MODELING OF ELECTROCHEMICAL GRINDING PROCESS

A THESIS SUBMITTED FOR PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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DECLARATION

This is to certify that the thesis work presented for the partial fulfillment for the award of the degree of Master of Science in Mechanical Engineering is done by B. M. Asaduzzaman in the Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. This thesis work or any part of the work has not been submitted to any other Institute or University for the award of any degree or diploma.

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Dedicated to

My Beloved Father

Approval

This is to certify that the project work submitted by B. M. Asaduzzaman entitled **"Modeling of Electrochemical Grinding Process"**- has been approved by the Board of Examiners for the partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering in the Department of Mechanical Engineering, Khulna University of Engineering and Technology, Khulna, Bangladesh.

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ABSTRACT

Electrochemical Grinding (ECG) process is a mechanically assisted electro-chemical process for material processing. The process is able to successfully machine electrically conducting harder materials at faster rate with improved surface finish and dimensional control. The process generates burr-free, stress free surface, unlike mechanical grinding at a lower cost of production. The material removal mechanism and the parametric effects of different process parameters on material removal rate have extensively been analysed. The interrelationship amongst the process parameters has been established.

The thesis includes the development of mathematical modeling for metal removal rate (MRR) in ECG process. The relative contribution of electrochemical dissolution and mechanical action to overall material removal rate has been evaluated. An experimental set-up has also been designed for electrochemical grinding process.

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CHAPTER 1

INTRODUCTION

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1.1 Nonconventional Machining Process

With the development of technology, more and more challenging problems are faced by the scientists and technologists in the field of manufacturing. In recent years a number of new materials have been developed which are being commonly used in space research, missiles and nuclear industries. These materials are more strong, hard, tough, heat and wear resistant and cannot be machined by conventional machining processes. This has led to the development of new metal removing processes called newer machining processes or non-conventional machining processes. These processes are not affected by strength, hardness, toughness and brittleness of materials and can produce intricate and complicated shapes of the workpiece [1].

These processes are used to reduce the number of rejects experienced by old manufacturing method by increasing repeatability, reduction in breakage of fragile workpiece or by minimizing detrimental effects on workpiece properties [2].

The non-conventional machining processes which have been industrially exploited in general are grouped according to their primary energy modes as shown in Table 1.1 [3].
Different forms of energy like electrical energy, chemical energy, high velocity jet of liquids or abrasives, electrochemical reactions, and high temperature plasma etc, are applied to process the materials. In this process electrolyte plays a major role in material removal like ECM. Generally, electrical energy is converted into mechanical energy in case of conventional machining operation such as turning, milling and grinding. But in non-conventional processes, material is removed in direct application of electrical energy to the workpiece. These processes include ECG which depletes material. Modern machining methods are classified according to the type of fundamental machining energy employed , for example, mechanical, electrochemical, chemical or thermoelectric. Table 1.2 gives a classification of the machining processes based on the type of energy used, the mechanism of metal removal, the source of energy requirements, etc [4]. The process economy and the process capabilities of different methods are summarized in Table 1.3 and 1.4 [4].

Table 1.1 Nonconventional Material Removal Processes

Mechanical	
AFM - Abrasive Flow Machining	AJM - Abrasive Jet Machining
HDM - Hydrodynamic Machining	LSG - Low Stress Grinding
RUM - Rotary Ultrasonic Machining	TAM - Thermally Assisted Machining
TFM - Total Form Machining	USM - Ultrasonic Machining
WJM - Water Jet Machining	
Electrical	
ECD - Electrical Deburring	ECDG-Electrochemical Discharge Grinding
ECG - Electrochemical Grinding	ECH-Electrochemical Honing
ECM - Electrochemical Machining	ECP-Electrochemical Polishing
ECS - Electrochemical Sharpening	ECT-Electrochemical Turning
ES™ - Electro-stream	EJ-Electro Jet
STEM™ - Shaped Tube Electrolytic Machining	
Thermal	
EBM-Electron Beam Machining	EDG-Electrical Discharge Grinding
EDM-Electrical Discharge Machining	EDS-Electrical discharge Sawing
EDWG-Electrical Discharge Wire Cutting	LBM-Laser Beam Machining
LBT-Laser Beam Torch	PBM-Plasma Beam Machining
Chemical	
CHM-Chemical Machining	ELP-Electro-polish
PCM-Photochemical Machining	TCM-Thermochemical Machining
TEM-Thermal Energy Method	

