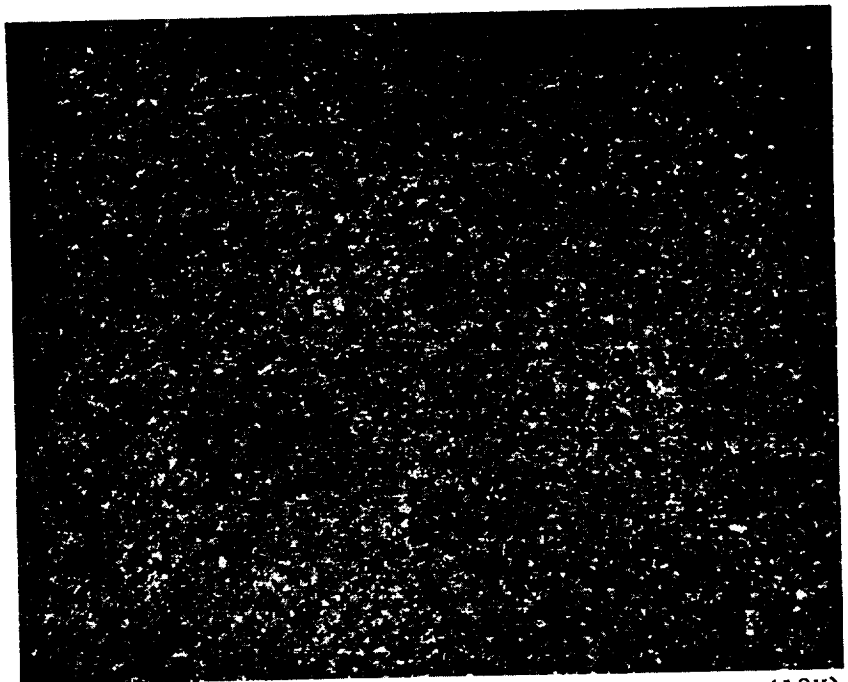


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FIGURE 73. MACROPHOTOGRAPH OF "AS RECEIVED" BERYLLIUM

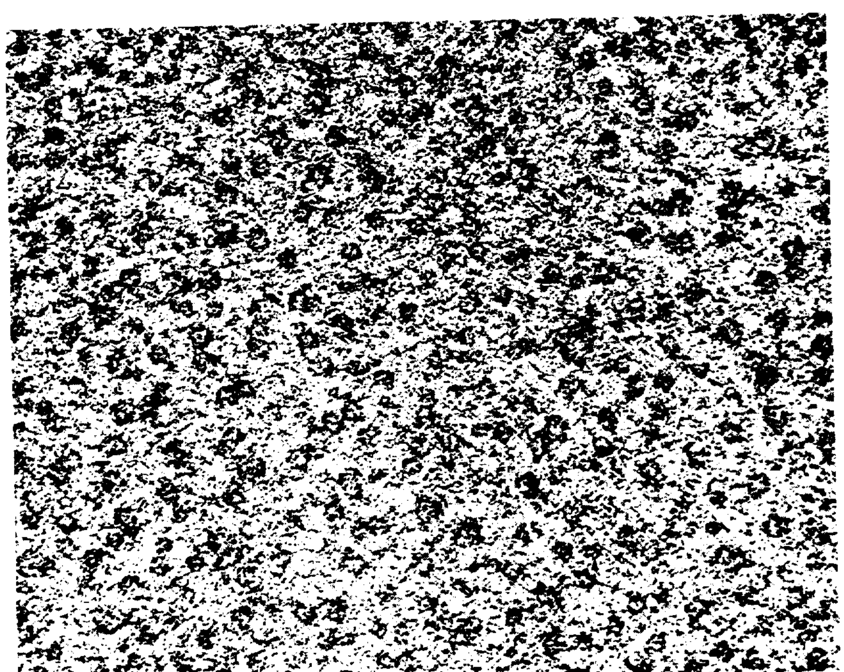

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FIGURE 74. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 10% SOLUTION OF SULFURIC ACID (SPECIMEN NO. 12)

