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FEASIBILITY STUDY FOR AN ELECTROCHEMICAL GRINDING (ECG) MACHINE--ETC(U)

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REPORT NO. MT-038
NOVEMBER 1975

FEASIBILITY STUDY FOR AN ELECTROCHEMICAL GRINDING (ECG) MACHINE FOR LARGE DIAMETER WORKPIECES

A PROJECT OF THE
MANUFACTURING TECHNOLOGY PROGRAM
NAVAL SEA SYSTEMS COMMAND

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FINAL REPORT



NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

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ABSTRACT

The objective was to conduct a feasibility study for an Electrochemical grinding machine that would include Electrochemical Grinding (ECG), creep feed, and conventional abrasive grinding. The machine would be a rotary type grinder with capacity to grind 14-foot diameter workpieces, particularly roller bearing paths for gun mount stands. The conventional grinders, production processes, and methods currently used at NOSL for roller paths were reviewed in detail. An in-depth analysis was made of the results expected of a theoretical ECG grinding machine, from both a design and a production viewpoint. Samples were ground on an ECG surface grinder to confirm hypotheses with regard to grinding rates, table speeds, etc. It was concluded that ECG for roller path production is not practicable at this time.

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FOREWORD

This is the final report of work completed under NAVORDSYSCOM's Work Requests WR 2-5674 and WR 3-5646 issued to investigate the feasibility of an ECG machine to grind large ball and roller paths with capacity to grind 14' feet diameter parts. The study was performed by the Naval Ordnance Station, Louisville, Kentucky. Funds were provided by the Industrial Resources and Facilities Division of NAVORDSYSCOM (ORD 047) under the Manufacturing Technology Program.

The Navy acknowledges the valuable assistance of ANOCUT Inc, Elk Grove Village, Illinois under contract N00197-74-C-0012 who provided machine design concept drawings and the gathering of ECM machining parameters for evaluation.

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SECTION 1.0

INTRODUCTION

When the large caliber gun mounts were first modernized with mechanical train and elevation drives to the present most modern gun mount, the basic design of the gun mount stand was not significantly changed. The gun stands have rows of horizontal and vertical roller bearings to support the weight of the gun mount and oppose the recoil of the mount. The roller paths are large in diameter because of the large forces involved with major caliber mounts. The roller path surfaces contacting the roller bearings by necessity are hardened and require grinding. Most of the Navy's gun mounts are overhauled at NOSL. This Station, built in the early 40's, has two grinding machines capable of grinding large roller paths. These machines, as a result of long and hard use, are considered beyond economical repair and in need of replacement. Prior to replacement, it was deemed important to examine the new or advanced technologies in this area before making a firm commitment. This study, "The Feasibility of an ECG Machine for Large Roller Paths," is intended to fulfill this examination of modern grinding techniques. If the gun stand can't be improved, maybe the method of its manufacturing can.

The builder of NOSL's grinding machines has ceased to exist and only one machine builder (reluctantly) has agreed to discuss the possible building of such a large rotary conventional grinding machine. This situation exists because of the almost nonexistent need by American industry for such a machine, which need is being met by using a grinding head on a conventional turning machine, such as a vertical boring mill. Because of the volume of work at this Station, this approach is unsatisfactory and the problem of replacing NOSL's two roller path grinders is critical. This has been an ideal time to make this study, since the replacement or major refurbishing of the grinding machines is imminent.

1.1 Purpose

The purpose of this project was to investigate the possibility of applying ECG to roller paths for possible savings, superior quality, reliability, and the advancement of the state of ECG art.

1.2 Goals

The specific goals of this investigation were:

- a. Conduct a feasibility study for an Electrochemical grinding machine that will include conventional ECG, creep feed, and conventional abrasive grinding with a capacity up to 14 feet in diameter; the determination of stock removal rates and finish limitation; establishment of surface cutting rate in inches/feet per minute; establishment of basic electrical power requirements and electrolyte compositions; and establishment of general machine structural design concepts.

b. Fully evaluate the process from the standpoint of product quality, productivity, and cost savings; findings to be tabulated in the final report.

SECTION 2.0

WORK PIECES AND MANUFACTURING PROCESSES

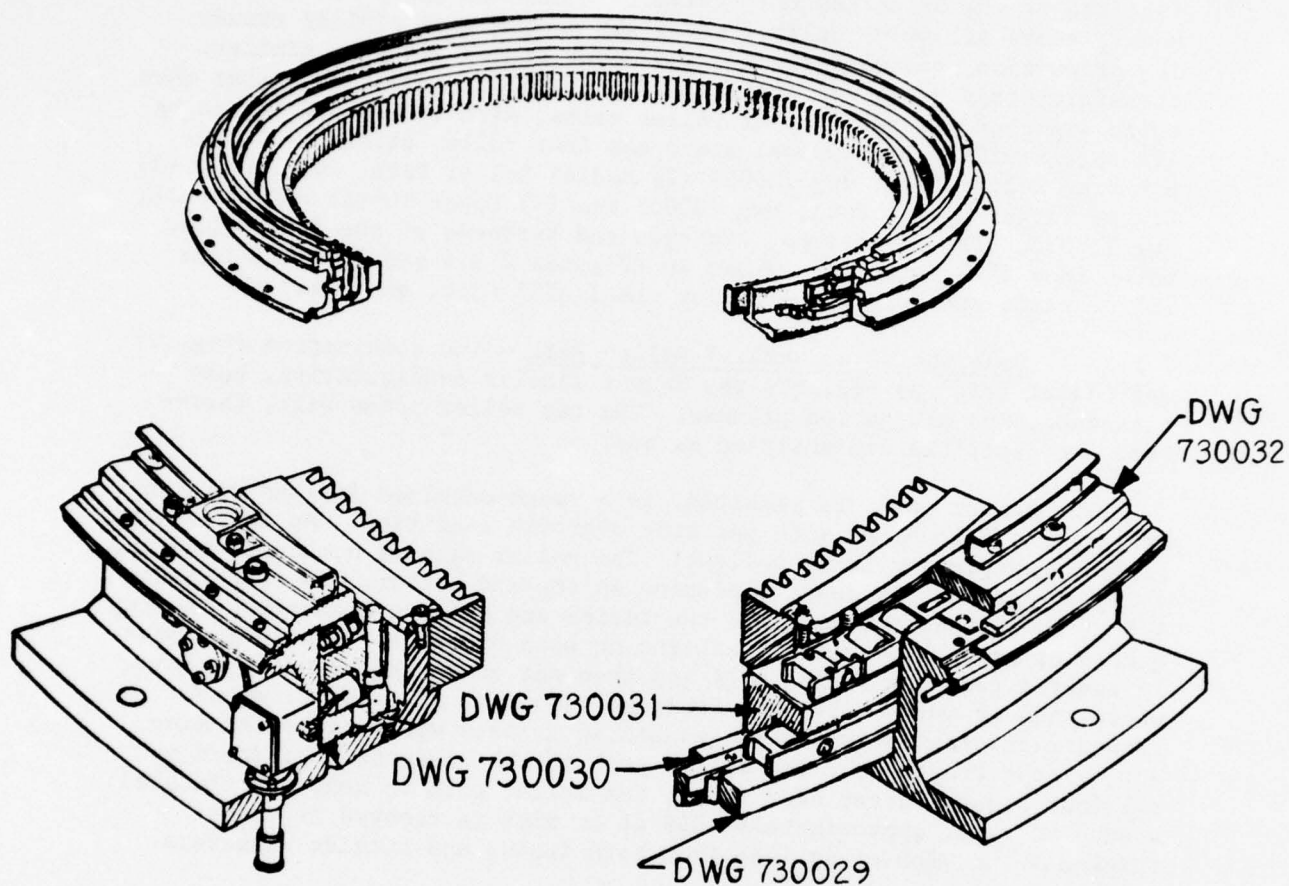
The type work to be ground on the proposed ECG machine can be typified by the Stand Assembly (Figure 1) used on the 5"/54 MK 42 Gun Mount, since all major caliber naval gun mounts have similar stands. The production processes for all gun mount stands are very similar; therefore, this study was confined to one typical gun stand rather than to an assorted diverse list of roller paths, with the report retaining its objectivity. The typical stand has four roller paths: (1) Combination Roller Path, dwg 730029 (2) Radial Roller Path, dwg 730030 (3) Center Thrust Roller Path, dwg 730031 and (4) Upper Thrust Roller Path, dwg 730032. The dimensions, finishes and hardness of the four roller paths in a 5"/54 stand are shown in (Figures 2,3,4 and 5). All four roller paths are forgings of alloy steel AISI 4340, annealed.

2.1 Combination and Radial Roller Path - The combination (Fig. 2) and radial (Fig. 3) roller paths have a similar configuration, heat treatment, and production process. The two roller paths will, therefore, be described and analyzed as one.

The roller path, as received, is a rough-machined forging with an approximate 3/16 of an inch per side oversize condition. An abbreviated process description is as follows: The roller path is machined, leaving a 1/32 of an inch oversize condition on top and bottom. An approximate 1/8 of an inch is machined off the inside and outside diameters, leaving a 1/16 of an inch oversize condition on each diameter. The roller path is removed from the boring mill and then set up in the grinding machine where .005 of an inch is semi-finished ground on all four sides to remove machining marks, as the machining grooves would cause cracking during heat treatment. The roller path is then induction hardened on all four sides. After heat treat, the roller path is semi and finished ground to size; approximately .056 of an inch is removed from the thickness and .060 of an inch from both inside and outside diameters.

2.2 Center Thrust Roller Path - On this roller path (Figure 4), only two surfaces are hardened. This roller path is also received as a rough machined forging with an approximate 3/16 of an inch excess material per surface for machining, grinding, and trueing-up allowances. The path is machined 5/16 of an inch from the inside diameter, leaving 1/16 of an inch stock for finishing. The outside diameter is machined to size. An approximate .050 of an inch total excess stock is left on the two surfaces that are hardened for grinding removal after heat treat.

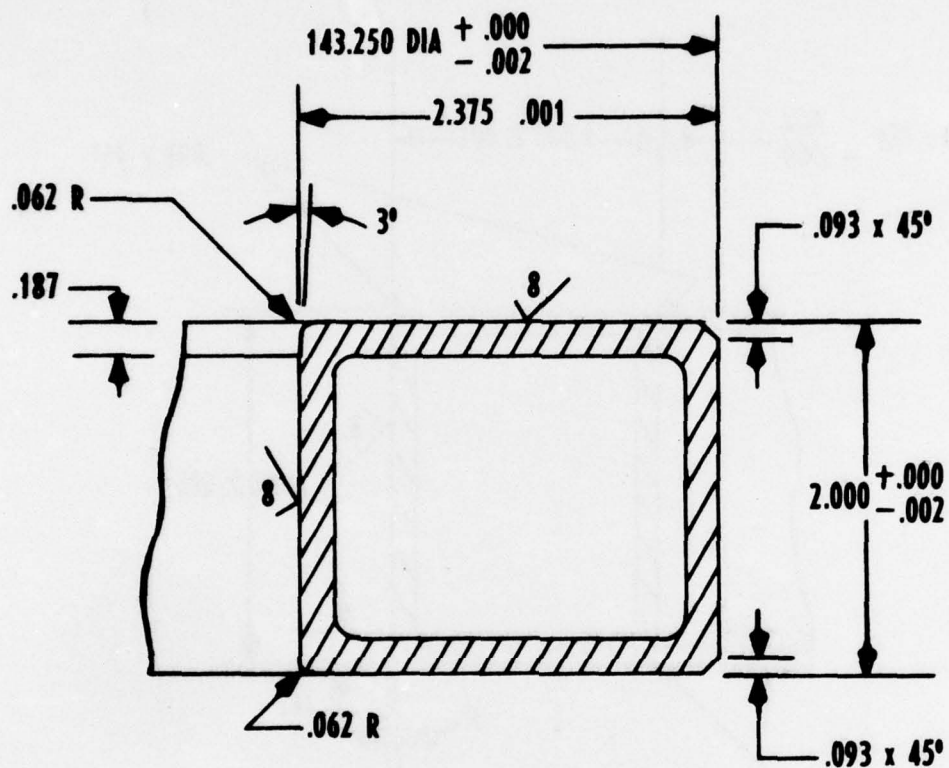
After induction hardening, the roller path is machined and ground to size. On unhardened surfaces, the piece is machined and finish ground to size. The two hardened surfaces require grinding to size, which involves removal of the .050 of an inch total metal removal from both surfaces.