Table 1.2 Classification of Modern Machining Process

Type of energy	Mechanism of metal removal	Transfer media	Energy source	Processes
Mechanical	Shear	Physical contact	Cutting tool	Conventional machining
	Erosion	High velocity particles	Pneumatic/ hydraulic pressure	AJM, USM, WJM
Electrochemical	Ion Displacement	Electrolyte	High current	ECM, ECG
Chemical	Ablative relation	Reactive environment	Corrosive agent	CHM
Thermoelectric	Fusion	Hot gases	Ionized material	IBM, PAM
		Electrons	High voltage	EDM, EBM
	Vaporization	Radiation	Amplified light	LBM
		Ion stream	Ionized material	PAM

Table 1.3 Process Economy for Nonconventional Machining Process

Process	Capital investment	Tooling and fixture	Power requirement	Efficiency	Tool consumption
USM	B	B	B	D	C
AJM	A	B	B	D	B
ECM	E	C	C	B	A
CHM	C	B	D	C	A
EDM	C	D	B	D	D
EBM	D	B	B	E	A
LBM	C	B	A	E	A
PAM	A	B	A	A	A
Conventional machining	B	B	B	A	B

NOTE: A-Very Low Cost B-Low C-Medium D-High E-Very High

Table 1.4 Process Capabilities for Nonconventional Machining Process

Precess	Metal removal rate mm/min	Tolerance	Surface finish CLA	Surface damage depth	Corner radii mm
USM	300	7.5	0.2-0.5	25	0.025
AJM	0.8	50	0.5-1.2	2.5	0.100
ECM	1500	50	0.1-2.5	5.0	0.025
CHM	15.0	50	0.4-2.5	50	0.125
EDM	800	15	0.2-12.5	125	0.025
EBM	1.6	25	0.4-2.5	250	2.50
LBM	0.1	25	0.4-1.25	125	2.50
PAM	75000	125	Rough	500	-
Conventional machining	50000	50	0.4-5.0	25	0.050

Before selecting any process for an application, the following aspects are to be considered:

i) physical parameters,

ii) properties of work material,

iii) complex geometry of the workpiece,

iv) process capabilities,

v) need for higher production rate,

vi) closer tolerance, surface finish and surface integrity, and

vii) economic considerations.

These processes are generally characterized by their high power consumption and lower material removal rate. As seen in Table 1.5, both USM and EDM require almost equal power. On the other hand, ECM is found to consume about forty times more power than EDM. Both ECM and EDM need electrically conductive material to machine. ECM has the advantage of a very low tool wear ratio [4].

Table 1.5 Physical Parameters of Nonconventional Machining Processes

Parameters	USM	AJM	ECM	CHM	EDM	EBM	LBM	PAM
Potential (V)	220	220	10	-	45	150000	4500	100
Current (Amp)	12 (A.C)	1.0	10,000 (D.C)	-	50 (Pulsed D.C.)	0.001 (Pulsed D.C.)	2 (average 200 peak)	500 (D.C.)
Power (W)	2400	220	100,000	-	2700	150 (average 200 peak)	-	50,000
Gap (mm)	0.25	0.75	0.20	-	0.025	100	150	7.5
Medium	Abrasive in water	Abrasive in gas	Electrolyte	Liquid chemical	Liquid dielectric	Vaccum	Air	Argon or hydrogen

1.2 Technology of Electrochemical Grinding

Principles of the electrochemical grinding process are relatively simple and straight forward. Though its name is grinding process, but actually it is a special form of electrochemical machining process. Any electrochemical process requires the immersion of two electrodes in conductive electrolyte solution. In this process workpiece acts as anode and electrochemically conductive grinding wheel acts as cathode, connected to a D.C. power source. When the electrolyte passes through the working zone, the work material is dissolved by anodic action and the resulting oxidized layer on the work surface is wiped away by the grits of the grinding wheel, preventing it from building up on the work and tool surfaces. The material is removed due to the combined effect of electrochemical decomposition and action of abrasive grids contained in the wheel [5].