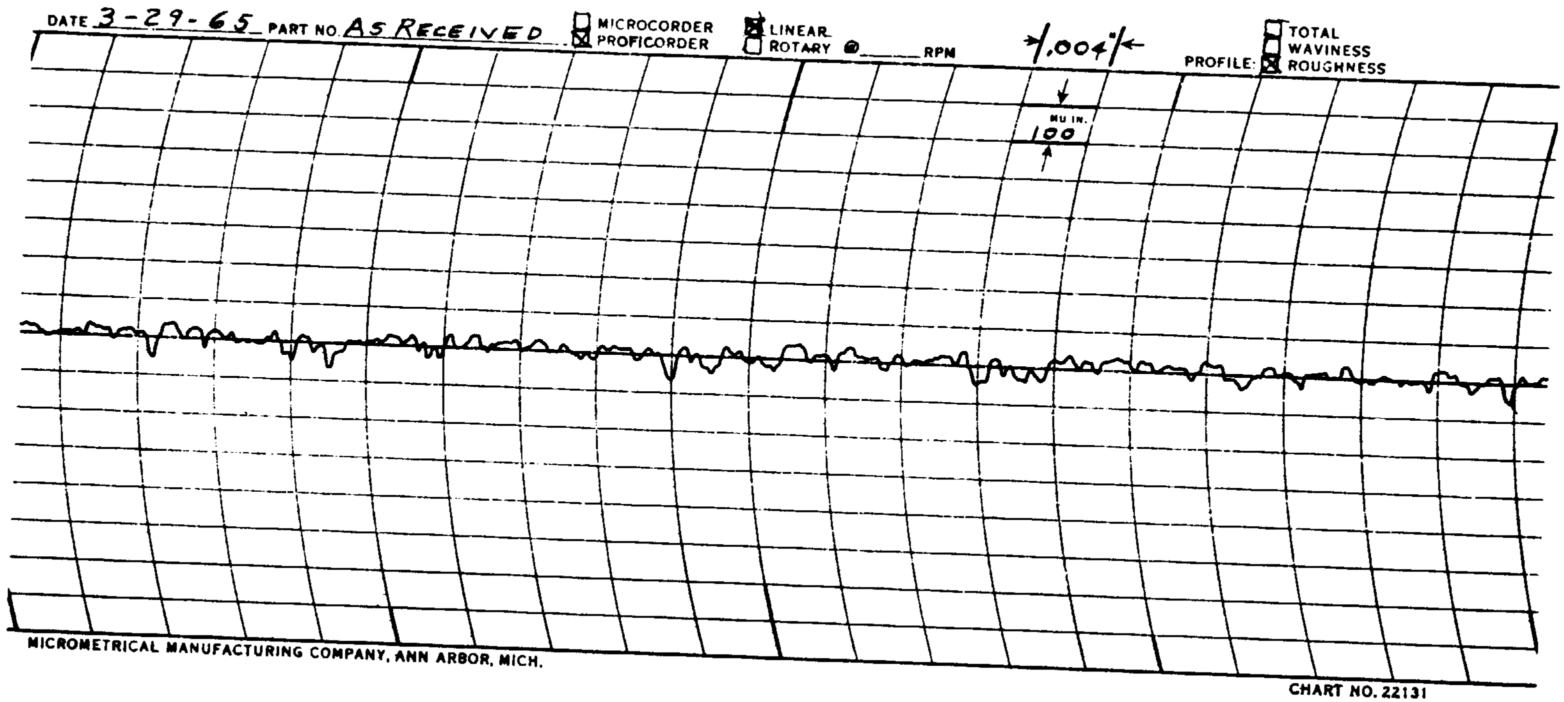

FIGURE 75. PROFILE OF "AS RECEIVED" BERYLLIUM

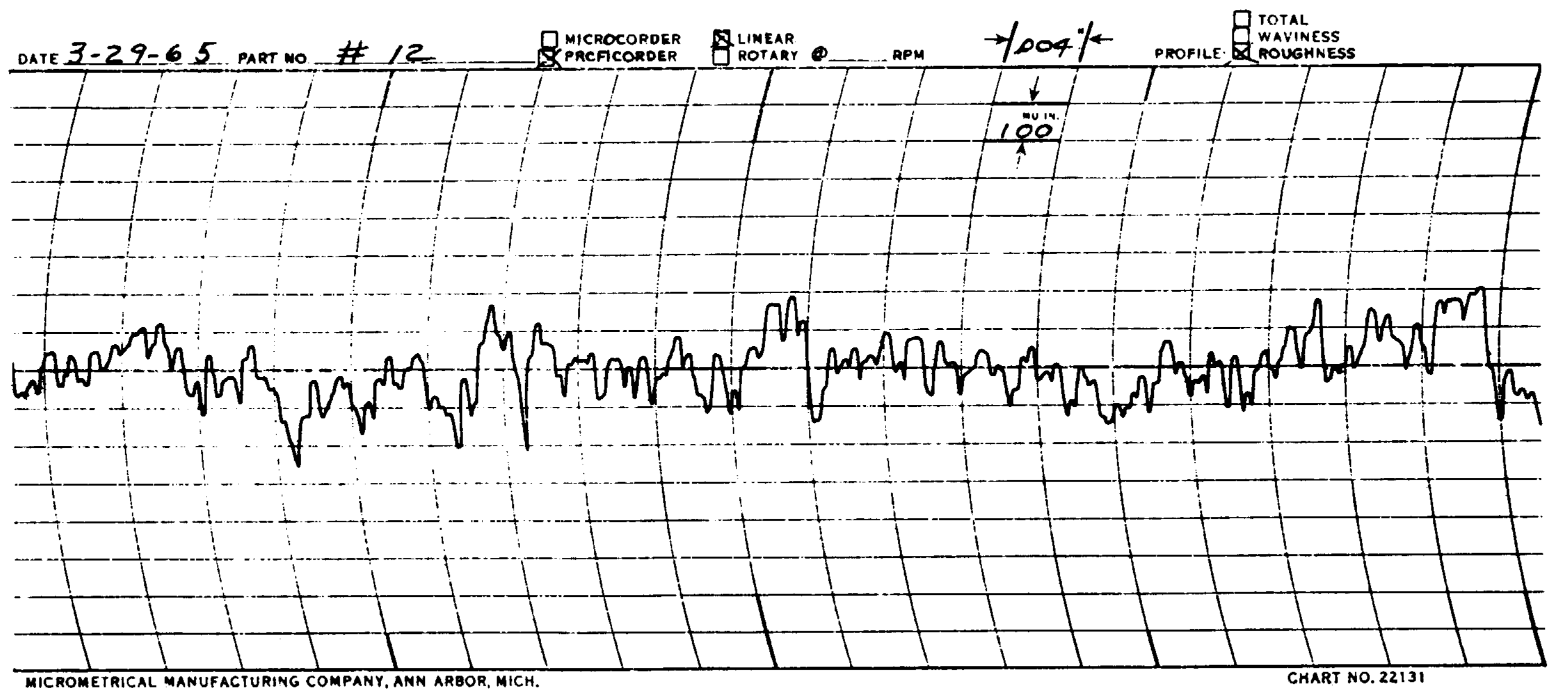

FIGURE 76. PROFILE OF AREA CHEMICALLY MILLED WITH A 10% SOLUTION OF SULFURIC ACID

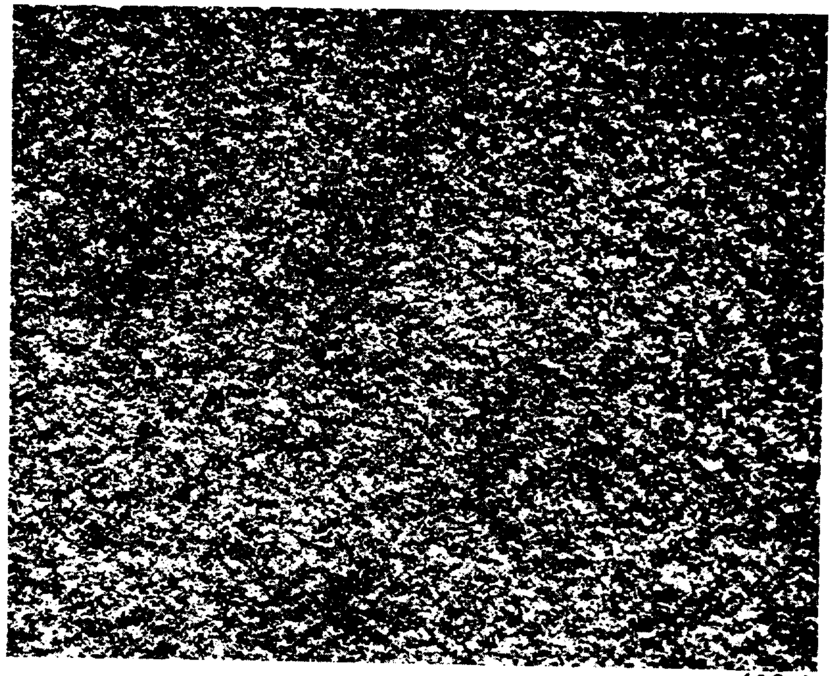

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FIGURE 77. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 10% SOLUTION OF SULFURIC ACID (SPECIMEN NO. 21)

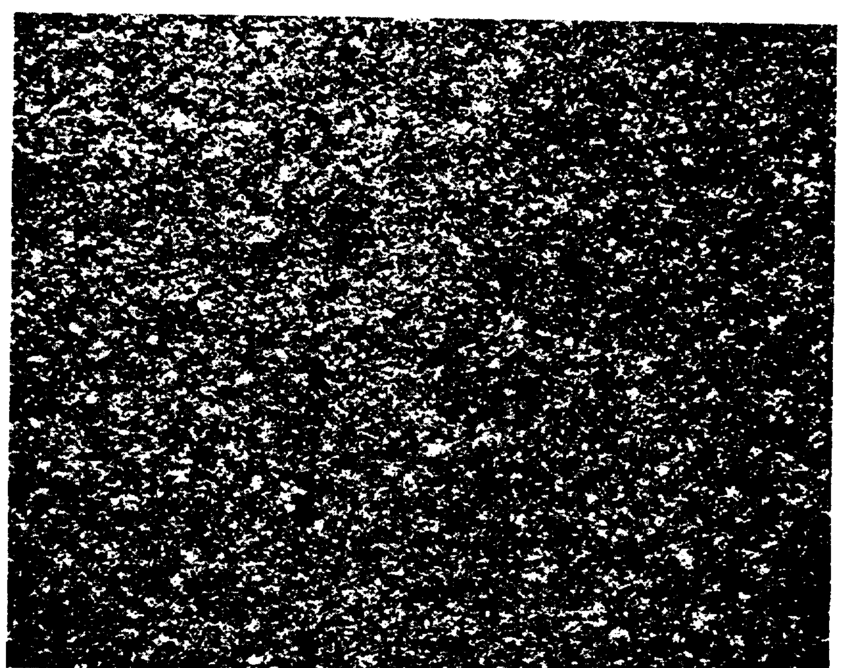

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FIGURE 78. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 7.5% SOLUTION OF SULFURIC ACID (SPECIMEN NO. 16)