**STAND ASSY MK 21 MOD 1
USED ON 5"/54 MK 42 MOUNT**

FIGURE 1

GRIND FINISH $\sqrt{31}$ EXCEPT WHERE NOTED OTHERWISE.

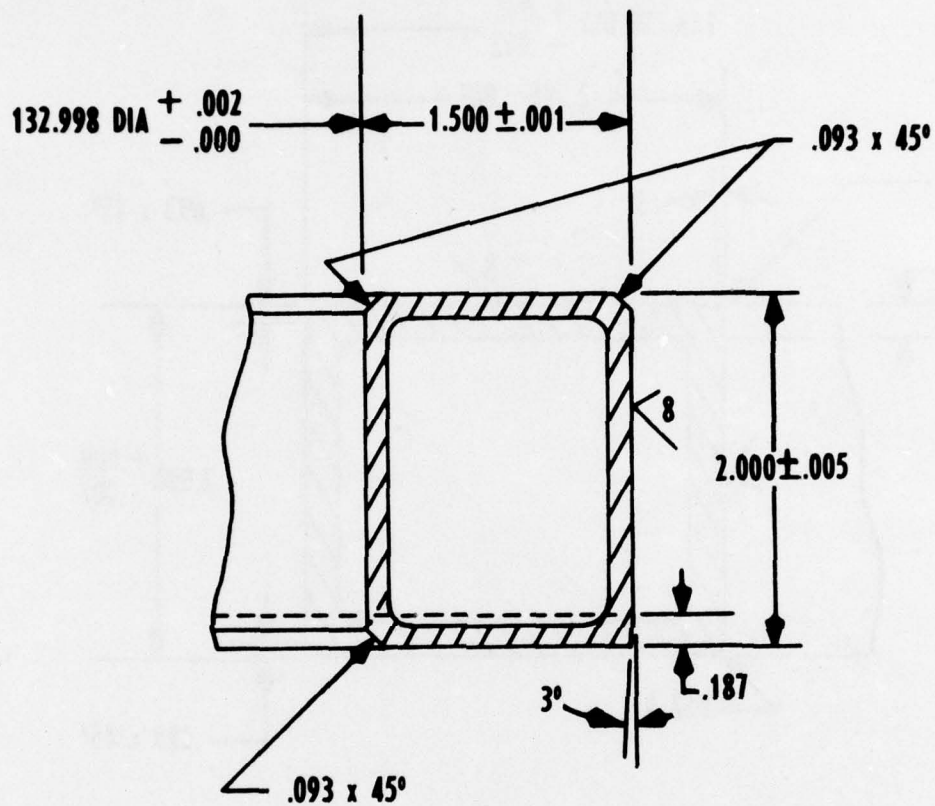


APPROXIMATE SURFACE HARDNESS PATTERN (Rc53-60) SHOWN CROSS HATCHED
SCALE 1/1

COMBINATION ROLLER PATH, DWG 730029

FIGURE 2

GRIND FINISH $\sqrt{32}$ EXCEPT WHERE NOTED OTHERWISE



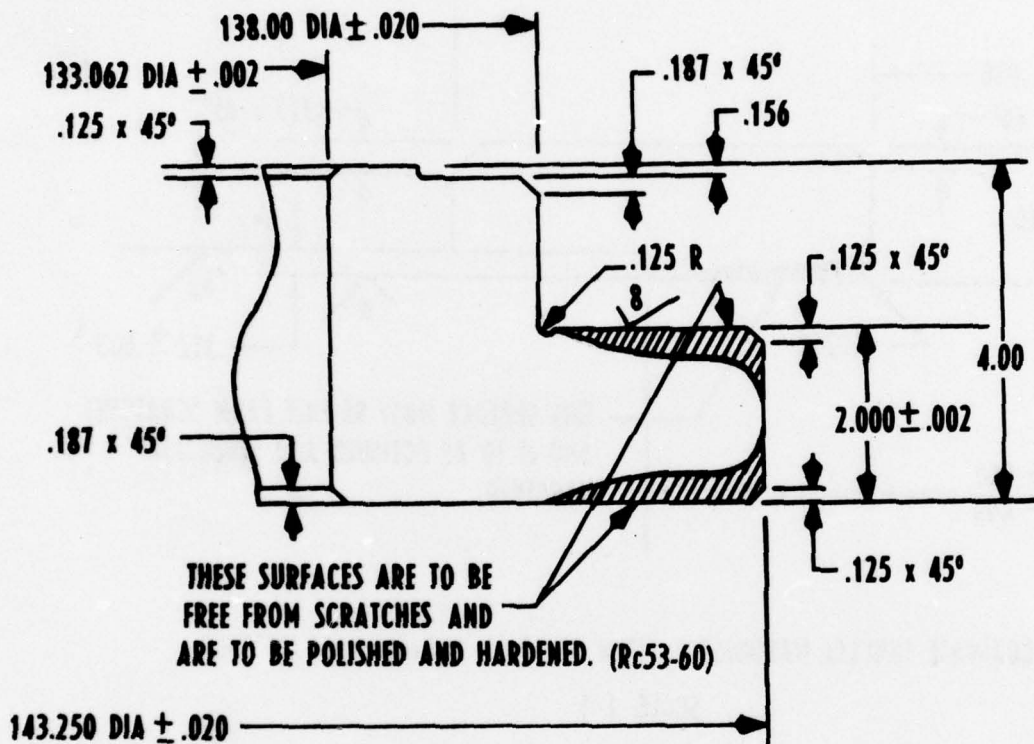
APPROXIMATE SURFACE HARDNESS PATTERN (Rc53-60) SHOWN CROSS HATCHED

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RADIAL ROLLER PATH, DWG 730030

FIGURE 3

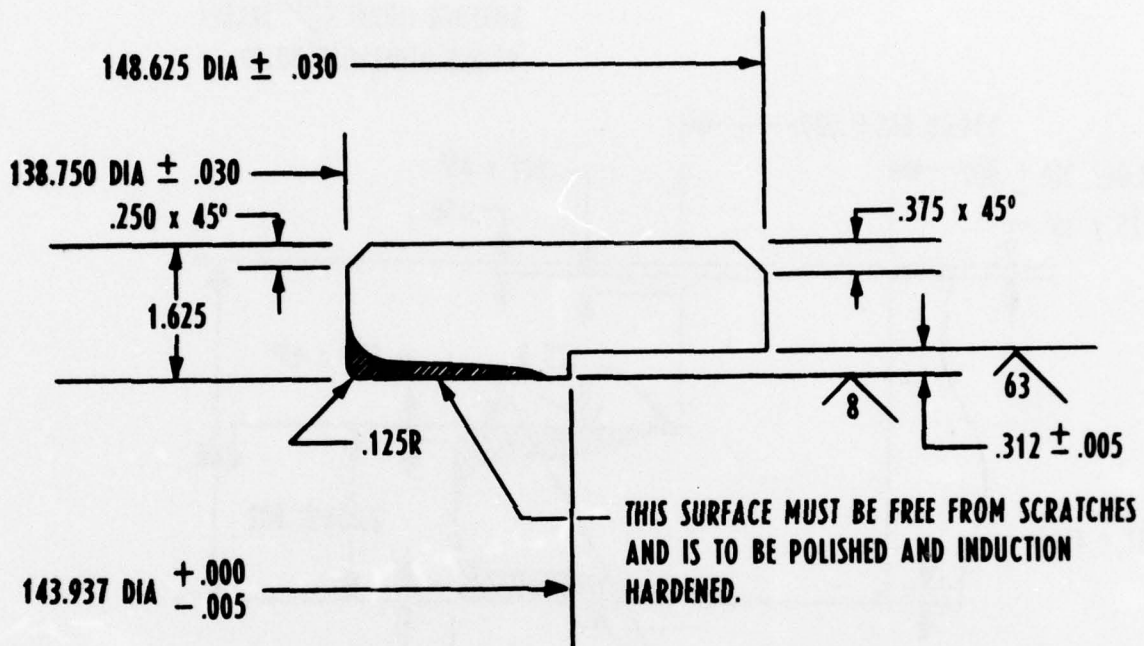
SURFACE FINISH $\sqrt{125}$ EXCEPT
WHERE OTHERWISE NOTED.



CENTER THRUST ROLLER PATH, DWG 730031

FIGURE 4

FINISH 125 ✓ EXCEPT AS NOTED



APPROXIMATE SURFACE HARDNESS PATTERN (Rc53-60) SHOWN CROSS HATCHED

SCALE: 1/1

UPPER THRUST ROLLER PATH, DWG 730032

FIGURE 5

Although there are more surfaces machined on the center roller path than the combination and radial roller paths, the hardened surface area that remains is very small in comparison.

2.3 Upper Thrust Roller Path - Only a small portion of this roller path (Figure 5) is hardened. The inside and outside diameters are machined to size and the thickness is machined .097 of an inch oversize. Tool marks are ground off for heat treat.

After induction hardening the one surface, only enough of the hardened surface to clean up is ground off. The soft opposite side is ground to thickness. This upper thrust roller path has very little grinding of hard surface area in comparison to the combination and radial roller paths.

2.4 Summary of Roller Path Production - A brief review of the preceding paragraphs reveals that the roller paths are received as forgings of an Alloy Steel AISI 4340, Annealed or equivalent. The roller paths have an approximate 3/16 of an inch excess material on each surface, because of the .001 of an inch flatness requirement of hardened ground surfaces distortion during induction hardening, and stock allowance for machining and grinding. The forgings also have rough tool marks that require removal before heat treat to prevent cracks from propagating from these grooves.

The roller path forgings are machined on boring mills. On surfaces that are not to be hardened, the roller path is machined to near finish size, leaving just enough stock for clean-up at the grinder; the surfaces to be hardened are machined to approximately 1/16 of an inch oversize.

The roller paths are then ground on either of the two Fruenthal grinders. Surfaces not to be hardened are usually cleaned up by grinding to size (approximately .005 of an inch if the surface wasn't machined to size); surfaces that get hardened are usually semi-finish ground approximately .005 of an inch to remove tool marks.

After induction hardening, the roller paths are returned to the Fruenthal grinders. The approximate 1/16 of an inch remaining hardened surfaces are semi-finish ground, leaving approximately .010 of an inch which is subsequently finish ground and polished to size.

The drilling of holes in roller paths is of no concern in this study and the grinding of chamfers and radii will be touched on later in ECG of roller paths. The art of machining and grinding roller paths has been avoided in this study; only the essentials for making the study have been considered.

The significant point of roller path production is: after induction hardening, there is less than 1/16 of an inch stock that requires grinding on hardened surfaces where ECG can be considered economically feasible.