Brushes are used to bring the current from the power source to the spindle from which it flows to the grinding wheel. The dissolution rate of different substances is proportional to their chemical equivalent weights. The machining rate is affected by the workpiece passivity and current efficiency. To choose an electrolyte, the requirements should be taken into consideration are high electrical conductivity, high specific heat, high thermal conductivity, and the most important one is the chemical composition compatible with workpiece material not to cause preferential removal of different elements.

When the workpiece contacts the bed of the machine, an electrolytic cell is formed, with the workpiece as anode and the body of the grinding wheel as cathode. The insulating abrasive particles in the grinding wheel protrude evenly above the wheel surface, and when the workpiece is passed into contact with these, the height of the abrasive particles above the wheel determines the effective gaps between the anode and cathode.

A D.C. voltage of about 5-15 V is generally applied between the workpiece and the grinding wheel. Current densities range from 2 A/cm^2 in grinding tungsten carbide to about 3 A/cm^2 in grinding steels. The electrolyte used in this process does not differ from that employed in electrochemical machining [4].

1.2.1 Process Capabilities

Electrochemical grinding exhibits material removal rate that goes up to 10 times faster than conventional grinding on materials harder than HRc 60. The average value of material removal rate is 1.6 cm^3 /min/ 1000 amp, with the range being from 0.6 cm^3 to 5 cm^3 [2].

Although removal rates are high, ECG cannot obtain conventional grinding tolerances. The current limits are ± 0.025 mm. using standard techniques and ± 0.0 12 mm. when a no current finishing pass is used. The minimum radius that can be produced on an inside corner is 0.25 mm, outside corners can be produced with a radius smaller than 0.025 mm.

Surface finishes average 0.2-0.8 , with plunge-grinding methods giving a 0.12-0.24 finish, and surface grinding producing finishes of 0.24-0.37 . No matter how hard, tough, or brittle a material is, ECG produces surfaces free of any grinding scratches, burrs, or burns. Electrochemical grinding produces a better surface finish than conventional grinding in non-homogeneous materials.

1.2.2 Advantages and Limitations

This process is best suited for fast machining very hard materials like carbides. High strength materials in the range of 200,000 – 400,000 psi tensile strength can be worked as readily as low strength materials. The machining of dissimilar metals such as brazed carbides tool assembly is highly productive in ECG process [6]. It provides high metal removal rate specially with cobalt-nickel-alloys and high tensile strength materials. It does not affect the yield strength, sustained load strength, ductility or hardness of most alloys and metals [7].

Hence the advantages offered by electrochemical grinding are higher material removal rate, practical elimination of mechanical or thermal cracking, deburring operations, stress-free in the component surfaces, undesirable reduction of wheel wear, independence of work material hardness, component accuracy [8].

Though electrochemical grinding has special advantages of its own there are some limitations. This process needs contact area between anode and cathode to draw a current for which a D.C. power source is very much essential. Initial cost of the machine is comparatively high. Some applications are restricted to grinding geometries. Small I.D. grinding operations would be impracticable [8].

Since only chemically conductive materials can be ground, the electrolyte used may corrode the workpiece. Therefore, electrolyte must be anticorrosive (cromoplated). Holding of sharp comers is a major limitation of this process as the electrolytic action is non-directional. Inside comers can not be ground sharper less than 0.25 to 0.40 mm radius because of the over cut and the accuracy is limited to 0.001 mm only [9,10].