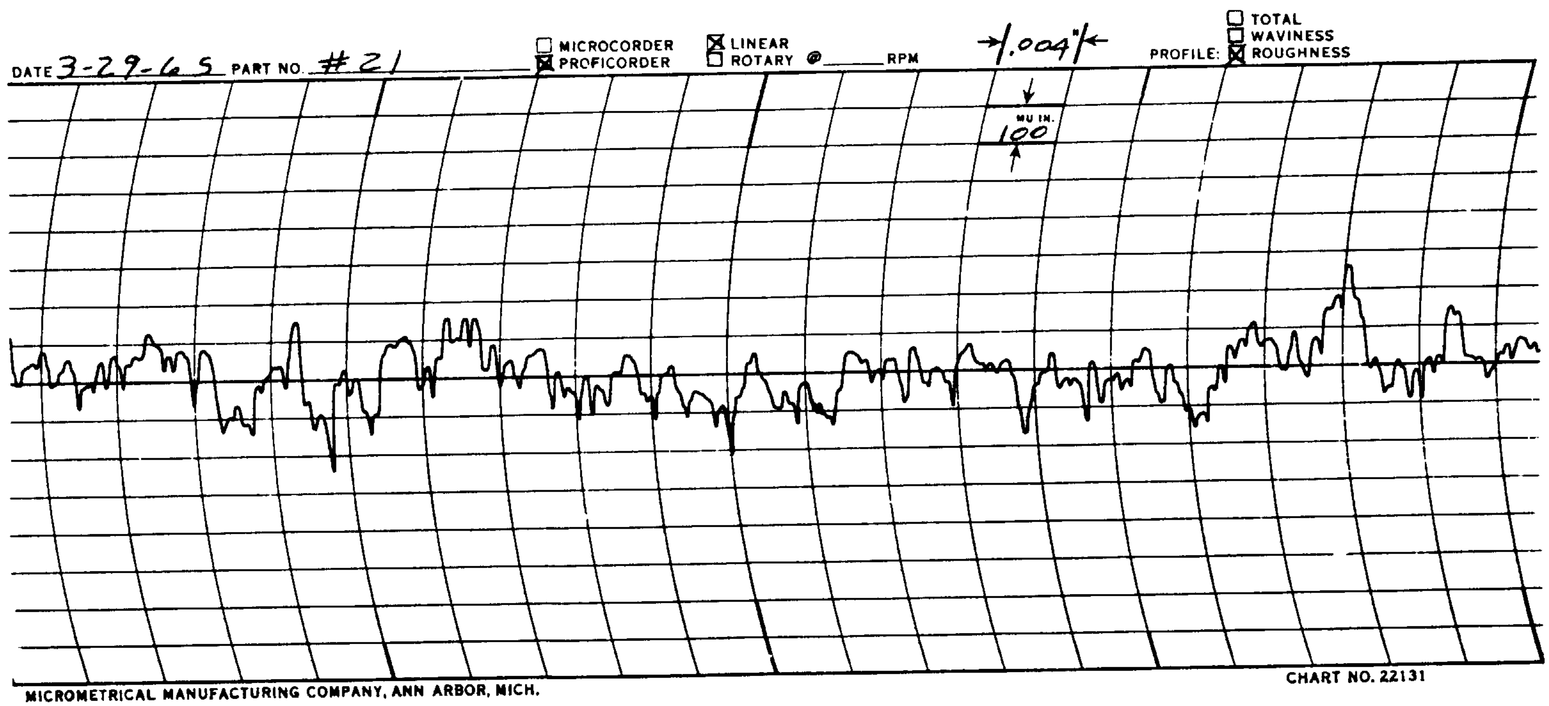

FIGURE 79. PROFILE OF AREA CHEMICALLY MILLED WITH A 10% SOLUTION OF SULFURIC ACID

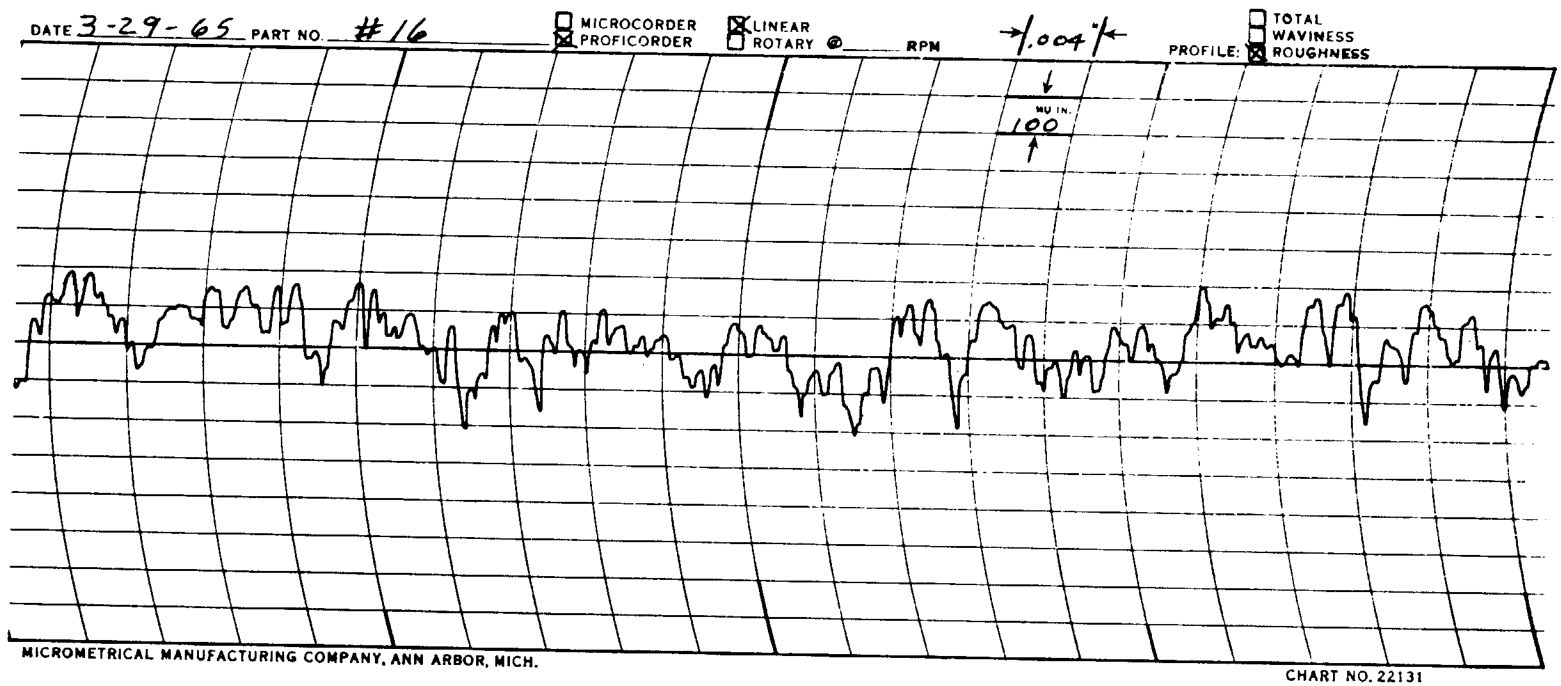

FIGURE 80. PROFILE OF AREA CHEMICALLY MILLED WITH A 7.5% SOLUTION OF SULFURIC ACID

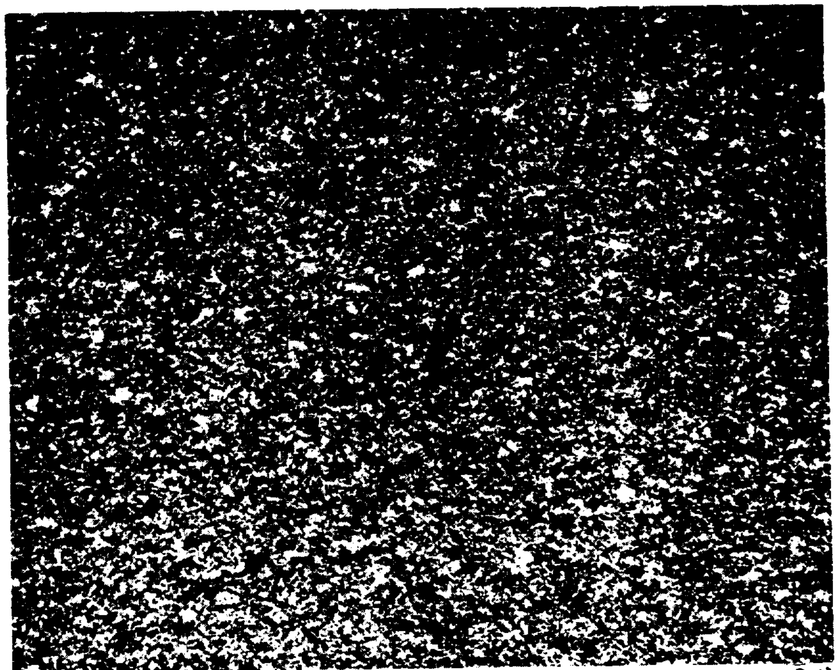

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FIGURE 81. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 12.5% SOLUTION OF SULFURIC ACID (SPECIMEN NO. 18)

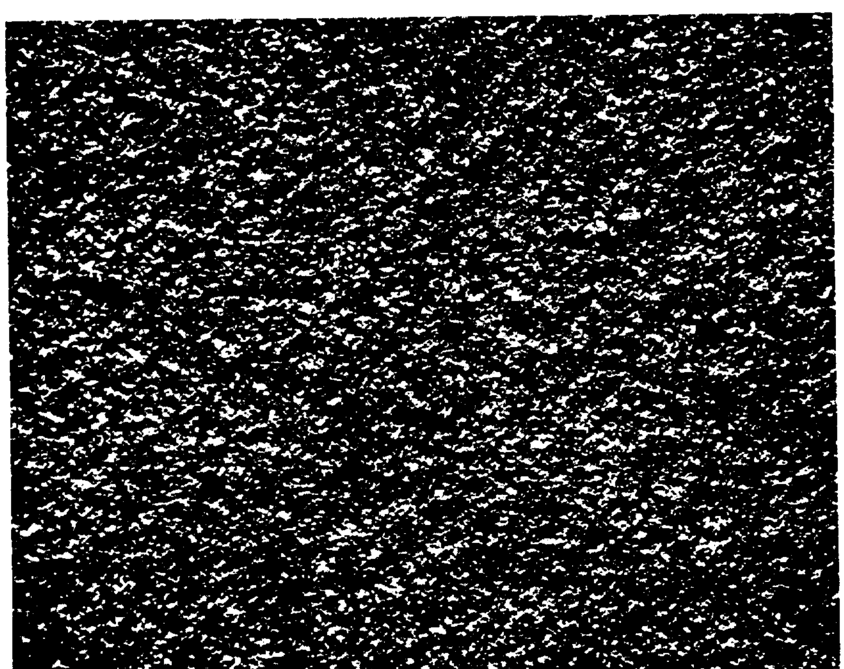

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FIGURE 82. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 7.5% SOLUTION OF AMMONIUM BIFLUORIDE (SPECIMEN NO. 15)