SECTION 3.0

CONVENTIONAL GRINDING

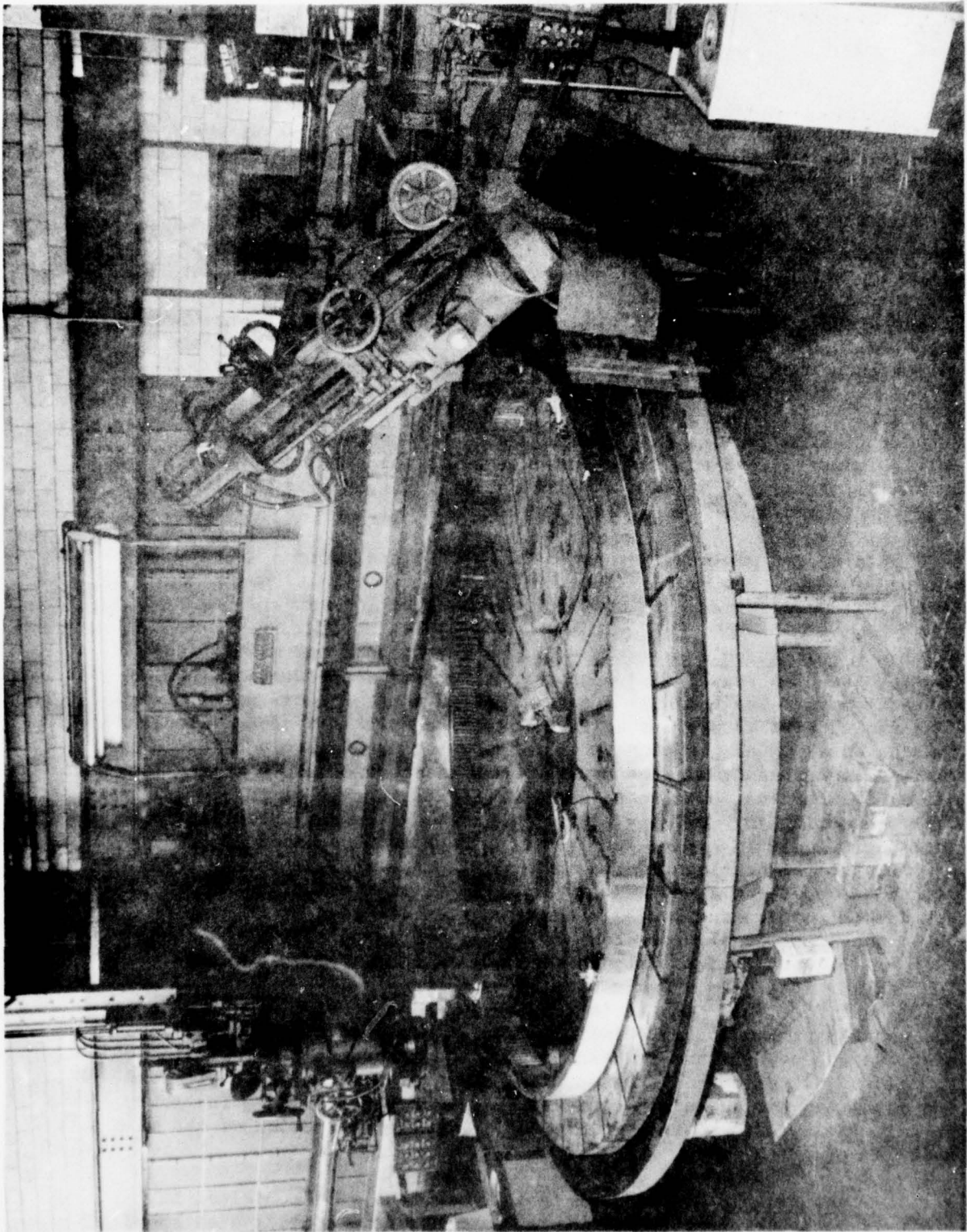
The conventional method of grinding large roller bearing paths at NOSL will be described so a better understanding of what a combination ECG and conventional grinding machine will entail.

3.1 The Frauenthal Grinder - Shortly before World War II, A. Harold Frauenthal, Inc., Muskegon, Michigan (no longer in business) developed a super-accurate grinding machine for handling large internal, external and surface grinding. The machine was used mainly for precision grinding gun turrets. One of the two 140 inch table size Frauenthal grinders can be seen in Figure 6. It is used to grind large roller paths for major caliber gun mounts. Due to their rugged construction, diameters and parallelism of faces have been ground to a tolerance of two ten-thousands of an inch (.0002). The Frauenthal Grinders, which are no longer available, were designed for grinding only. Industry presently uses conventional metal cutting machines, such as boring mills, which are adaptable for grinding by fitting with auxiliary attachments.

This report would be incomplete without a description of this unique machine. See Figure 7 for the general specifications of the Frauenthal Grinders used at NOSL for grinding roller paths.

3.1.1 Work Spindle Assembly - The table, spindle and main spindle housing are of a rugged design construction, and are assembled into an integral unit. The table is a semi-steel casting of heavy section with deep radial ribs to prevent deflection and has radial T-slots for clamping the work. NOSL has magnetic chucks, which are securely bolted to a large diameter flange on the spindle, the diameter of the spindle flange being of sufficient size to permit wide radial spacing of the bolts, thus overcoming any tendency of the table to tilt under eccentric loading. The spindle is a semi-steel casting carried by preloaded anti-friction roller bearings in the main spindle housing, alignment being maintained by the wide spread of the anti-friction roller bearings. The top double row tapered roller bearing carries the load of the table, while the lower double row straight roller bearing provides the alignment of the work table. Both top and bottom bearings are pressure lubricated. The main spindle housing is a heavy walled and ribbed semi-steel casting. This casting is provided with an outside wide flange on the upper part in close proximity to the top or load carrying bearing seat, which supports the spindle housing and transmits the load direct to the foundation holding the vertical distance between the table load and foundation to a minimum, thus minimizing any vibration. The lower or aligning spindle bearing is carried in the lower section of the main spindle.

3.1.2 Work Table Drive - The table drive is a self-contained infinitely variable speed unit equipped with a remote control dial speed indicator, having push button control of speed. The push button control and indicator are mounted within easy reach and view of the operator.



140" TABLE SIZE FRUENTHAL GRINDER

FIGURE 6

SERIES 2200 — GENERAL SPECIFICATIONS — 140" DIAMETER TABLE

Diameter of table	140"
Diameter of swing	150"
Height under rail	20" Standard — Or to Customer Requirements
Table Drive	Worm Type
Grinding Wheel Spindle Drive	7½ H.P. direct connected
Minimum length hydraulic actuated vertical stroke	1¼"
Maximum length hydraulic actuated vertical stroke	8"
Minimum travel with hydraulic actuator	7" per minute
Maximum travel with hydraulic actuator	120" per minute
Maximum vertical travel of spindle with feed screw	20"
Range covered by vertical actuator	Any 8" cycle within the 20" total range
Minimum length hydraulic actuated horizontal stroke	1¼"
Maximum length hydraulic actuated horizontal stroke	36"
Maximum horizontal travel of spindle with feed screw	18"
Maximum horizontal travel of spindle with combined hand and hydraulic feed	49"
Range covered by horizontal actuator	Any 36" cycle within the 49" total range
Range of table speeds	2.25 to 13.51 RPM—Or to Customer Requirements
Minimum distance between center line of RH or LH wheel spindle head and center of table	27"
Maximum distance between center line of RH and LH wheel spindle heads	157"
Height above floor level	8'-10"
Floor space — R. to L. x F. to B.	24'-2" x 12'-0"
Weight of complete grinder	

3.1.3 Columns - The superstructure carrying the two vertical grinding heads is a unit anchored independently of the work table, and is held in alignment to the table by means of positive insulation to prevent sympathetic vibration between elements and to eliminate vibration and chatter. The superstructure consists of two deep, double "H" section columns with wide rib bracing. The ribs with the up-right columns are securely mounted on a fabricated structural steel base and anchored in the deep concrete foundation.

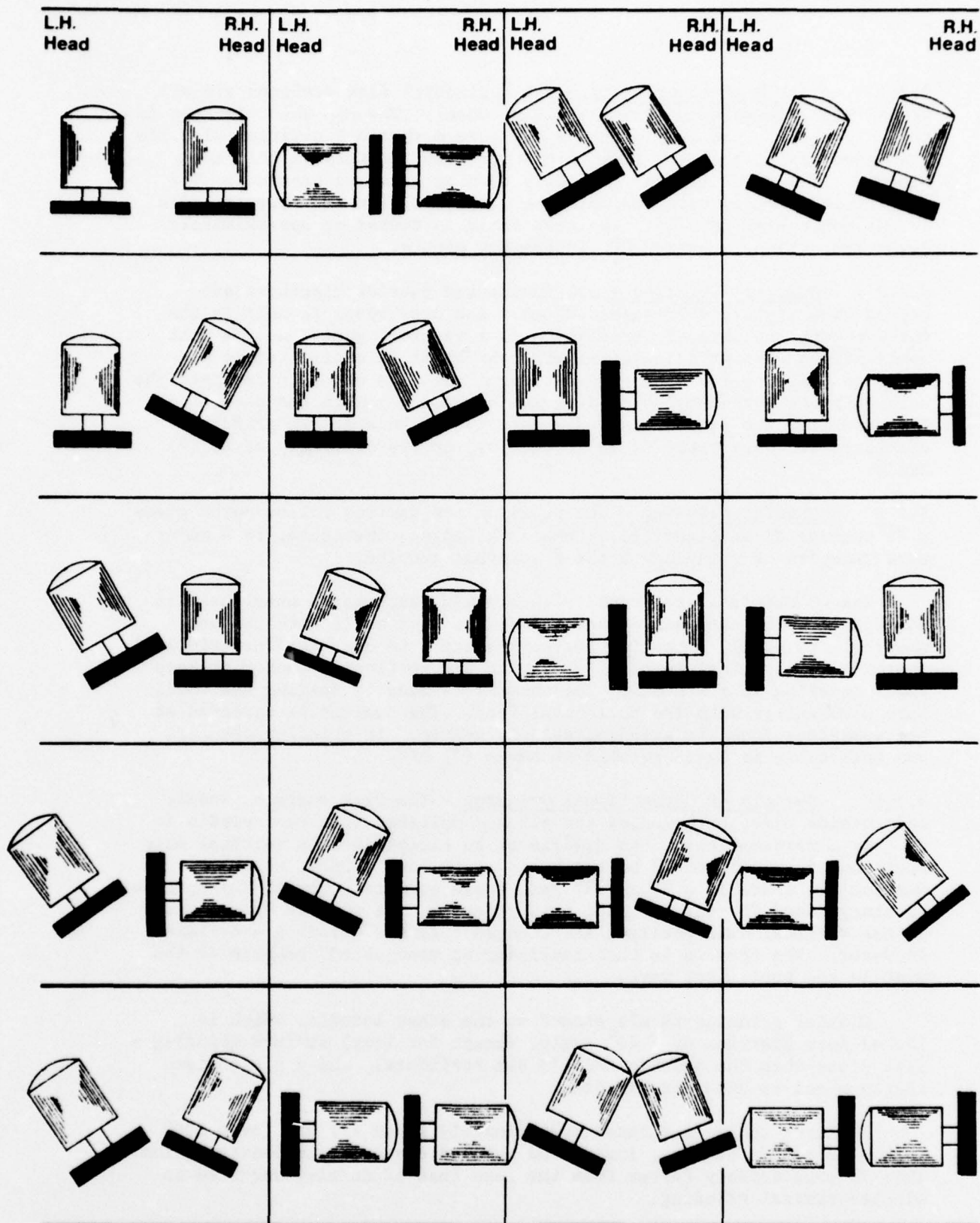
The top of the two upright columns is rigidly tied together by a fabricated triple channel section and a plate cross tie, which the two compounds are mounted on. Each compound consists of one adjustable cross rail, which is supported by the cross tie, one horizontal slide, and one vertical slide. The adjustable cross rail is a semi-steel casting for the rigid mounting of the horizontal slide, and for carrying the horizontal hydraulic actuator. The rail is mounted on a pivot bolt to the cross member, and after alignment, is securely bolted to the cross tie.

3.1.4 Grinding Spindles - The grinding units are direct connected, self-contained units mounted on the vertical slides, the motors having ultra-precision bearings. The grinding heads are rated for continuous heavy duty service, equipped with reversing switches to meet any conditions of surface and cylindrical grinding. The head can be fed horizontally and vertically on the slides with large hand wheels and with suitable gearing, an extra fine feed permits precision grinding on this machine. The head, in addition to feeding horizontally and vertically, can be tilted or indexed from a vertical to a horizontal position to permit the spindle axis to be set at any angle before being securely locked into position for grinding the work piece. See Figure 8 for various spindle positions possible on the Frauenthal grinder.

3.1.5 Hydraulic Actuators - Horizontal and vertical actuators are employed to oscillate the horizontal and vertical travel of the grinding spindle head. The actuator operates either automatically or manually, or by a combination of both as desired. Adjustable stops control the length of the stroke; a valve adjustment controls the speed of oscillation. The horizontal actuator also has lever controls, which permit rapid traverse of the grinding head.