It is not economical for soft materials and needs high preventive maintenance cost. Copper-resin-bonded diamond wheels may be dressed to simple forms only. Intricate forms with multiple radius tangents and very deep forms require single layer, plated-metal bonded diamond wheels [11].

1.2.3 Applications

Electrochemical grinding is applicable where conventional abrasive grinding is unsatisfactory. Such areas include:

i) form grinding of difficult -to-grind ductile metals,
ii) grinding of heat and stress sensitive materials,
iii) generating burr and distortion free pieces, and
iv) stock removal on extremely hard to grind materials [9].

This process has received wide application in the field of aircraft turbine industry for the production of blades, vanes, honey comb seal rings, and also employed in rail-road industry to profile locomotive traction motor gears. This has also been found for extensive use in the textile industries and automotive instrumentation, and industrial knife market [7]. The increased use of stainless steel and new exotic materials such as medical devices, instruments and forceps, pace maker shells, precision nozzles, instrument coupling and air rotor motors, and grinding of carbide cutting tools have all successfully been accomplished with ECG [4,12].

1.2.4 Objective of the Project

From the forgoing discussion it has become evident that ECG process offers many advantages and applications over conventional process. Though it can not replace any of the conventional process, it has its own special features and advantages.

Based on the above idea the objectives of the present research program (project) are-

a) To develop the mathematical modeling for metal removal rate.
b) To design an experimental set up for electrochemical grinding process.
c) To analyze the behavior of the material removal mechanism and the parametric effects of the various process parameter on metal removal rate.

CHAPTER 2

LITERATURE SURVEY

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The first commercial machine tool using the electrochemical method of removing metal from a workpiece was grinding machine in which electrolyte action was used to assist the abrasive action of the grinding wheel. Electrochemical grinding machine was first appeared in U.S.A. around 1953 for machining of tungsten carbide cutting tools [13]. Till then the research with electrochemical grinding process has been going on for many years. The rapid growth in the development of materials have pushed manufacturing engineers to think more realistically to overcome major problems, such as machining difficult-to-machine alloys, hardened, fragile, and thermal sensitive parts. Past research pertaining to material removal mechanisms in ECG, surface finish and surface integrity, influence of process parameters, and recent development of grinding wheel and ECG machines are included in this section.

2.2 Electrochemical Grinding Process

2.2.1 Material Removal Mechanisms

The fundamental removal modes involving mechanical abrasion and one, having no mechanical contribution viz. (1) totally mechanical removal, (2) electrochemical removal combined with mechanical removal and a zero overcut, (3) electrochemical removal combined with mechanical removal and an overcut greater than zero and (4) totally electrochemical removal. Nimonic 105, commercial cold-rolled mild steel and die steel were machined with single pass peripheral electrochemical grinding using a diamond grit wheel at small depth. The effect of operating conditions on surface finish and wheel wear were presented by using different wheel parameters [14].

With the increase in current densities the metal removal rate increases. However the possibility of increasing the removal rate by higher voltage is limited. The arc and area of contact as well as material removal are of great importance from the viewpoint of the electrochemical process [15].

Another study provided that Faraday's law does not control electrochemical grinding process as is generally accepted in the technical literature. The most important factor in ECG performance has been identified to be the wetting of the grinding wheel surface. A new approach was presented in achieving a uniform layer of water of the wheel surface [16].

Electrochemical penetration velocity based on Faraday's first law and mechanical metal removal rate depending on the peripheral velocity of the wheel. Investigation of electrochemical and mechanical actions in the total removal rate in ECG and determination of the efficiency of the ECG process were carried out. With the results from these theoretical studies, some recommendations for the optimization of ECG process is also provided [17].

It is shown that electrochemical dissolution into the cobalt phase occurs initially at a much faster rate than into the carbide phase. Malkin and Levinger also investigated the method for measuring the degree and depth of damage in the WC-Co surface layer, weakened by preferential electrochemical removal of Cobalt after ECG [18].