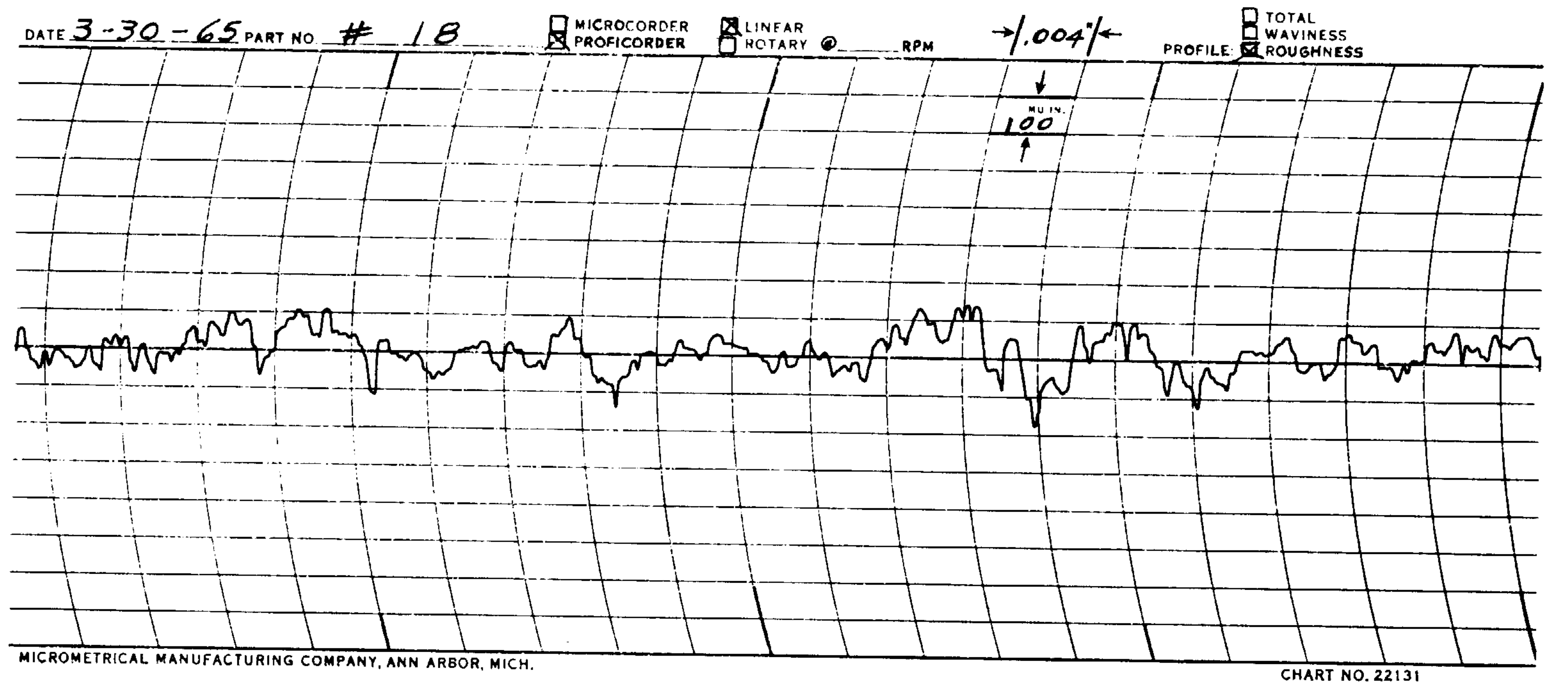

FIGURE 83. PROFILE OF AREA CHEMICALLY MILLED WITH A 12.5% SOLUTION OF SULFURIC ACID

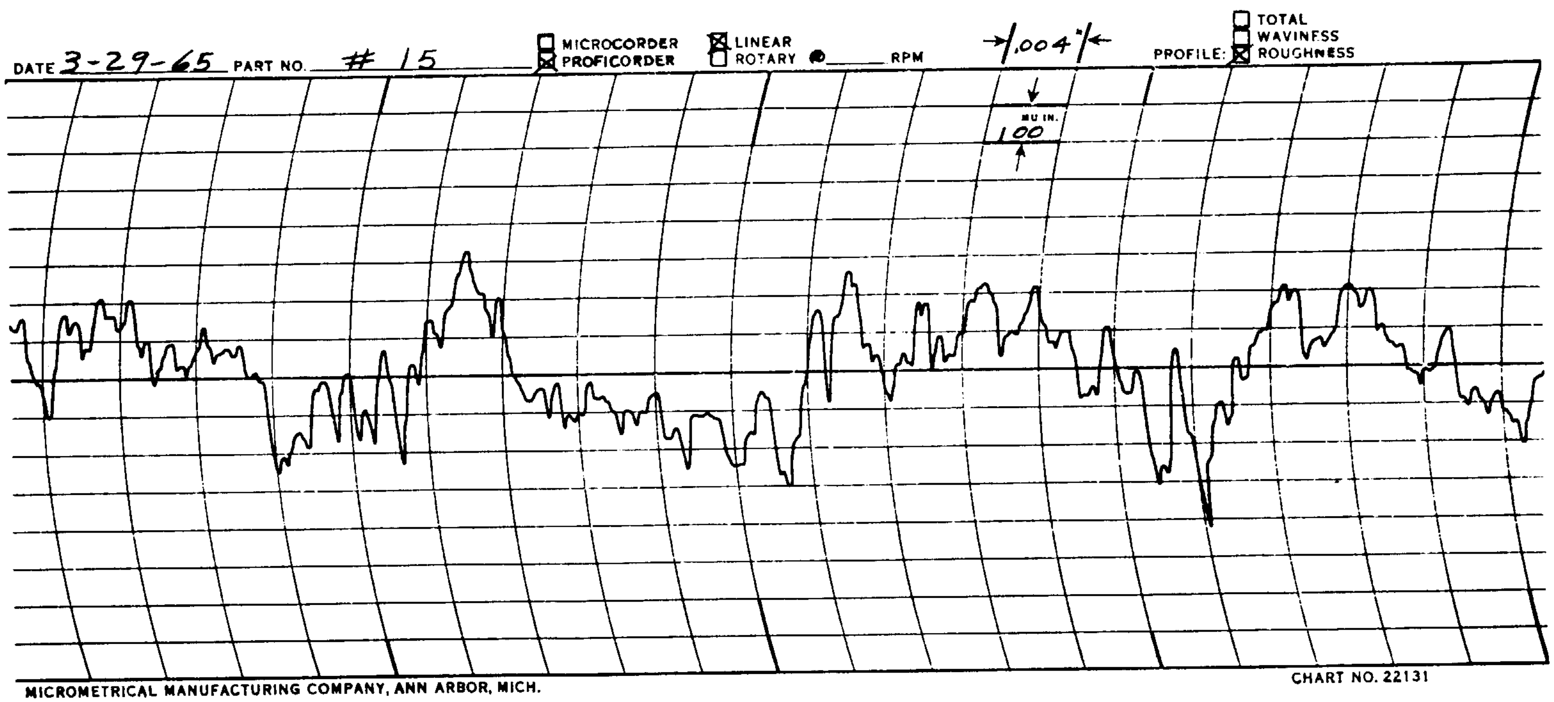

FIGURE 84. PROFILE OF AREA CHEMICALLY MILLED WITH A 7.5% SOLUTION OF AMMONIUM BIFLUORIDE

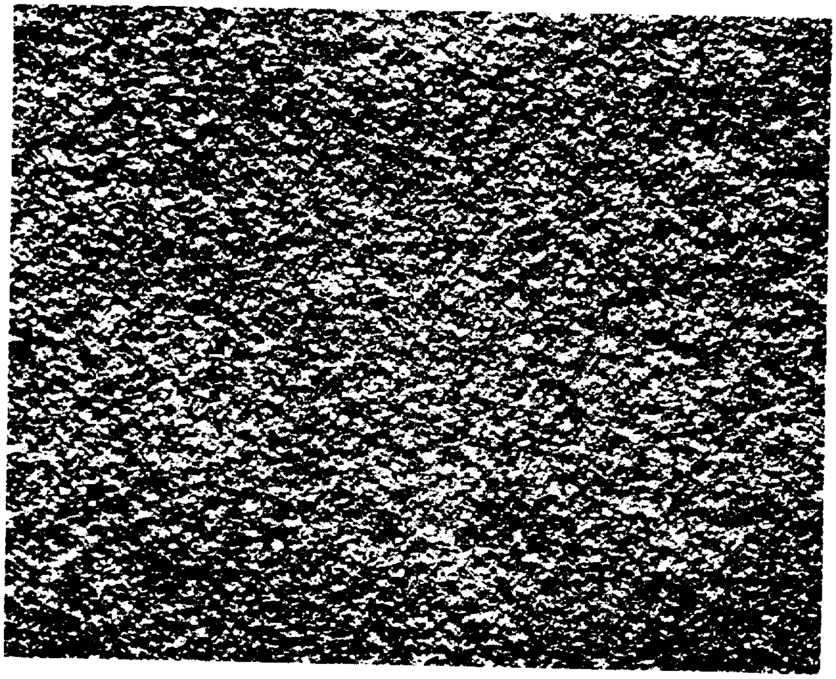

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FIGURE 85. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 10% SOLUTION OF AMMONIUM BIFLUORIDE (SPECIMEN NO. 6)

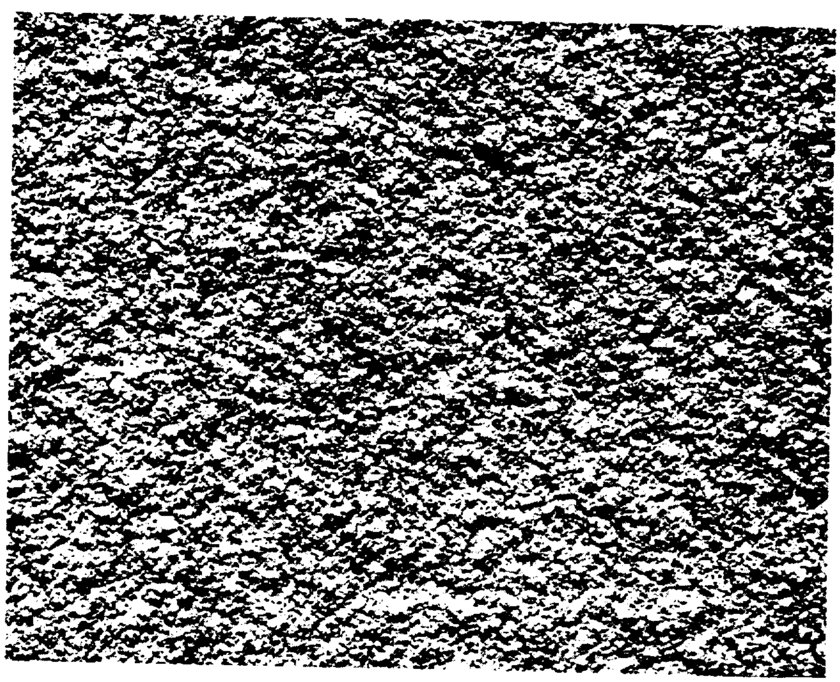

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FIGURE 86. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 15% SOLUTION OF AMMONIUM BIFLUORIDE (SPECIMEN NO. 10)