3.1.6 Coolant and Guards - The machine has a coolant pumping and recirculating system with the necessary coolant troughs and splash guards. The coolant system has nozzles at both spindles. Substantial removable grinding guards to permit changing grinding wheels are mounted on the grinding motor housing.

3.2 The Grinding Process - The shape of the grinding wheels used on most work that is ground on the Frauenthal machines can be envisioned by a look at the shape of the roller paths (Figures 2,3,4 and 5). The basic types of grinding operations will be briefly described.



POSSIBLE SPINDLE POSITIONS OF FRAUENTHAL GRINDER

FIGURE NO. 8

3.2.1 Flat Surface Grinding - The horizontal flat surfaces are all ground with a simple cup-wheel grinding wheel. The cup wheel is held in the spindle with the axis of the spindle in a vertical position with the wheel dressed so that the flat in contact with the work is held to a minimum. The wheel is fed vertically down as grinding proceeds. The coolant is normally directed onto the workpiece from the other spindle or the nonworking spindle. The work table is turned at approximately seven RPM, which is over 3,000 inches per minute.

3.2.2 Diameter Grinding - All inside and outside diameters are ground with a plain disc-shaped wheel. The disc wheel is held in the spindle with the axis of the spindle in a vertical position. On most applications when grinding diameters, the wheel is oscillated up and down, so that wheel dressing is not required. The wheel is fed into the work with the horizontal feed as grinding proceeds with the coolant directed from the grinding spindle onto the workpiece. In grinding diameters the work table is again revolved at approximately seven (7) RPM's.

3.2.3 Chamfer Grinding - The radii on the various roller paths gives a 45° chamfer as an alternate. Chamfer grinding, therefore, is a major type category of grinding on the Frauenthal machine.

The 45° chamfers are ground with a plain disc-shaped wheel held in the spindle with the axis of the spindle at a 45° angle with the periphery of the wheel contacting the work piece. On most chamfer grinding operations, the wheel is oscillated with the vertical actuator to keep wheel dressing to a minimum. The chamfer is made by feeding the wheel into a workpiece with the horizontal feed. The coolant is directed at the workpiece from the grinding spindle nozzle. In grinding chamfers the work table is again rotated at seven (7) RPM.

3.2.4 Summary of Conventional Grinding - The flat surface, inside and outside diameter grinding are all accomplished with the spindle in or near a vertical axis. An example of an exception to a vertical axis position of spindle would be the roller path, dwg 730029, where in Section ZZ, there is a 3° x .187 inch angle surface. One of the spindles is always used for the vertical axis grinding, the spindle being locked in the vertical axis position and changed only for grinding a different diameter. The spindle is then realigned or readjusted, because of the wear in the horizontal ways.

Chamfer grinding is all ground on the other spindle, which is locked into position at a 45° angle, except for (say) surface grinding a flat plate when the spindle axis is set horizontal, and a plain disc-shaped wheel is used for grinding.

The work table is rotated approximately seven (7) RPM (over 3000 in/min) for flat surface, inside and outside diameter and chamfer grinding. This is considerably faster than the less than 12 in/min. required in electrochemical grinding.

SECTION 4.0

ELECTROCHEMICAL GRINDING

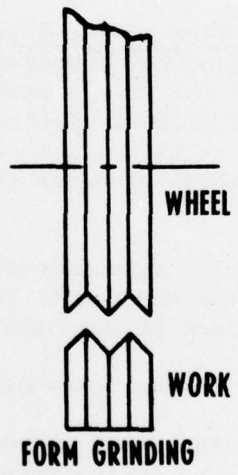
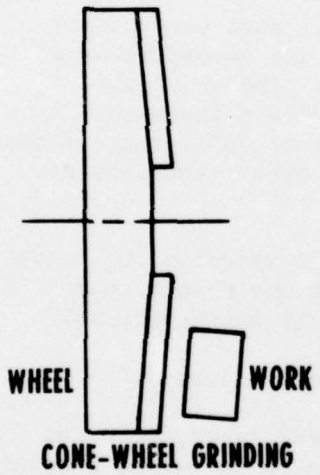
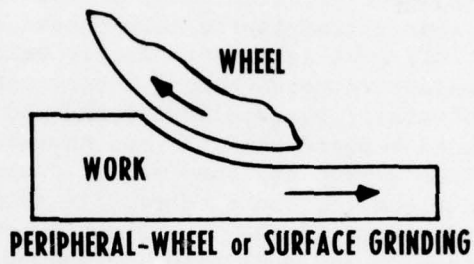
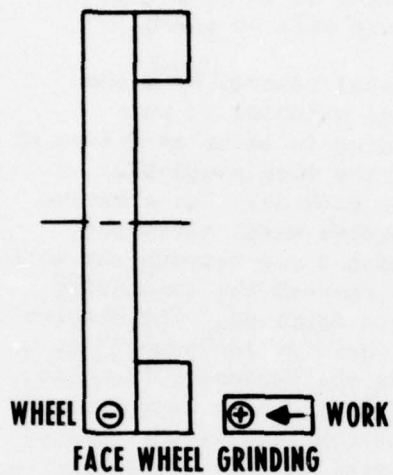
In order to begin the feasibility of ECG applied to large roller bearing paths, a brief description of the process will be given.

Electrochemical grinding can range from metal removal by a combination of electrolytic grinding and mechanical grinding to pure electrolytic grinding. Pure electrolytic grinding is actually a form of electrochemical machining. In both instances, the work piece acts as the anode and the grinding wheel or tool as the cathode. The abrasive particles impregnated in the metal-based conductive wheel serve two purposes: (1) Acts as a nonconductor maintaining a gap between the work and the conductive metal-bonded wheel, and (2) removes the insulating products of electrolysis allowing the process to continue. The electrolyte is introduced between the work and the wheel, where it is "pumped" by the abrasives acting as "pump vanes", supplying the necessary fluid to pass the current for the electrolytic process and flushing away the products of electrolysis. The flushing process continually uncovers a fresh surface on the work piece, allowing the electrolytic process to continue.

4.1 Function of the Grinding Wheel - The wheel must conduct current; the rate of metal removal is proportional to the conductivity of the wheel, but the wheels cannot be too conductive. The wheel must provide a good flow of electrolyte between the wheel and the work. A wheel turning at 5500 f.p.s. can produce a pressure of 150 p.s.i. of the electrolyte, which produces the electrolyte flow. Other functions of the wheel are:

- a. The nonconducting abrasive serves as a spacer between the work (+) and the conductive bonding material (-) of the wheel; otherwise, the contact between the work and material would short-circuit.
- b. The abrasive produces close dimensional accuracy.
- c. The abrasive can increase metal-removal rates, with the ECG becoming a deburring operation. The bulk of the material is removed by conventional abrasive grinding.
- d. The abrasive can improve the surface finish by turning the ECG power off.

4.2 Application of the Grinding Wheel in ECG - In electrochemical grinding there are four methods of applying the wheel to the work: (1) Face-wheel Grinding, (2) Peripheral-Wheel or Surface Grinding, (3) Cone-Wheel Grinding, (4) Form Grinding. (See Fig. 9 for the various applications of the grinding wheel).



APPLICATIONS OF THE GRINDING WHEEL

FIGURE 9

4.2.1 Face-Wheel Grinding Method - This application can't be used on roller paths for many reasons, the principal objection being the required long electrolyte flow path, which should not be over one inch approximately. Another major obstacle is the difficult design of the nozzle and related paraphernalia required to inject the electrolyte between the wheel and work piece. This type of grinding application is definitely not suitable for ECG of roller paths.

4.2.2 Peripheral-Wheel Method - This second application, and the most common type used in ECG work, is definitely suitable for roller path grinding. The electrolyte flow path is not too long, and there is no problem in introducing the electrolyte. Further elaboration on this method will be given in more detail later.

4.2.3 Cone-Wheel Method - This application is not particularly suitable for ECG of roller paths. The work piece (roller path) is so large (continuous in this situation) that the electrolyte path becomes too long, resulting in short-circuiting when small cone angle wheels are used. With large cone-angle wheels (45° and greater) and combined with deep grinding depths, (.125 and greater) the electrolyte path again becomes too long for satisfactory ECG work.

When large cone-angle wheels are combined with light grinding depths, ECG is feasible, resulting in greater contact area than peripheral wheel grinding. This advantage is greatly offset, however, by the added expense of forming and dressing the cone wheels to match the part configuration. The advantage of cone-wheel grinding is further reduced when the cone wheel would be used to ECG two surfaces (such as a top surface and a diameter) at once, which requires different stock removal depths, a common expected occurrence when ECG grinding roller paths.

4.2.4 Form-Grinding Method - This application is definitely not applicable to roller path grinding.

The remaining report will, therefore, be confined to peripheral wheel or surface grinding of roller paths in relation to ECG. (For an illustrated ECG surface grinding operation, see Fig. 10).

4.3 Electrochemical Grinding Removal Rate - The current between the wheel and work piece, without shorting, is the controlling factor in stock removal. In practice, it is safe to assume that a current density of 1000 amps per square inch of wheel-to-work contact can be obtained. Another commonly accepted normal is that 0.1 cubic inch per minute per 1000 amps is the metal removal rate for ECG or ECM at 100% efficiency. The area of contact between the ECG wheel and the workpiece is, therefore, of prime importance for a high metal-removal rate; since, this is the variable in the ECG process that can be effected most.

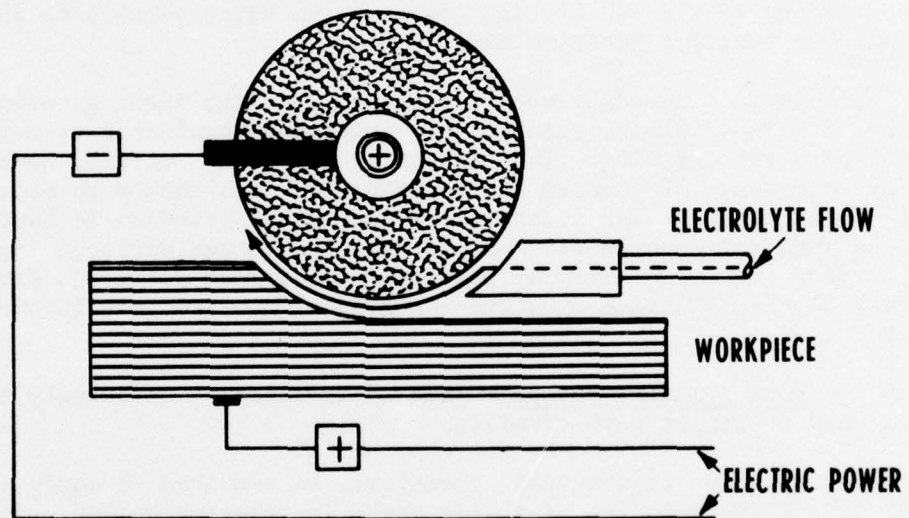


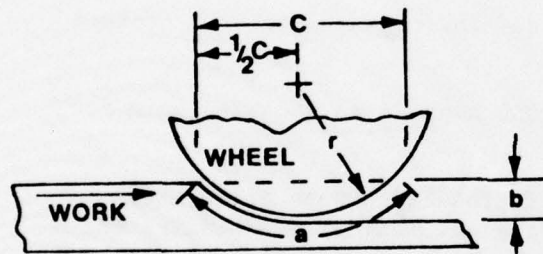
ILLUSTRATION OF ECG SURFACE GRINDING

FIGURE 10

It is imperative for economical ECG to obtain maximum contact area for high-metal removal rates. A critical limitation of this area is that the electrolyte flow path is limited to approximately one inch. This limitation, as explained in par. 4.2 "Application of the Grinding Wheel in ECG", has confined the ECG grinding of roller paths to the peripheral-wheel type grinding application. Since the wheel-to-work contact area is of such importance to the ECG process, it shall be intensively investigated for this type of grinding.

4.3.1 Peripheral Wheel Area of Contact - Of the various methods of applying the grinding wheel to the work (see par. 4.2), the peripheral-wheel type grinding affords the least area of contact. It is also unfortunate there is no literature available for determining this area, except for generalities. Since determining this area is so critical in evaluating the economics of ECG as it applies to roller path production, an approximation will be derived theoretically, and evaluated later for accuracy from data of roller path samples tested.