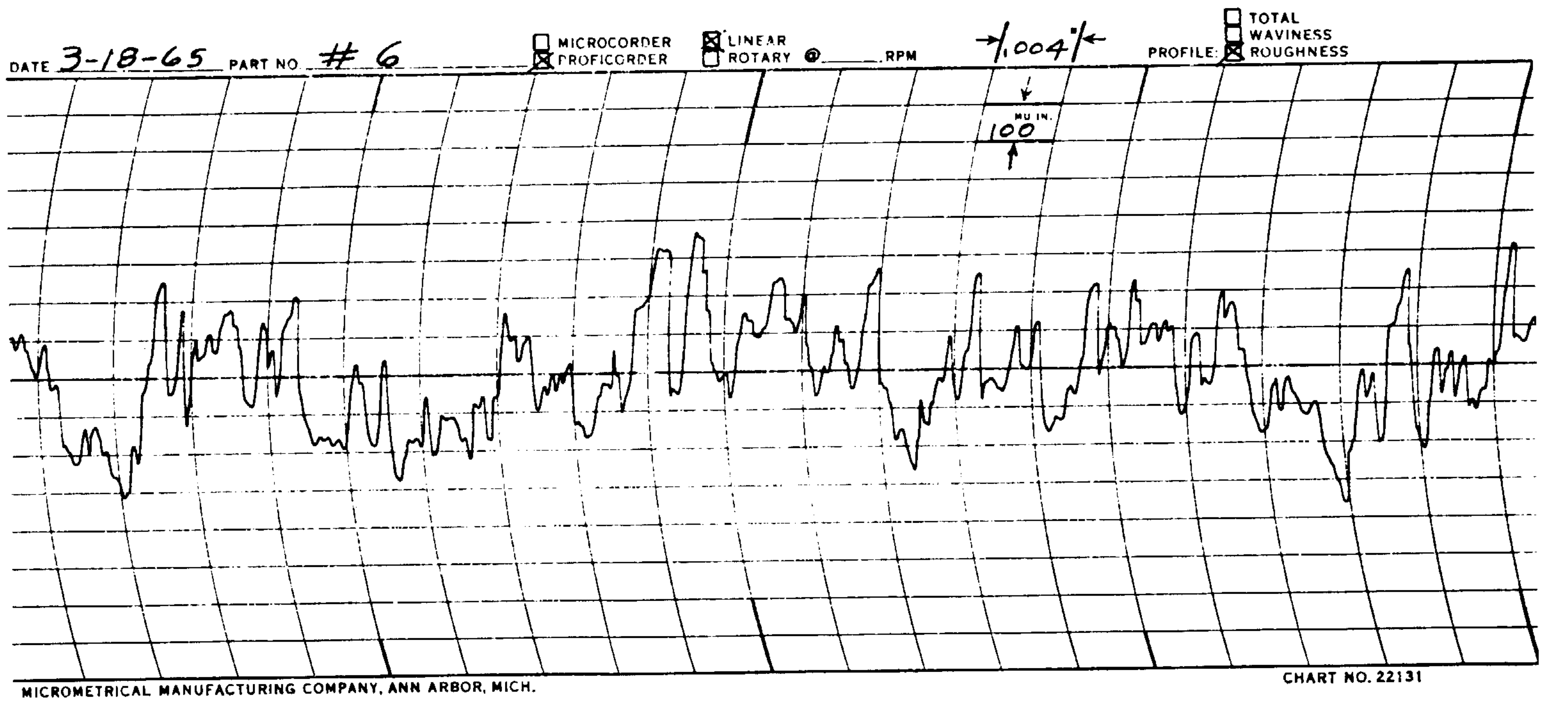

FIGURE 87. PROFILE OF AREA CHEMICALLY MILLED WITH A 10% SOLUTION OF AMMONIUM BIFLUORIDE

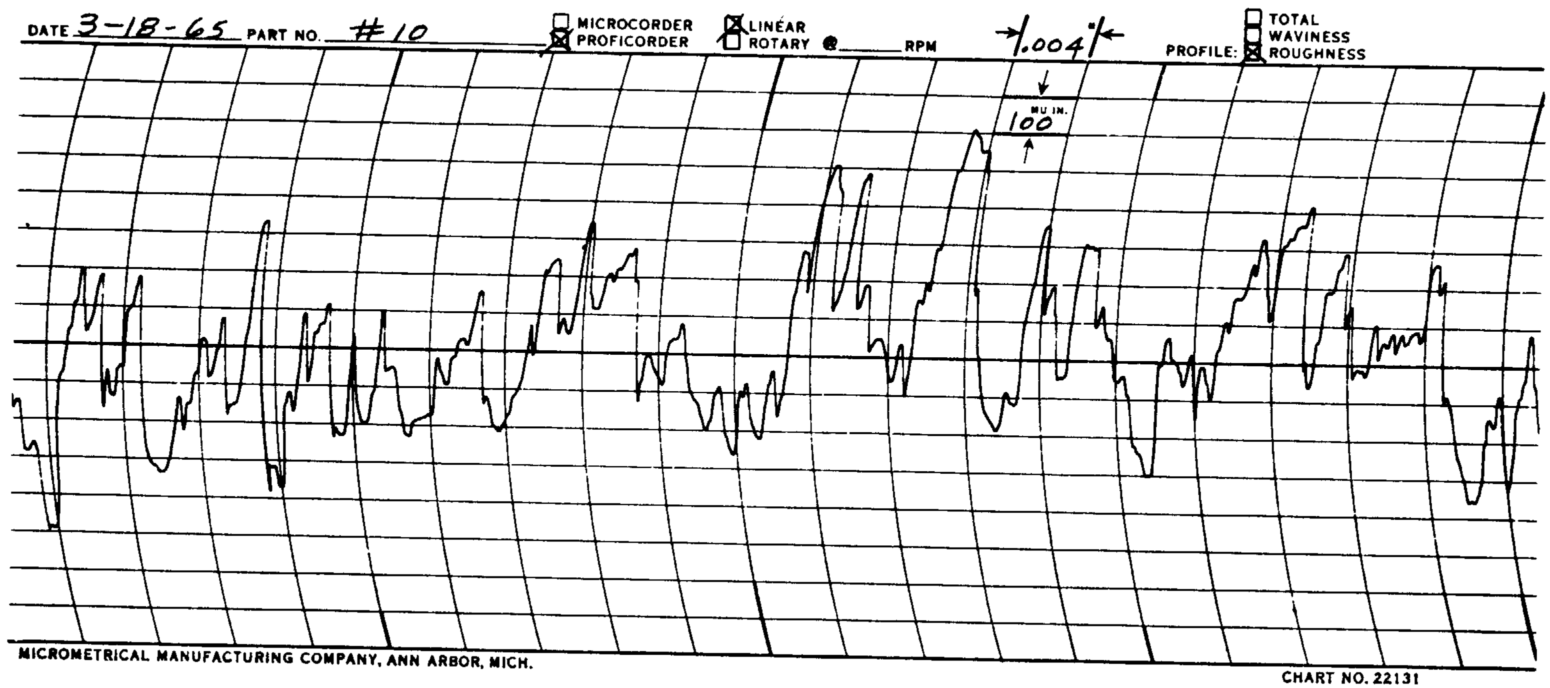

FIGURE 88. PROFILE OF AREA CHEMICALLY MILLED WITH A 15% SOLUTION OF AMMONIUM BIFLUORIDE

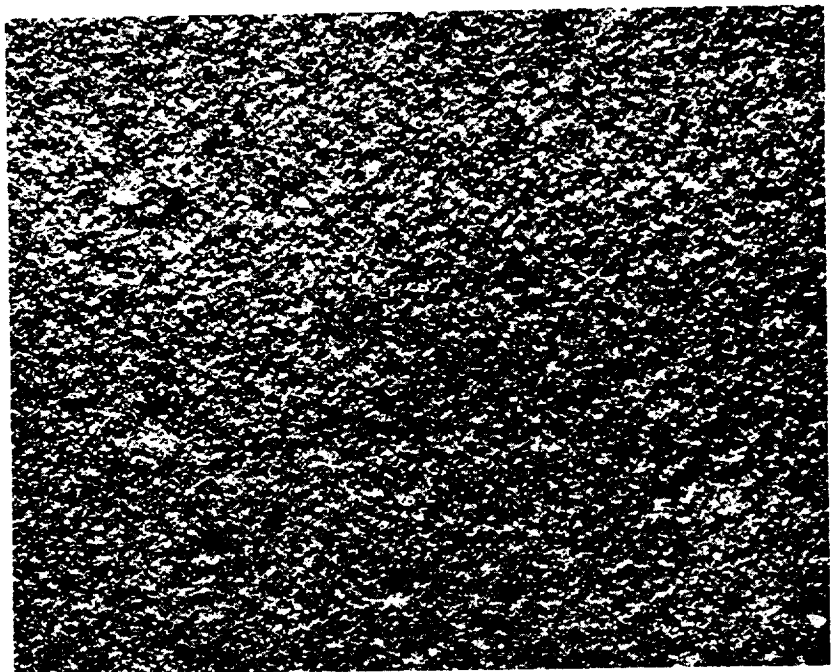

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FIGURE 89. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 20% SOLUTION OF AMMONIUM BIFLUORIDE (SPECIMEN NO. 13)

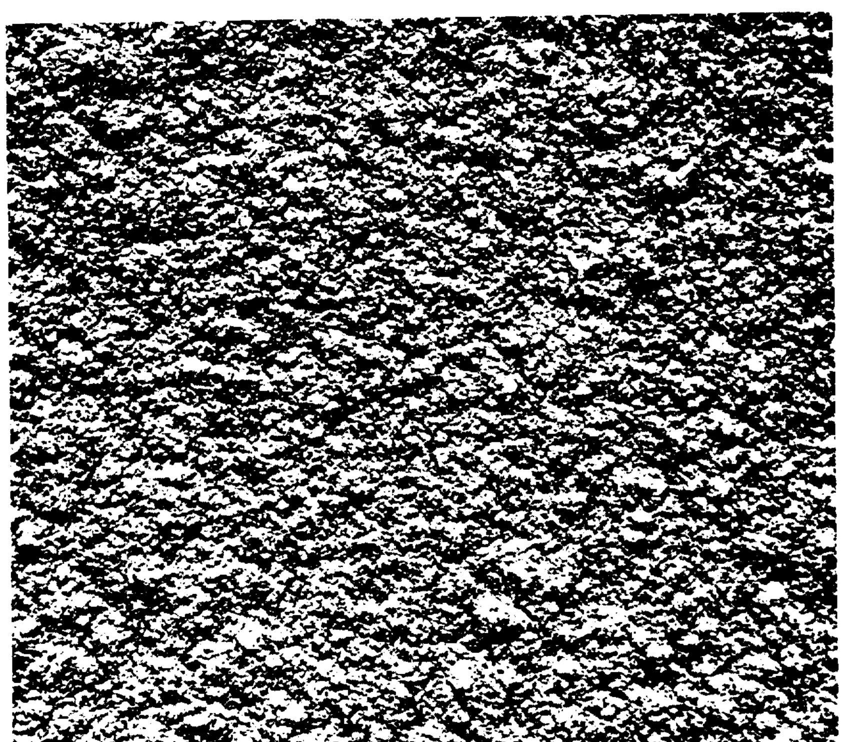

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FIGURE 90. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 30% SOLUTION OF AMMONIUM BIFLUORIDE (SPECIMEN NO. 23)

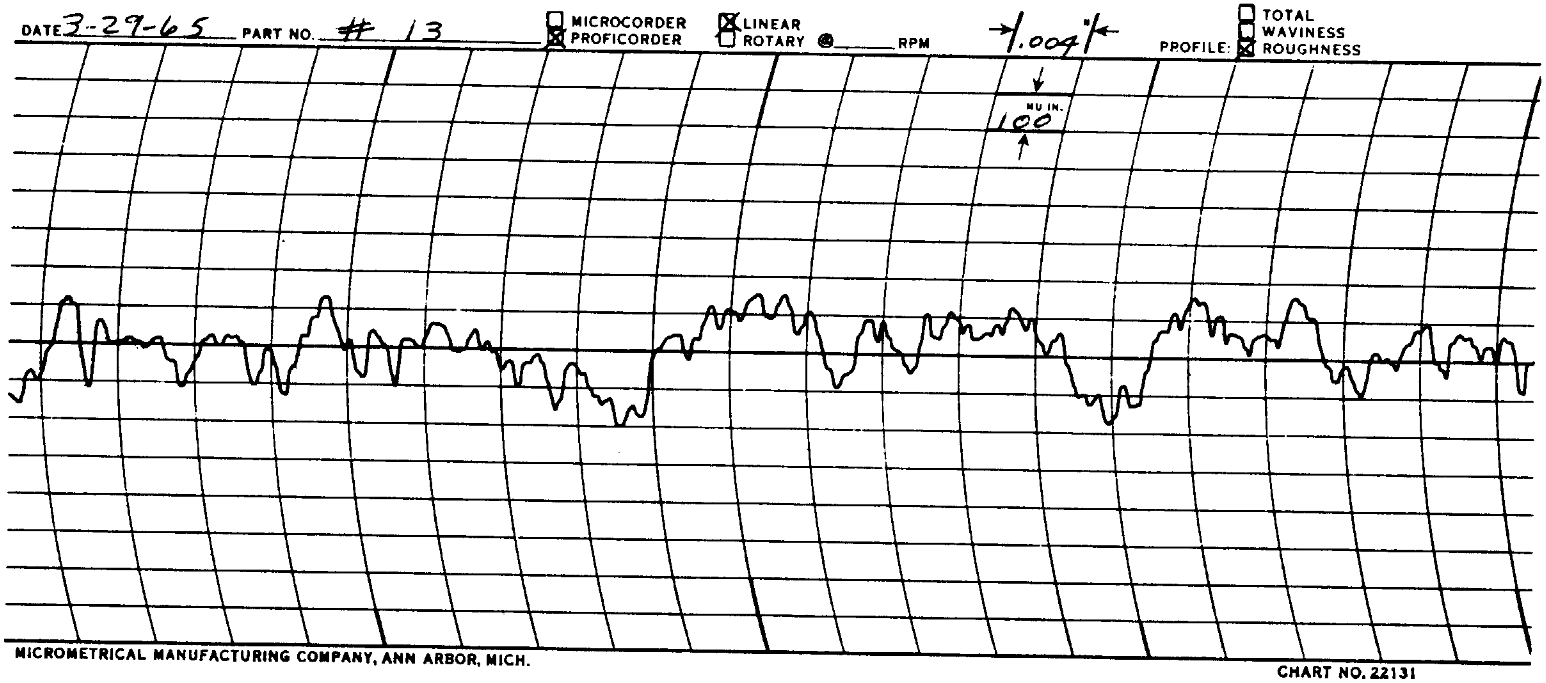

FIGURE 91. PROFILE OF AREA CHEMICALLY MILLED WITH A 20% SOLUTION OF AMMONIUM BIFLUORIDE

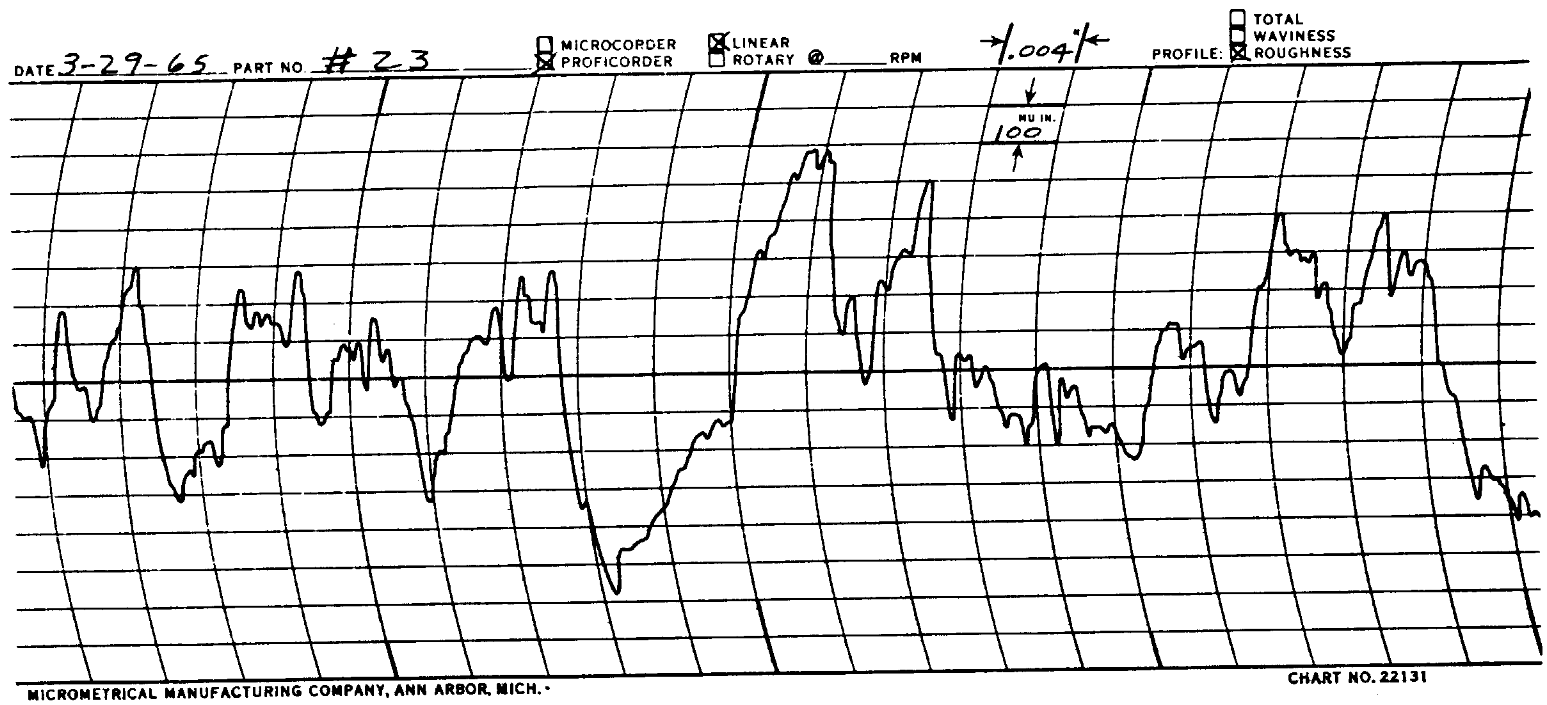

FIGURE 92. PROFILE OF AREA CHEMICALLY MILLED WITH A 30% SOLUTION OF AMMONIUM BIFLUORIDE

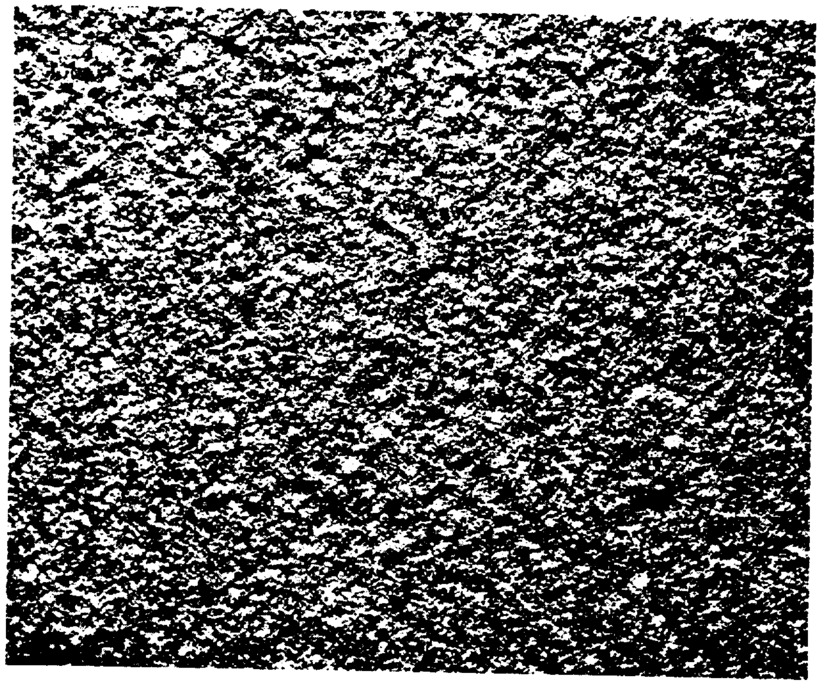

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FIGURE 93. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 45% NITRIC ACID - 3% HYDROFLUORIC ACID SOLUTION (SPECIMEN NO. 7)

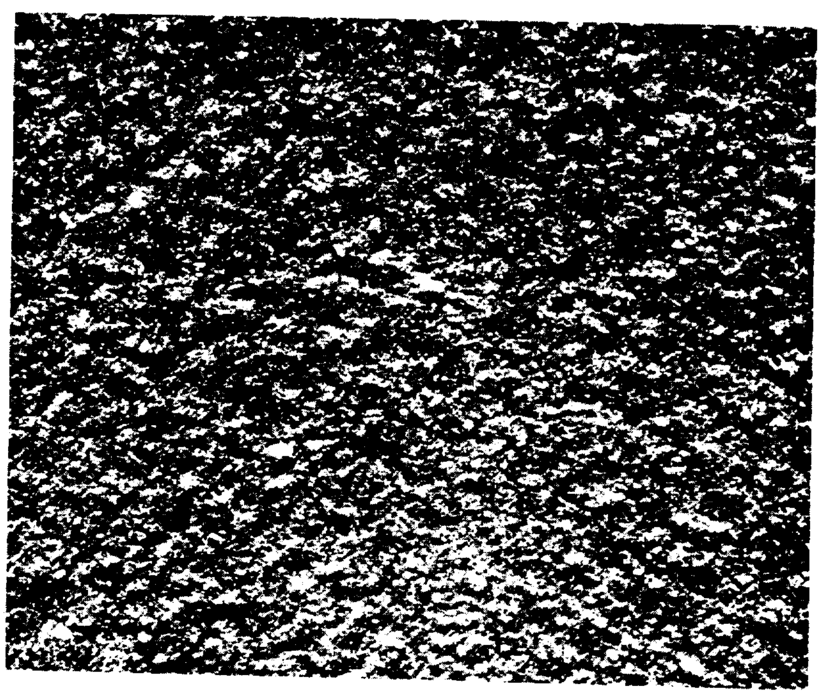

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FIGURE 94. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 50% NITRIC ACID - 25% HYDROFLUORIC ACID SOLUTION (SPECIMEN NO. 9)