Since the wheel-to-work piece area equals the arc of the work section of the wheel times the wheel thickness, the arc of the wheel in contact with the work will be calculated. The figure below is used for this derivation with the required dimensions to determine the arc.



r = Radius of grinding wheel
 b = Depth of grinding wheel
 $\frac{1}{2}c$ = Chord length of arc of wheel in contact with work.

When b is small, relative to r , arc a is very near equal to chord c ..

$$\text{Chord } c = 2 \sqrt{2br - b^2} \quad (\text{A mathematical fact})$$

$$\frac{1}{2}a = \frac{1}{2}c$$

$$\frac{1}{2}a = \sqrt{2br - b^2}$$

$$\text{or } A = W \sqrt{2br - b^2}$$

A = Peripheral wheel area
 W = Wheel width

This is an approximation, similar to other approximations, when solving ECG and ECM hypothesis. Deviations will occur at near zero grinding depth, because of spurious ECG, and at too high stock-removal rates, because stock removal will result from the abrasive action of the wheel rather than by ECG, resulting in "shorting".

As seen from the formula, $A = W \sqrt{2br-b^2}$, it is advantageous for the wheel (r) to be as large a diameter as practically possible in order for a maximum area deriving from a given grinding wheel depth. This results in greater current and, hence, a greater metal removal rate. Other advantages of a large diameter wheel are: (1) better accuracy, because of less exposure time for etching; and (2) better electrolyte flow, because of less centrifugal force on the periphery of the wheel, where the electrolyte is applied.

From an analysis of the present conventional grinding machines, past experiences, literature research, and retaining the feature of conventionally grinding roller paths on any future ECG machine; the top limit on the grinding wheel would be a 14" peripheral grinding wheel diameter.

The width of the grinding wheel should be a minimum of the width of the part ECG'd for efficiency and prevention of stray machining.

4.3.2 Table Speed - As summarized in par. 3.2.4, the work table for conventional grinding is turned 7 RPM or over 3000 inches per minute. The table speed for ECG grinding roller paths will now be approximated.

The accepted normals for ECG are:

a. A current density of 1000 amps/sq.-in. of wheel-to-work contact can be obtained.

b. 0.1 cubic inch per minute per 1000 amps is an accepted norm for metal removal rate for ECG.

The table speed for given grinding depths can now be calculated with an accuracy, which is dependent on the accuracy of the summarized factors: the two commonly accepted ECG normals (a) and (b); the one parameter, wheel diameter (14") fixed; and the arc of contact, and derived depth of cut to wheel radius relationship ($\frac{1}{2}C = \sqrt{2br-b^2}$) established.

The table speed for a grinding depth of .005 will be calculated, using the factors above per 1" wheel width for peripheral wheel ECG grinding:

$$A = W \sqrt{2br-b^2}$$

$$A = (1) \sqrt{2(.005) (7)-(.005)^2}$$

$$A = .264 \text{ sq-in.}$$

Roller paths for the 5"/54 gun mount are approximately 144" dia. The volume of metal per revolution is $\pi (144) (.005) = 2.262$ cubic inches. Assuming the accepted current density of 1000 amps/sq-in., this gives an operating current of 264 amps/lineal inch of wheel.

$$\text{Time} = \frac{10,000}{264}(2.262) = 86 \text{ minutes/revolution}$$

$$\text{Feed Rate} = \frac{\pi(144)}{86} = 5.25 \text{ in/min at .005 depth}$$

Tabulated below are the calculated theoretical figures for various grinding depths per inch of wheel width assuming 100% ECG:

Grinding Depth (inches)	ARC Length (in.)	Current (Amps)	Time (min/rev)	Table Speed (in/min)	Volume (cu-in) 1 rev	Volume (cu-in/min)
.005	.264	264	86	5.25	2.262	.026
.010	.353	353	128	3.53	4.524	.035
.015	.458	458	148	3.05	6.786	.046
.030	.647	647	209	2.16	13.572	.065
.062	.926	926	302	1.50	28.048	.092
.125	1.299	1299	438	1.03	56.549	.129
.187	1.607	1607	501	.90	84.587	.169

The tabulated figures above are based on 100% ECG, but from re-searching other ECG work, the optimum conditions for the process involves 90% ECG and 10% conventional grinding. The time and table speeds in the above table could, therefore, be increased 10% to allow for optimum grinding conditions for the proposed ECG machine.

The proposed combination grinding machine would require two widely separated table speed ranges: a table speed of, say, 50 to 500 minutes per revolution and 2 to 14 RPM for conventional grinding. For ECG work, the feed rate must be consistent, requiring a ball screw feed with a d-c drive, a precision hydraulic drive, or a similar precision drive specified for the accurate machining requirements of the roller paths. A simpler, speedier conventional variable drive would be required for the conventional abrasive grinding work of roller paths on the proposed combination grinding machine.

4.4 Limitation of Electro-Chemical Grinding Roller Paths Because of Table Speed

A brief review of roller path production, par. 2.4, and the tabulated table speeds, par. 4.3.2, quickly indicates the limitation of ECG in roller path production. When making a comparison of the data in these two paragraphs, and the method sheets for roller paths, there is conclusive evidence of the following:

- a. It is not economically feasible for ECG to compete with removing the 3/16" metal on unhardened surfaces on roller paths that are presently removed conventionally with carbide tools and ground. After setting the part up for ECG, over 7 hours would be required to remove metal at a depth of 3/16", which is considerably more time allowed presently.
- b. It also is not feasible to ECG the approximate 1/8" metal on surfaces that are removed before they are hardened. These are now machined and conventionally ground. After setting the part up for ECG, over six hours would be required to ECG each surface at a depth of 1/8", which again would be too time consuming.
- c. Because of the greatly reduced area of contact between the wheel and work piece (hence, low ECG metal removal rate and table speed), the ECG of chamfers both before and after heat treat is totally impractical.

The logical conclusion of the above three statements, is: the only area of roller path production that ECG has a possible chance of practicality is the grinding of the approximate 1/16" of hardened metal surfaces after heat treatment. The feasibility of ECG of these surfaces will be further pursued in this report.

4.5 Electrochemical Grinding Tests - In conducting this feasibility study, some test samples of actual hardened roller paths were run to establish various ECG parameters. A detailed report of these tests, conducted by Anocut Inc., can be found in Appendix I (June 1974 report). The test data only is included in this section of the report to substantiate or refute what has been theoretically established concerning feeds, speeds, and electrochemical grinding rates. (See the appendix for a detailed analysis of the test runs, e.g. why the various parameters were changed, etc.) One of the test samples can be seen in Figure 11.

4.5.1 Test Data - All tests were conducted on an ECG surface grinder, using a 14" dia. x 1" wide pyco-bond wheel. The test data found in Appendix I is repeated on Figure 12 with additional columns of calculated information with explanations given in the footnotes. The derivation of the additional calculations for one of the runs (e.g. #3) will be given for clarity:

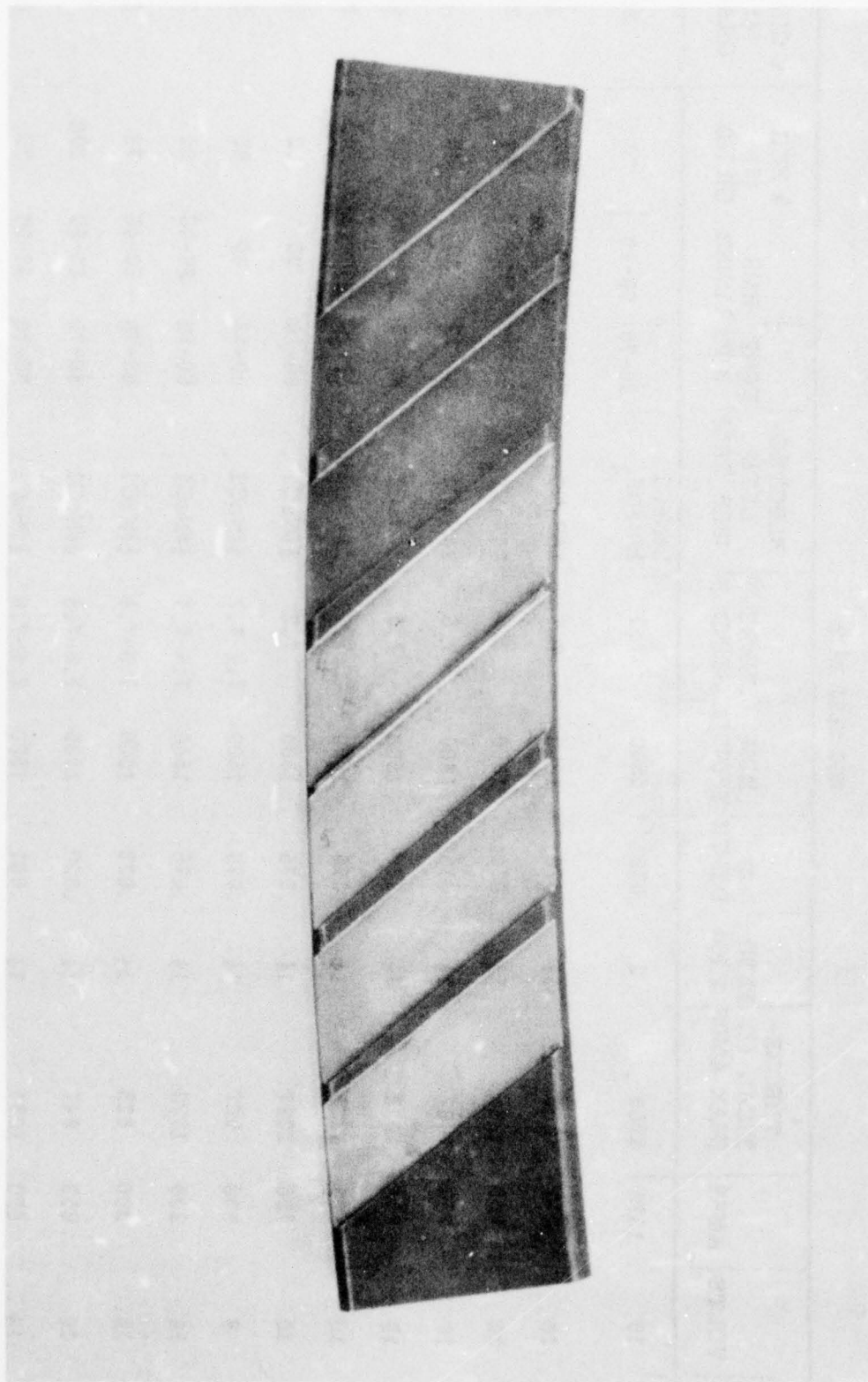


FIGURE 11 TEST SAMPLE

FIGURE 12

ECG TEST DATA

RUN NO	VOLTS	AMPS	THEORE- TICAL (2) MAX AMPS	FEED 1.PM	(2) DEPTH	RPM SPINDLE	CURRENT SPINDLE	ELECTRO- LYTE (PER GAL)	TEMP (OF) FINISH	RMS GRIND	% ECG (3) GRIND	% CONV. (4) GRIND
1	10	1175	1008	2	.072	1500	7.3	2#NaCl 2#NaNO ₂	80-70	80-80	80	20
2	10	800	987	1½	.070	1500	7.7	1#N ₂ NO ₃	80-70	100	76	24
3	10	850	1015	1½	.074	1500	7.5	2#NaNO ₃	80-70	120	77	23
4	10	750	1027	1½	.078	1500	7.5	1#NaCl	80-70	90	88	34
5	10	875	1035	1½	.077	1500	7.5	2#NaCl	80-70	100-150	76	24
6	10	900	1027	1½	.078	1500	7.7	1½#NaCl	80-70	100-150	79	21
7	10	700	1027	1½	.078	1500	7.2	½#NaCl	80-70	30	82	38
8	8	650	987	1½	.070	1500	7.7-7.7	½#NaCl	80-70	40	82	38
9	14	900	1002	1½	.075	1500	7.4-7.4	½#NaCl	80-70	30-40	80	20
10	10	300	625	1½	.028	1500	7.8-7.8	½#NaCl	80-70	30-40	72	28
11	14	650	647	1½	.030	1500	7.8-7.8	½#NaCl	80-70	40-50	100	
12	14	850	1061	1½	.081	1500	7.6-7.6	½#NaCl	60-70	40-50	70	30
13	14	900	1061	1½	.081	1800	7.5-7.5	½#NaCl	60-70	40-50	74	26
14	14	950	1055	1½	.080	2000	7.8-7.8	½#NaCl	60-70	40-50	79	21

15	14	1350	1284	2	.115	2000	7.8-7.8	‡NaCl	80-70	15-25	59	41
16	14	1850	1247	2‡	.112	2000	7.8-7.9	‡NaCl	60-70	15-25	58	41
17	14	1350	1002	2‡	.075	2000	7.7-7.8	‡NaCl	80-70	100-150	72	28
18	14	1250	1015	2‡	.074	2000	7.7-8.0	‡NaCl	80-70	100	88	32
19	14	1400	1008	3	.071	2000	7.8-8.0	‡NaCl	60-70	75	84	38
20	14	1200	1015	3	.078	2000	7.8-7.8	‡NaCl	80-70	100	54	46

(1) Based on formula $A = W \sqrt{br - b^2}$ derived in paragraph 4.3.1 and max. current of 1000 amps/sq-in.