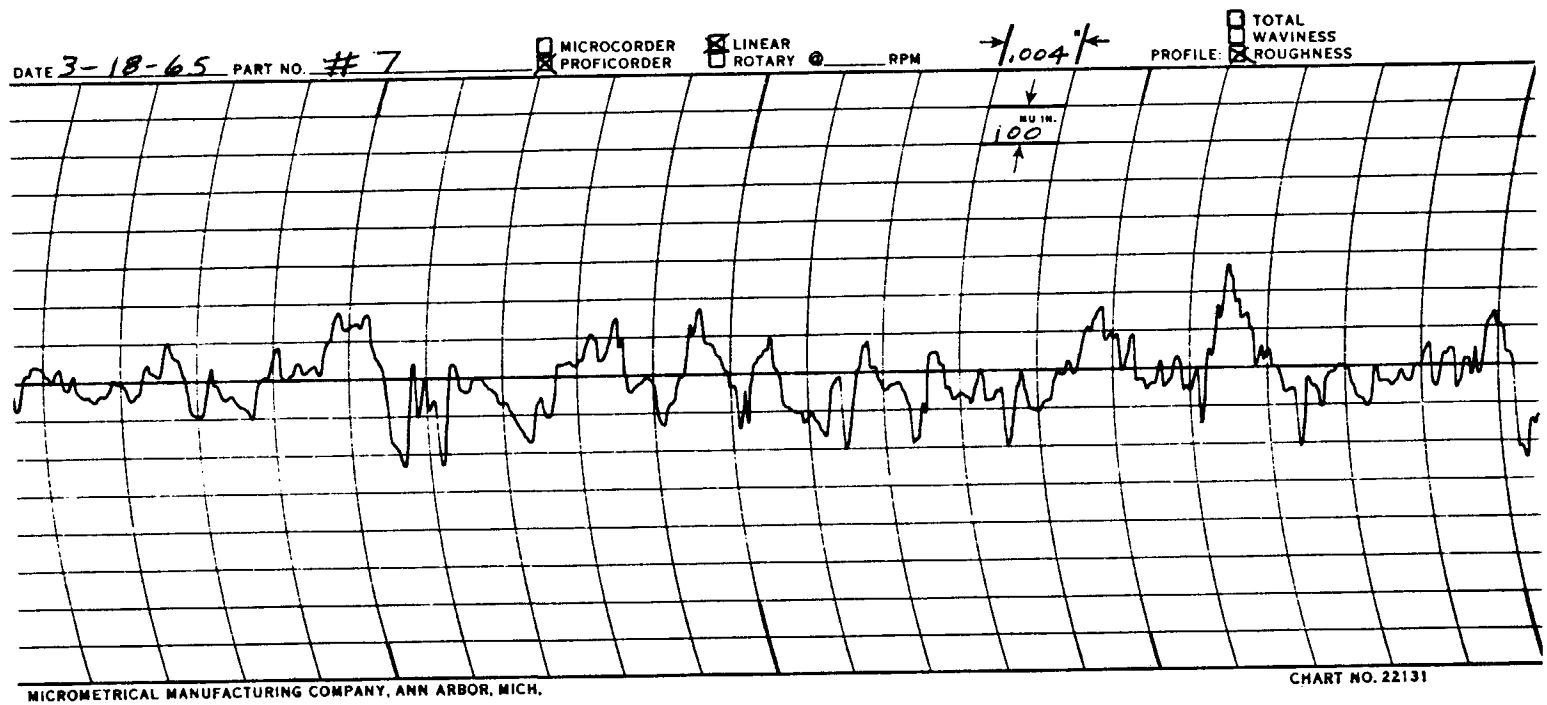

FIGURE 95. PROFILE OF AREA CHEMICALLY MILLED WITH A 45% NITRIC ACID - 3% HYDROFLUORIC ACID SOLUTION

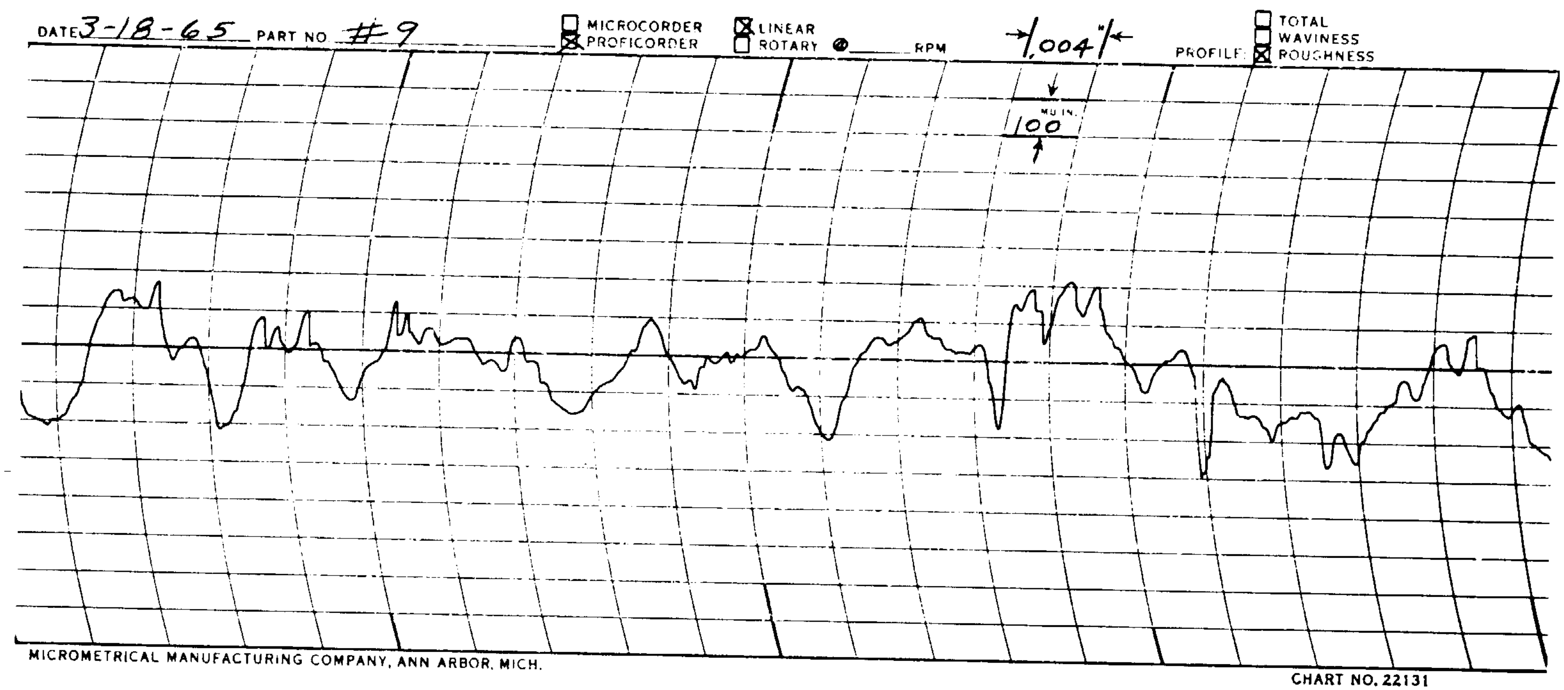

FIGURE 96. PROFILE OF AREA CHEMICALLY MILLED WITH A 50% NITRIC ACID - 25% HYDROFLUORIC ACID SOLUTION

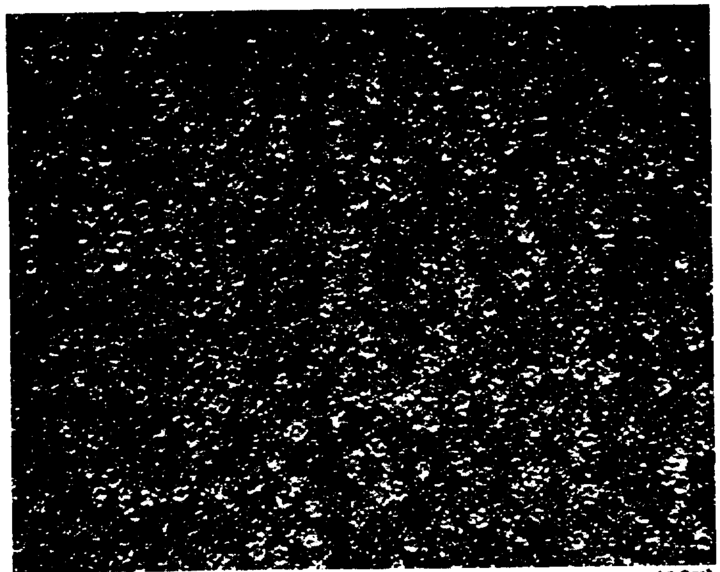

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FIGURE 97. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 50% PHOSPHORIC ACID - 20% SULFURIC ACID SOLUTION (SPECIMEN NO. 4)

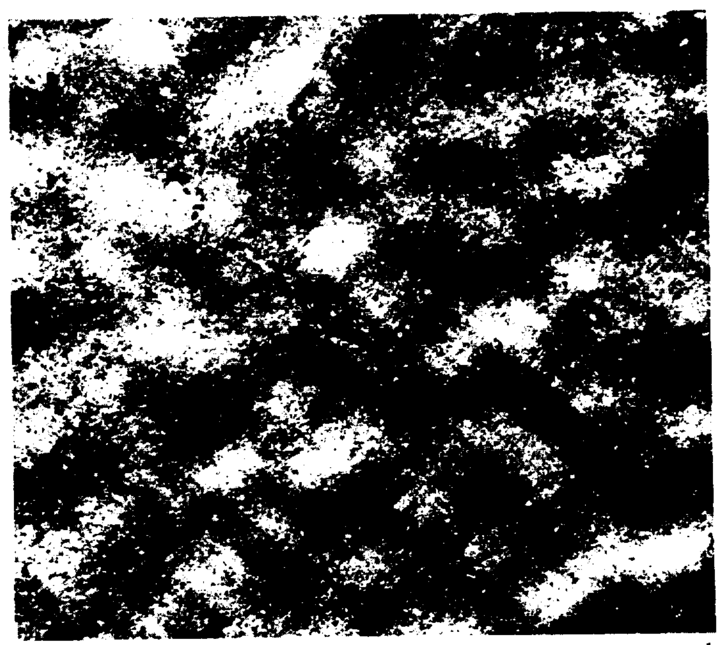

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FIGURE 98. MACROPHOTOGRAPH OF AREA CHEMICALLY MILLED WITH A 5 PARTS (VOL.) PHOSPHORIC ACID - 2 PARTS (VOL.) SULFURIC ACID - 5 PARTS (VOL.) WATER SOLUTION (SPECIMEN NO. 8)

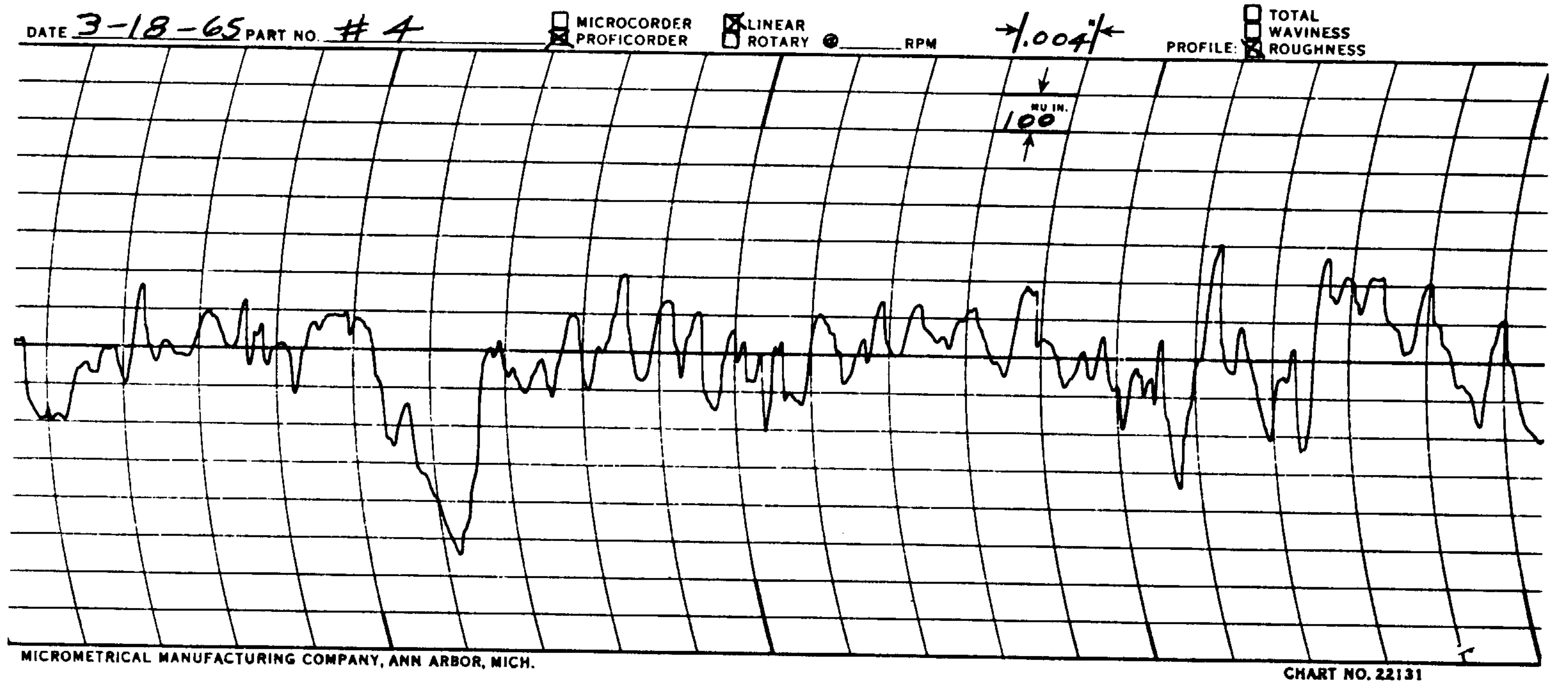

FIGURE 99. PROFILE OF AREA CHEMICALLY MILLED WITH A 50% PHOSPHORIC ACID - 20% SULFURIC ACID SOLUTION

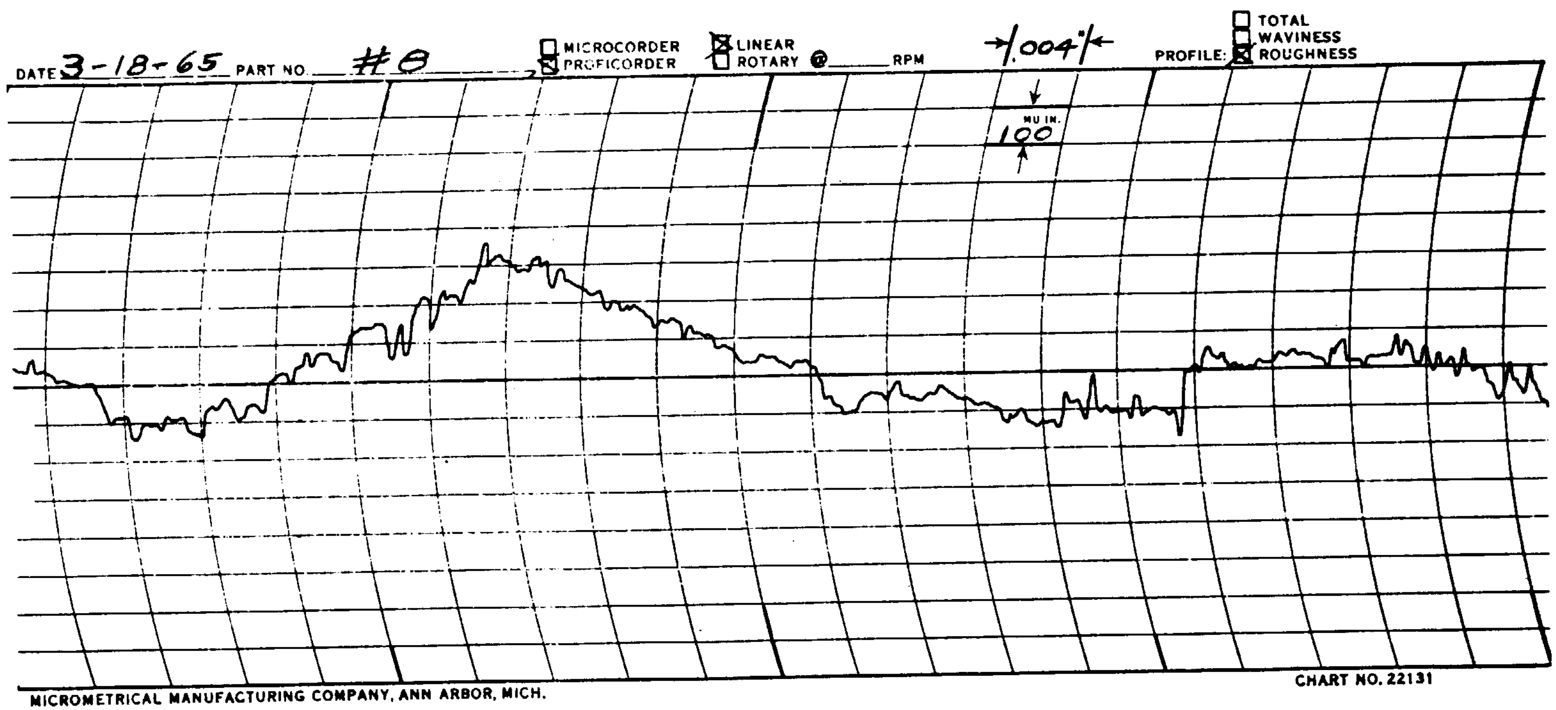

FIGURE 100. PROFILE OF AREA CHEMICALLY MILLED WITH A 5 PARTS (VOL.) PHOSPHORIC ACID - 2 PARTS (VOL.) SULFURIC ACID - 5 PARTS (VOL.) WATER SOLUTION

SECTION VII. CONCLUSIONS AND RECOMMENDATIONS

Punching or piercing is not recommended for use in producing holes in beryllium sheet material. The current drilling procedures are adequate for all production line requirements.

The current procedures of abrasive wheel cutting have proven to be entirely reliable and satisfactory.

The present machining (turning) procedures satisfy all current requirements. Approximately 400 surface feet per minute appears to be the best cutting speed for machining (turning) beryllium. However, at this speed, an enclosure must be used to contain the fine dust-like chips. Reasonable tool life has been attained with ceramic tool inserts used at speeds up to 800 surface feet per minute.

The present milling procedures are adequate for all forseeable requirements; no significant future developments are anticipated. The current success of milling operations is largely dependent upon the individual skill and care exercised by the machine operators, and therefore, is subject to human error. The application of numerical control will be particularly advantageous.

The Electrical Discharge Machining process has been used for miscellaneous "straight line" cutting and for drilling extremely fine holes. Tensile test specimens, being programmed for this machine, should provide more accurate and consistent test results. Additional developmental work is required to support a specific application.

Sulfuric acid, ammonium bifluoride, or both, are acceptable for chemically milling beryllium. The strength of the solution, particularly in the case of sulfuric acid, and the level of the bath should be carefully controlled. Thermostatic control of the temperature of either solution is mandatory if close tolerance, predictable results are to be attained. Careful attention to the details should result in the production of smooth surfaces bounded by even edges and radii.

APPROVAL NASA TM X-53453

THE FABRICATION OF BERYLLIUM - VOLUME III.

METAL REMOVAL TECHNIQUES

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission Programs has been made by the MSFC Security Classification Officer.

This report, in its entirety, has been determined to be unclassified.

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