(2) Actual measured depth of grinding.

(3) Calculated % based on: actual ECG current; 10,000 amps/min to remove 1.0 cu-m/min; actual feed rate; and actual grinding depth.

(4) % of grinding not accounted for by ECG.

$$A = W \sqrt{2br-b^2} \quad (\text{Derived in par. 4.3.1})$$

$$A = 1 \sqrt{2(.074)(7)-(.074)^2}$$

$$A = 1.015 \text{ Sq-in.}$$

Theoretical current is 1015 amps

Actual current was 850 amps.

$$\text{ECG removal rate} = \frac{850}{10,000} = .085 \text{ cu-in/min.}$$

$$\text{ECG feed rate} = \frac{.085}{.074} = 1.148 \text{ in/min.}$$

$$\text{At } 1\frac{1}{2} \text{ min, Volume} = 1\frac{1}{2} (.074) (1) = .111 \text{ cu-in/min}$$

$$\frac{.111 - .085}{.111} = 23\% \text{ conventional grinding}$$

$\frac{.085}{.111} = 77\%$ ECG grinding. The tabulated RMS finish was checked with an NOSL profilometer.

4.5.2 Partial Analysis of Grinding Tests - Although the results of the ECG test runs on the roller path samples are not conclusive to establish optimum parameters for an ECG machine, they were conclusive in confirming some of the postulates concerning ECG contained in this report. Some of this information will be used to evaluate the feasibility of ECG of roller paths, since the crux of this report revolves about the metal removal rate of ECG vs. the present traditional production machining rates.

To get the required $\sqrt{8}$ finish on the hardened rollers path surfaces, which is not obtainable by ECG, the power supply would be cut off, and the abrasive quality of the electrochemical grinding wheel, or grinding conventionally is used. The test samples indicate .005 to .010 of an inch depending on the resulting ECG finish, of conventional grinding would be required to get the required $\sqrt{8}$ finish. Therefore, the ECG process would not result in a product improvement, but must be decided by the comparative metal removal rates of the two processes, although collaborated by other documented ECG records, the tests indicate the ECG removal rate can be accurately predicated.

Other comments concerning the sample tests not covered in the more detailed report in the appendix:

a. The depth of grinding given in Fig. 12 are actual measured grinding depths; the depths recorded in Appendix I are approximate depths and should be disregarded.

b. The actual amps in runs 1, 11, and 15 through 20 are greater than the theoretical maximum current, but the absence of resulting arching imperfections must have been removed by the conventional grinding of the abrasive particles in the ECG wheel or inaccurate meter readings.

c. The good finish, 15/ to 25/ of runs 15 and 16 is certain to be a result of the high percentage of conventional grinding by the ECG wheel.

The grinding tests were a practical confirmation of the theoretical conclusions made concerning limitation of table speed, par. 4.4 of this report. The area of roller path production that ECG has economical possibilities is the grinding of the approximately 1/16" hardened surfaces after heat treat. This 1/16" is further restricted by the approximate .005 of an inch required to obtain the required 8/ finish, which will require conventional grinding.

4.6 Advantages and Disadvantages of ECG of Roller Paths - The advantages of Electrochemical Grinding are:

- a. Higher metal removal rate of the hardened surfaces.
- b. Low tool wear.
- c. Produces burr-free parts.
- d. Machines without inducing stresses into the workpiece.
- e. No grinding burn.

NOTE: The advantages of c, d, and e are of small consequence in regard to grinding roller paths, because of their massiveness.

The disadvantages of Electrochemical Grinding are:

- a. Lower metal removal rate when compared to machining with carbide tools before heat treat.
- b. Approximately equal stock removal rate when comparing ECG to conventional grinding of path before heat treat.
- c. Greater original and replacement tooling costs.
- d. Less size control.
- e. Less quality of the surface finish compared to conventional grinding (overcome by turning power off for finish grinding).

- f. Greater machine construction costs.
- g. Greater complexity of machine.
- h. More and greater complexity of controls for the operator.
- i. More deterioration of machine when not in operation.
- j. Maintenance costs higher.
- k. Longer set-up and shut-down time.
- l. Less flexibility.

In addition to the above disadvantages of ECG, there are some unknown factors related to ECG of roller paths. The research conducted involved surface grinding of one foot long section of roller paths, since there was no available radial ECG machine to conduct tests on a complete roller path. One unknown factor is the question of the match-up or blending of the surface when the ECG process traverses the path 360°. This may or may not be a problem, but does pose a question that hasn't been investigated in this phase of the program.

Another factor that hasn't been resolved (and can't be unless the grinding machine is actually built) is the question of the effects of ECG'ing the 1/16 of an inch from the roller path in one pass. At present the roller path is ground on one side, flipped over and ground on the other side, etc. until the path is to size. The roller path is rough ground near to size by "hogging" the wheel into the workpiece and then finish ground with light wheel pressure. After heat treat the path is in a stressed condition, and as grinding proceeds the magnetic chuck holding the path to the work table sometimes suddenly releases, because of the stresses in the path, and the operator must stop the work table immediately to prevent gouging and possible scrapping of the roller path. The heat of the grinding operation could possibly cause these stresses, but because of the piece's ability to absorb heat due to their massiveness and flood cooling of the work, the stresses are certain to be caused by the heat treatment. This "popping" up of the work piece occurs when conventionally grinding a few thousandths depth; it certainly is a factor to consider when 1/16 of an inch of metal is to be removed by ECG in one pass. An adverse answer to this question would nullify any hope of using ECG, economically on roller paths.

There is also the question of the ability to position a hardened roller path on the work table, calculate how much metal must be removed from each surface in one grinding pass (all four surfaces of paths dwg 730029 and dwg 730030 are ground), and result in having enough remaining material to finish out to the drawing dimensions. This problem would be insurmountable, if, after making an ECG pass at full depth thereby removing some of the residual stresses, the roller path would distort after releasing the magnetic chuck that holds the path to the work table. This is a reasonable explanation why the operators keep

flipping the roller path over as grinding proceeds, keeping the path in a "relaxed" condition. If the ECG process were limited to, say, .005 or .010 of an inch per pass, the work table speed would render the process uneconomical for grinding roller path by ECG. Also, one of the basic premises of this study, the saving of set-up time in flipping the path continuously as grinding proceeds, wouldn't justify the construction of an ECG machine, which hasn't, and couldn't, be resolved in this report.

Only the construction of a full size ECG Machine could resolve the questions in this paragraph.

4.7 ECM and Conventional Grinding Rates of Hardened Roller Paths

Much has been said in this report about and the justification of an ECG machine based on the metal removal rates of ECG and conventional grinding of hardened roller paths. The metal removal rates of each process will be briefly described.

4.7.1 Conventional Grinding - The conventional grinding rate of hardened roller paths is well established, although it will vary from one roller path to another identical roller path because of size, processing, and induced stress variations. A conscientious operator can grind a flat hardened surface of a roller path under average circumstances approximately .032 of an inch in an 8 hour shift or .004 of an inch per hour. The same operator can grind hardened diameter surfaces approximately .064 of an inch per 8 hour shift or .008 of an inch per hour. The doubling of the flat surface removal rate in grinding diameters is because of the greater wheel contact; a cup-wheel used for flat surfaces, a plain disc-shaped wheel for the diameters (see par. 3.2.1 and 3.2.2). The cup-wheel has an approximate .5 inch contact with the work piece, the disc-shaped wheel is 1.5 inch or larger in width. The nature of the grinding machine and work doesn't permit the use of the disc-shaped wheel on flat surfaces and still maintain dimensional and surface finish requirements.

The above grinding rates are not found in the process sheets of the roller paths, the sheets covering the grinding operations aren't broken down to individual operations, but are accepted and practical grinding rates by experienced and knowledgeable operators.

4.7.2 ECM Grinding - The electrochemical grinding rate of hardened roller paths has not been established, and is more difficult to obtain than the conventional grinding process. However, the removal rate can be calculated theoretically. Based on the test samples electrochemically ground for this study and from researched ECG case histories, the ECG removal rate of a full size ECG machine can be estimated with a fair degree of accuracy. The tabulated data in par. 4.3.2 of this report is a reliable basis for estimating ECG removal rates at various grinding depths for roller paths and is partially retabulated below with another column, Equivalent Thousandths Per Hour of Grind. This is the volume

per hour of metal removed by ECG at the specified depth, divided by the area of the complete roller path one inch wide ($1 \times 144" = 452$ sq-in.). This is a convenient method of comparing metal removed by ECG vs. that by conventional grinding, which removes hardened flat surfaces at a rate of .004 of an inch per hour and a diameter rate of .008 of an inch (per surface) per hour.

ESTIMATED ECG RATES FOR VARIOUS GRINDING DEPTHS

Grinding Depth (inches)	ECG VOLUME (cubin-inch/min)	Equival. Thousandths Per Hour of Grinding
.005	.026	.0035
.010	.035	.0047
.015	.046	.0061
.030	.065	.0086
.062	.092	.0122
.125	.129	.0172
.187	.169	.0224

EXAMPLE:

$$\frac{60 \times .026}{452} = .0035 \text{ in./hr}$$

4.7.3. ECG VS. CONVENTIONAL GRINDING RATES

A few general statements can be made in reviewing the preceding paragraphs on ECG and Conventional Grinding.

The ECG Process is not economically feasible at a grinding depth over approximately .062 of an inch, since that is the grinding depth ground on hardened surfaces of the roller paths. The electrolyte flow path also becomes greater than the maximum one inch for depths greater than .062 of an inch. The ECG removal rate is not greater than conventional grinding from 0 to .007 of an inch on flat hardened surfaces, and from 0 to .014 of an inch on inside and outside diameter hardened surfaces. The .005 to .010 of an inch of conventional grinding is required on the surface for getting the required surface finish on the roller paths.

4.8 Applicability of ECG to Roller Paths - For current manufacturing process of the four types of roller paths used on gun mount stands, see par. 2. ECG applies to each type of roller path as follows:

4.8.1 Combination and Radial Roller Paths - The Combination type (dwg 730029 and the Radial Type (dwg 730030) are related similarly. The two paths have a rectangle shaped cross section, are hardened, and ground on all four side, as seen in Figures 2 and 3.

Approximately .056 of an inch is ground from the thickness of the paths. If we assume one half of this ECG ground from each side in one pass, and .005 of an inch of conventional grinding is required to obtain the required surface finish, we get a result of .023 of an inch

($\frac{.056}{2} - .005 = .023$) that can be ECG ground. Assuming we can ECG in one pass, the optimum condition (table of Par. 4.7.2) indicates that this should take 3.1 hours:

$$\left(\frac{.023}{.0074} = 3.1 \right)$$

to ECG. Conventional grinding would require 5.7 hours:

$$\left(\frac{.023}{.004} = 5.7 \right)$$

Approximately .060 of an inch is removed from both the inside and outside diameters. Again, interpolating the Table of Par. 4.7.2, we see that if the path can be ECG in one pass, it would require 4.8 hours:

$$\left(\frac{.005}{.0014} = 4.8 \right)$$

Conventional grinding would require 6.9 ($\frac{.005}{.008} = 6.9$) hours.

The summation of the above indicates 15.8 (3.1+3.1+4.8+4.8 = 15.8) hours of ECG required, which would require 25.2 (5.7+5.7+6.9+6.9 = 25.2) hours of Conventional Grinding. This indicates a possible saving of 9.4 hours by using ECG, where possible, rather than Conventional Grinding. The process sheets allows: 26.275 hours set-up and 68.601 hours working time for roller path dwg 730029; 26.316 hours set-up and 66.908 hours working time for roller path dwg 730030. The difference of time allows set-up and working time for machining and grinding before heat treat, grinding chamfers, etc. By using ECG there is an approximate 14% potential savings of actual working time. The set-up time would probably be equal on the two roller paths; the savings in fewer set-ups required by ECG would be offset by the more complex setups of ECG.

4.8.2 Center Thrust Roller Path - The Center Thrust Path, dwg 730031 has a multi-surfaced cross section, and is hardened on all but two small surfaces, as seen in Figure 4. Approximately .050 of an inch total grinding stock is left on the two surfaces that are ground after heat treat.

This allows an approximate .020 of an inch ($\frac{.050}{2} - .005 = .020$) on two surfaces that can be considered economical for ECG. Again, assuming that this can be ECG'd in one pass, the table of par. 4.7.2 indicates this would require three (3) hours per side by ECG or five (5) hours by Conventional Grinding, resulting in a potential savings of four (4) hours each roller path.

The process sheets allow 30.172 hours set-up time and 104.389 hours working time. Again the set-up time would certainly not decrease on this roller path. There would be an approximate 4% potential savings in actual work time by ECG, which is not considered feasible for the Center Thrust Roller Path.

4.8.3 Upper Thrust Roller Path - The Upper Thrust Roller Path, dwg 730032 has one small surface on its flat cross section that is hardened and ground as seen in Figure 5. After heat treat, only enough of the hardened surface to clean up is ground off. Thus, ECG would not be feasible on the Roller Path.

4.8.4 Review of Applicability of ECG to Roller Paths - On both the Combination and Radial Roller Paths, there is an approximate 9.4 hours of potential savings or 14% saving of conventional working time on each.

The Center Thrust Roller Path offers an approximate four (4) hours or 4% potential saving of conventional working time.

The Upper Thrust Roller Path offers no savings, and is not feasible to consider for ECG.

4.8.5 Design and Operating Considerations - The proposed ECG machine has many basic requirements in common with a conventional grinding machine. The ECG machine should be capable of conventional grinding for roller path production not feasible for ECG, such as the Center Thrust and Upper Thrust Roller Paths, chamfers required on the roller paths, and as a final-pass finishing operation. The machine requirements apply to such fundamental factors as strength, rigidity and accuracy of a conventional grinder.

In addition to the mechanical requirements of a conventional grinder, there are the specific requirements applying to an ECG Process: power supply, electrolytic system, special spindles and grinding wheels, corrosion protection, and the machine should be easy to clean in order to remove as much excess electrolyte as possible.

Even with good corrosion protection, an ECG machine cannot be shut down for extended periods, as would happen on the proposed machine when grinding roller paths conventionally. When an ECG Machine is shut down for more than a few days, the electrolyte will attack the machine components. If the machine is used daily, the electrolyte is kept in motion preventing localized concentrations of salts in solutions to prevent oxidizing of metallic surfaces so quickly.

For additional more specific design considerations for an ECG grinder for roller paths, see Anocuts, ECM Final Report, Appendix II.

SECTION 5.0

CREEP FEED GRINDING

"Creep Feed" grinding is a relatively new application of conventional grinding. To make a true evaluation of the applicability of the process, research would be required on actual roller paths. This report will present some of the technical aspects of creep grinding.

In comparison to standard conventional grinding, "creep feed" grinding removes large masses of material. This is accomplished by the wheel removing all of the material the wheel contacts. The contact area is large, because of the increased depth of cut. The wheel acts as a holder of many tiny cutting tools, each removing its maximum amount of material possible on each revolution of the wheel.

The following features of a "creep feed" grinding machine in comparison to a conventional grinder are:

- a. More rugged frame.
- b. Greater H.P. spindle motor.
- c. Large coolant system.
- d. High coolant pressure (350 psi)
- e. Large coolant flow--this requires large drains.
- f. Machining area totally enclosed due to high coolant psi and flow.
- g. Accurate cross feed in table necessary.
- h. Usually ball screw drive required.

The above inherent requirements for a creep feed grinder makes this grinder more costly than a conventional grinder. No data was collected on the advantages of creep grinding vs. conventional grinding, but the question was discussed earlier on whether the roller path with induced stresses during heat treat could be held to the work table with a magnetic chuck when a deep cut is made. However, no definite answer can be found unless a complete roll path were tested, but past experience indicates the roller path would not hold.

SECTION 6.0

CONCLUSIONS

As a result of this feasibility study, the following conclusions are made:

6.1 Creep Feed Grinding - Creep feeding grinding is not suitable for grinding because of the residual induced stresses in the work piece from heat treatment.

6.2 ECG Form Grinding - Form grinding (having the spindle set at, say, 45° to increase the surface contact to facilitate a greater ECG metal removal rate) is not recommended for roller path production, because of the disadvantage of requiring a formed wheel for all grinding operations, and the anticipated wheel wear necessitating expensive frequent wheel dressing.

6.3 ECG Grinding - ECG is not economically feasible for grinding roller path surfaces before the work piece surfaces are hardened. The ECG Process is also not economically feasible for either the upper thrust or center thrust roller paths after heat treat, which are two of the four roller paths that go into a gun mount stand.

There is an approximate 14% potential saving of conventional grinding time on both the combination and radial roller paths of ECG is used after heat treat. The savings are termed "potential" because it isn't certain the paths can be ECG'd in one pass due to induced stresses during heat treatment. The savings would come at the cost of inherent disadvantages of the ECG process as enumerated in par. 4.6.

An ECG Machine for roller paths would be used for extended periods of time for conventional grinding, since a large portion of the roller path cannot be economically ECG'd. This would be detrimental to an ECG system, even though it was built corrosion resistant.

A dual system of controls would be required of such a "hybrid" grinding machine, and the work table speed would require two diverse ranges of speed at approximately 0 to 10 inches per minute for ECG and 3000 inches per minute, or 7 RPM for conventional grinding.

SECTION 7.0

RECOMMENDATIONS

As a result of the research made on NOSL's roller path grinding, documented performance of ECG installations, and sample testing, the following recommendations are made:

7.1 ECG Machine - Until ECG advances to the stage of giving higher metal removal rates, it is recommended that this program be aborted. The disadvantages of an ECG installation for roller paths outweigh the potential advantages on the grinding operations where ECG is applicable. A "break-through" in ECG would be required to warrant reconsideration of the process for roller path production.

7.2 NOSL Grinding Machines - It is recommended that the present grinding machines be completely overhauled. This is based on the following: the questionable tenability of an ECG machine; there is only one machine builder, who is willing (but reluctant) to manufacture a conventional grinder for roller paths; the precision required (and obtained) on the present Fruenthal grinding machines; the condition of the Station's two roller path grinders; and contact with the Station's operations and maintenance people. For an estimated \$30,000 each, the grinding machines can be refurbished to "better than new" condition. The worn ways and sides can be replaced with adjustable wear plates; worn bearings, gears, castings, etc. replaced as required.

It is suggested the metal removal rate can be increased by using DoAll's "Cool Grinding" attachment to cool the wheel and the work piece to give better dimensional control, reduce warping, and extend wheel life without making any major changes in the present grinding machines.

APPENDIX I

ANOCUT INC. INTERIM REPORT

JUNE 1974

C O N T R A C T

No. N 00197-74-C-0012

PERFORM FEASIBILITY STUDY ON MACHINING ROLLER PATHS BY ECG

JUNE 1974

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Introduction:

This report covers work done on Task A. This data attempts to establish electrolyte composition, metal removal rates, and surface finish by conducting grinding tests on an ECG surface grinder. Also included are explanations of possible failure or faults which could occur, and what is required to overcome these faults in order to minimize damage to the workpiece.

Summary:

This report includes data pertaining to electrolyte testing. Of the various electrolytes which can possibly be used for ECG, the two most common ones were tested. If the sodium chloride electrolyte yields an acceptable finish, we have no reason to test other more expensive, exotic, and possibly dangerous electrolytes. We would like to have your comments on the surface finish of those test parts as submitted.

From these tests we believe that the optimum metal removal rate can be achieved by increasing the RPM of the spindle 15-20% above what has been considered normal in the past as long as the manufacturers of the wheel can certify that it is safe to do so.

We should expect to operate at 14 volts without any problems. Sustained cutting is done at this voltage in other areas of electrochemical machining. The only requirement will be that of a cooling source to remove the BTU's from the electrolyte.

Most of the unusual occurrences related to power failure, arcing, short circuits, stop, restart, and overlapping can be anticipated and suitable preventive circuits be included. Hydraulic residual can be utilized to remove the spindle from the cutting area when a main or power unit failure occurs.

Arcing is minimized by automatically modulating the voltage downward. Voltage regulation for ECG power units are normally included. Pre-start short protection will interlock the machine preventing the operator from turning on the machine when a short prevails.

When an ECG cut is interrupted for some reason, it is a problem to restart and completely eliminate the possibility of an additional over-cut or under-cut. A slow rise voltage control will minimize this problem, but it is doubtful that it can entirely eliminate it.

Recommendations:

We recommend using a 6-12% solution of sodium chloride electrolyte for grinding roller path parts. The spindle RPM should be increased to give more efficient machining. We recommend using a Pyco-Bond wheel although we will need to further justify the recommendation by performing some tests using the silver bonded type wheel.

We recommend Naval Ordinance send 15-20 additional test pieces to perform tests on tolerance, repeatability, and flatness.

The preventative measures mentioned in this report should be used in any ECG machine built for this purpose. Any specification written for an ECG machine should require voltage regulation, spark suppression, slow rise voltage control, pre-start short, and automatic spindle retreat for power failure.

TASK A

1. Establish electrolyte composition for optimum machining and associated finish limitations (i.e. tolerance, flatness, surface finish, etc.) for ECG of roller path material as defined on drawings 730029, 730030, 730031, and 730032.

The initial testing on the test pieces was to determine the most suitable electrolyte. The various electrolytes were evaluated on the basis of conductivity and surface finish. Sodium chloride and sodium nitrate electrolytes were tested in seven different combinations and concentrations. The combined sodium chloride - sodium nitrate electrolytes produced the poor finish shown in cut no. 1. The next tests were made using only sodium nitrate electrolyte at two different concentrations. Again the finish produced with sodium nitrate was not acceptable.

The following series of tests using sodium chloride at various concentrations produced the best results. The least concentration; $\frac{1}{2}$ lb./gal. of electrolyte, produced the best results as shown on test 7, 8, and 9.

2. Establish metal removal rates, depth of cut, surface feet per minute relationships.

The next series of tests were to determine the effects of voltage and spindle RPM in an attempt to increase cutting rate while maintaining or improving finish. By examining runs 7, 8, and 9, we can see that a wide voltage range can be used without impairing finish. The higher voltage (14) was then held constant for the remainder of these tests. By using the higher voltage which usually gives greater over-cut, we anticipated obtaining a greater removal rate.

In cuts 12, 13, and 14 we experimented with spindle RPM. As the spindle RPM was increased, the current became greater indicating more efficient metal removal. We attempted RPM greater than 2,000,

however we experienced some vibration, and therefore returned the RPM to 2,000. The increased RPM appears to yield better metal removal rate due to the increased electrolyte efficiency. Therefore, at this time we increased the feed from $1\frac{1}{2}$ inches per minute to 2 inches per minute. Then we further increased the feed to $2\frac{1}{2}$ inches per minute. The results were favorable, and a final feed of 3 inches per minute was achieved without problems.

These tests show that ECG efficiency can be increased somewhat by using higher voltage than normal, and by increasing RPM. We are not sure what caused the imperfections which appear as arcing in one area of cuts 18 and 19. However we believe they are caused by lack of sufficient electrolyte. This condition may have come about by one side of the wheel leaving the cut before the other side finishes. Thus, the electrolyte has a tendency to take the path of least resistance.

These tests were conducted using a 14" dia. Pyco-Bond graphic wheel. Additional tests using a different type of wheel to confirm our results and test the efficiency of the wheel will be made pending receipt of additional test pieces.

3. Establish effects of preventive measures needed to safeguard machine, grinding wheels and workpiece in the event of:

a. Main input power failure

This condition will cause possible damage to the workpiece and the grinding wheel. Therefore safeguards are required to prevent or minimize damage. The primary source of damage will be the mechanical forces on the wheel due to power failure. Since the feed system is hydraulic, the residual energy of such a system can be utilized by reversing valves automatically when a power failure occurs. Thus the spindle position can retract to its starting position allowing the spindle, electrolyte pump, and rotating table to coast to zero without damage.

b. Power pack supply failure

If the power supply should fail during operation, the same condition as in "a." will prevail except the machining will tend to continue by 100% mechanical grinding instead of electrochemical grinding. Normally the circuits are interlocked sequentially to prevent damage

When starting, and in this condition the interlocks can remove power from such circuits and automatically return the spindle to its starting or neutral position. Although the spindle retraction is almost immediate, there may be a brief period of mechanical grinding. This small period of mechanical grinding should not prevail long enough to incur any damage.

c. Arcing or short circuit effects

A modulating circuit will reduce output voltage as a spark intensity increases. In practice the responsiveness of this control may be adjusted by the operator. This control is referred to as "spark suppression". A voltage regulator circuit is required to hold the voltage at the optimum level as the current load changes. It is characteristic of all electrical equipment - because of the exhaust resistance in the components of the power supply, i.e. cables, switches, contacts, brushes, collector rings, etc. - that as the demand for current increases, the voltage tends to fall off. This occurs in electrochemical grinding as the wheel first approaches the work drawing a small amount of current and then engages the entirety of the cut. To prevent this drop in voltage, the control senses the voltage actually present between the wheel and the work. If the voltage tends to drop under load, the sensing wires carry the signal back to the power supply, through a solid state control system causing an automatic increase in the output voltage of the power supply. These circuits in a power supply will prevent unnecessary arcing.

Any direct short-circuit on the power supply should be detected by another circuit known as "tooling short". This sensor will immediately shut down the power supply thus starting a sequence of events which retracts the spindle and stops the feed and pumps. In the event there is a short circuit prior to engaging the DC power, the power supply will not come on.

d. Stop and restart within the cycle

Intentional stopping during a machining cycle will automatically actuate the necessary circuits to disable power, stop feed, retract spindle, and shut off pump. Restarting during the middle of the machining cycle requires that caution be exercised to prevent secondary machining in the cut while restarting the power supply. The restart sequence will be to advance the spindle forward in rapid

traverse, rotate work piece toward the restarting point, and at a pre-set distance (.030") from the restart point change over to feed and start electrolyte pump. When the wheel approaches the work, .010 or less, the power unit must be turned on. When this is done the power supply should be restricted from suddenly putting out full voltage by using a slow-rise circuit to minimize the secondary machining.

e. Over lap at start-stop point on the radial or flat surfaces

This problem is much the same as in part d. This irregularity of surface may be more than can be tolerated. Therefore it may be necessary to machine the final .001" to .002" by conventional grinding. This final mechanical grind can be done using the same wheel as long as the appropriate wheel is used.

f. Adaptive control breakdown

Breakdown of adaptive safeguard controls is as follows:

<u>VARIABLE PARAMETER</u>	<u>CONTROL MEANS</u>
Line input voltage effect on output	Automatic DC output regulator compensates for input line variations up to $\pm 10\%$
DC output voltage	Closed-loop feedback maintains machining voltage within 0.5% under load current variations, except when overridden by spark suppress signals.
Sparking intensity	Suppression circuitry automatically reduces output voltage with severity of sparking. The allowable level may be manually adjusted.
Tooling short circuit	If contact resistance between wheel and work approaches a short circuit value, the effect will be as described under "short circuit" above. If a short circuit condition prevails prior to machining, all operations will be locked out until circuit is cleared.
Spindle motor overload	If spindle motor is overloaded for any reason, a meter relay will stop all operations and spindle will retract.

NAVAL ORDINANCE GRINDING TESTS

14" Dia. 1" Wide Pyco-bond Wheel

Run No.	Volts	Amps	Feed IPM	Depth	Spindle	Spindle	Elec- trolyte (per gal)	Temp (°F)
1	10	1175	2"/m	.065	1500	7.3	2# NaCl, 2# NaNO ₃	60-70
2	10	800	1½/m	.065	1500	7.7	1# NaNO ₃	60-70
3	10	850	1½/m	.065	1500	7.5	2# NaNO ₃	60-70
4	10	750	1½/m	.065	1500	7.5	1# NaCl	60-70
5	10	875	1½/m	.065	1500	7.5	2# NaCl	60-70
6	10	900	1½/m	.065	1500	7.7	1½# NaCl	60-70
7	10	700	1½/m	.065	1500	7.2	½# NaCl	60-70
8	8	650	1½/m	.065	1500	7.7-7.7	½# NaCl	60-70
9	14	900	1½/m	.065	1500	7.4-7.4	½# NaCl	60-70
10	10	300	1½/m	.015	1500	7.6-7.6	½# NaCl	60-70
11	14	650	1½/m	.015	1500	7.8-7.8	½# NaCl	60-70
12	14	850	1½/m	.065	1500	7.6-7.6	½# NaCl	60-70
13	14	900	1½/m	.065	1800	7.5-7.5	½# NaCl	60-70
14	14	950	1½/m	.065	2000	7.8-7.8	½# NaCl	60-70
15	14	1350	2/m	.105	2000	7.8-7.8	½# NaCl	60-70
16	14	1650	2½/m	.105	2000	7.6-7.9	½# NaCl	60-70
17	14	1350	2½/m	.065	2000	7.7-7.8	1# NaCl	60-70
18	14	1250	2½/m	.065	2000	7.8-8.0	½# NaCl	60-70
19	14	1400	3/m	.065	2000	7.8-8.0	½# NaCl	60-70
20	14	1200	3/m	.065	2000	7.8-7.8	½# NaCl	60-70

APPENDIX II

CONTRACT N00197-74-C-D012

PROCUREMENT SPECIFICATION 2012-73-001

FINAL REPORT

INTRODUCTION

This program was conducted to determine the feasibility of designing and building an ECG grinder capable of grinding large diameter components such as a gun mount roller path. The investigation covered mechanical design concepts, electrical design concepts, electrolyte investigation, wheel evaluation and optimizing ECG parameters. Most of the efforts of this investigation were directed toward applying the principles of ECG to the large diameter components, and toward utilization of current knowledge and experience as a basis of creating design criteria for these components. Each segment of the progress reports covered the results of the work established under Task A and Task B of the specifications.

HISTORY AND DISCUSSION

Although ECG has been used throughout industry to machine carbide and tough alloys, we know of no case which attempts to use the process to machine large diameter components. Since the principles had been already established, the major efforts in this project was to investigate various electrolytes known to be successful in other applications. It has been established that electrolytes which contain several combinations of ingredients are primarily beneficial when machining carbides or more exotic alloys. Materials such as the roller path material is usually machined with sodium chloride or sodium nitrate. Either electrolyte will machine the material, however sodium chloride is more efficient

for metal removal. Since it is also the least expensive electrolyte we feel that it is the most suitable to use on the roller paths. There are possibly two conditions which may prevent the use of sodium chlorides. One is possible metalurgical damage. The second is excessive aggressive etching on portions which have already been machined. Both of these conditions should be examined if or when further tests are made.

The four major types of wheels used for ECG were investigated. Diamond wheels are normally used when no other wheel is suitable such as when grinding carbides. The high cost prevents more widespread usage. The metal bonded aluminum oxide wheel is the next wheel considered. This wheel costs less than the diamond wheel, but it is a difficult wheel to use when form grinding because it is difficult to dress. We therefore considered the copper compounded wheel and a newer carbon/graphite bond wheel. The copper compounded wheel has had wide acceptance and use. It is more easily dressed than the diamond or aluminum oxide wheels. Its conductivity is good but uniformity is not always assured. The graphite bond wheel has the same advantages of the copper bonded wheel along with uniform conductivity. The graphite type wheel is more complicated to produce and the production of these wheels takes an excessive amount of time. The graphite wheel was successfully used for these tests.

During the grinding tests we systematically varied each parameter attempting to obtain optimum results while reaming within practical limits. As we increased the wheel rpm we were able to increase the feed of the table, thus remove more material. We found the limit to be attributed to the centrifugal force throwing off the electrolyte and the closer working gap allows less electrolyte into the work area causing increased mechanical grinding and a decrease in electrochemical grinding.

We examined the effects of malfunctions and failures related to the power. Several types of preventative measures have been used in other ECG and ECM machines. When a main power failure occurs, the residual mechanical forces can cause damage to the workpiece and the grinding wheel. When using a hydraulic feed system reversing valves must be used to prevent damage. This applies to the table and also can be applied to the spindle feed as well. Circuits for doing this are within standard electrical techniques.

When a failure occurs at any point which affects applying DC to the spindle, electrolyte to the work, spindle failure, or too much force applied to the wheel regardless of its source, electrical monitoring and safeties are available. These adaptive control measures can be done by the following electrical systems. Line input voltage

effect on output can be regulated with automatic DC regulators which compensates for variations up to $\pm 10\%$. This circuit is standard on most of the better ECG power supplies. Closed loop feedback will maintain machining voltage within a 5% under load current variation. This circuit is also standard in most good power supplies. Modulating circuits for suppression of spark intensity is standard in Anocut power supplies. Tooling short circuits to prevent start up is also a standard preventive electrical circuit. Spindle motors in all ECG machines should be monitored with spindle current meters. These meters are necessary to determine if mechanical grinding is taking place instead of ECG. Overload relays can be included in this circuit to prevent excessive damage.

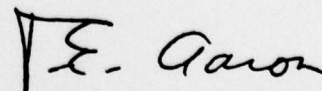
A bridge type structure gives enough flexibility to allow the machine to accomodate all the various sizes which must be considered. The design elements must function properly in the typical ECG environment without deteriorating. The machine must have dual capability, grinding by ECG and conventional. The best accuracy can be attained through electronic controlled hydraulic positioning of the spindle, and table rotation. These controls are considered the first phase of adaptive control for ECG.

CONCLUSIONS AND RECOMMENDATIONS

The work accomplished in this program went far in determining the feasibility of designing and building a grinder capable of grinding large diameter components. In Task A we performed tests attempting to establish optimum machining conditions. At this point we feel that optimum conditions were not established. More work is required in comparing other types of wheels. Additional tests should be made on test pieces to establish maximum metal removal rates. Most of the tests were done on a surface grinder machining on the periphery of the wheel. The most productive and accurate ECG machining done to date utilized the cone angle on a wheel to increase contact area. This concept should be tried.

The machine concept will accomodate the parts in question. The table should use x-bearing as described in previous reports. The spindle with hydraulic position represents the latest in ECG.

We recommend that additional tests be performed in order to establish the best operating conditions for optimum metal removal. The machine concept presented in the study should be further developed by additional detailed design. Preventive measures established in the study are adequate, and they should become an integral part of the electronic portion of any grinder designed for this purpose.


T. E. Aaron

TEA/lk

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20. (Cont'd)

An in-depth analysis was made of the results expected of a theoretical ECG grinding machine, from both a design and a production viewpoint. Samples were ground on an ECG surface grinder to confirm theoretical hypothesis with regard to grinding rates, table speeds, etc. It was concluded that ECG for roller path production is not practicable and effective at this time.