A theoretical analysis of ECG process is introduced by Shan. In this study equations were derived for amounts of material removed by electrochemical dissolution and mechanical grinding. Conditions were determined when no material and when maximum material is removed by electrochemical action [19].

The Faraday current efficiency of the electrolyte part of the process was found to be near 100% at the extremely high current densities. Several phenomena of the process were explained on the basis of hydrogen gas pressure in the work-wheel interface. A formula was also presented for calculating the hydrogen gas pressure [20].

The physical model is over simplified and focused on the relationship between the gap resistance and the feeding force, given by an empirical model [21].

The effects of magnetic field on metal removal rate, power consumption, current density, and process efficiencies in ECG were provided. It has been claimed that magnetic field affects the rates of both the mass transport controlled processes and the activation (charge transfer) process [22].

The introduction of the conic wheel to vertical spindle electrochemical surface grinding process could be widened by permitting large depth of cut at reasonably high table feed rates [23].

The volume of material removed by the ECG process is proportional to the current flow across the gap between the workpiece and the wheel. However this does not take into account the metal that is removed mechanically by the abrasive grits in the wheel. It is generally accepted as a rule of thumb that the volume of material removed electrochemically by ECG is 27.3 mm^3/s for each 1000 amperes of current flow through the gap. Two fundamental factors that are directly affecting the specific current density in the area of electrolyte action were specified as: (1) the ionization rate of the electrolyte and (2) the relative affinity of the electrolyte anion for the workpiece metal [4].

2.2.2 Overcut

Over-etching of the work surface and rounding of the cutting edge occurs with the use of high voltages. If the work area is large, it was mentioned that it is preferable to mill the excess away or grind some of it back on a grit wheel before grinding the workpiece [24].

Overcut in ECG was defined as the amount of stock removal over and above that determined by the shape and depth of cut setting of the cathode wheel. The parameters affecting overcut such as voltage, current density, electrolyte, feed rate, and workpiece composition data was obtained with three materials (17.4 PH, Udimet 700, and M-2 tool steel) and a discussion of the data points towards techniques were presented to permit close tolerance machining in controlling overcut [25].

When an overcut has formed, while mechanical action remains in the region of the machining zone, the interelectrode gap geometry is such as to cause the electrolyte solution flow to be separated into discrete streams which creates striations in the workpiece surface [14].

2.2.3 Surface Finish and Surface Integrity

The resulting surface finish was found to exhibit remarkably consistent characteristics with the metal removal nodes. It was also determined that the surface finish data was useful in identification of the appropriate operating parameters. As mechanical contact retreats around the wheel, with increasing applied voltage, the non-uniformity of electrolyte flow has increasingly aggravated the deterioration of surface finish [14].

Peripheral electrochemical grinding was focused on eight typical commercially available sintered carbide tool grades, with emphasis on surface integrity.

The different wheel – workpiece regions (the "contact; region; characterized by a simultaneous electrochemical and abrasive action, and the after-wheel region in which only the electrochemical aspect is present) were examined with a microscope. Geometrical surface parameters such as overcut and surface roughness were found to be related to those of the main process. Electrochemical surface parameters such as selective etching, oxide layer formation and local activation were evaluated by optical and scanning electron microscopy.

The effect of magnetic field on surface roughness was investigated [22]. They showed that the magnetic field increased the activity of electrolytic process and the roughness was the outcome of complex dynamic process of anodic dissolution.

Surface finish vary with the type of grinding, and the material being worked on. Most steel and alloys that have been ground electrolytically have a surface finish of 0.37 to 0.7 micrometers. In general, the finishes have a dull, etched appearance. In some instances, it may be desirable to perform a finish pass, cutting with only the abrasive wheel and no electrochemical action. This is done to provide shiny surface or to grind out any stray machining caused by multiple passes [23].

Current density in one of the important factors in determining the electrochemical action and surface finish. A chart, for determining contact length and feed rates with respect to different depths of cut, is shown in **Fig. 1** [3].

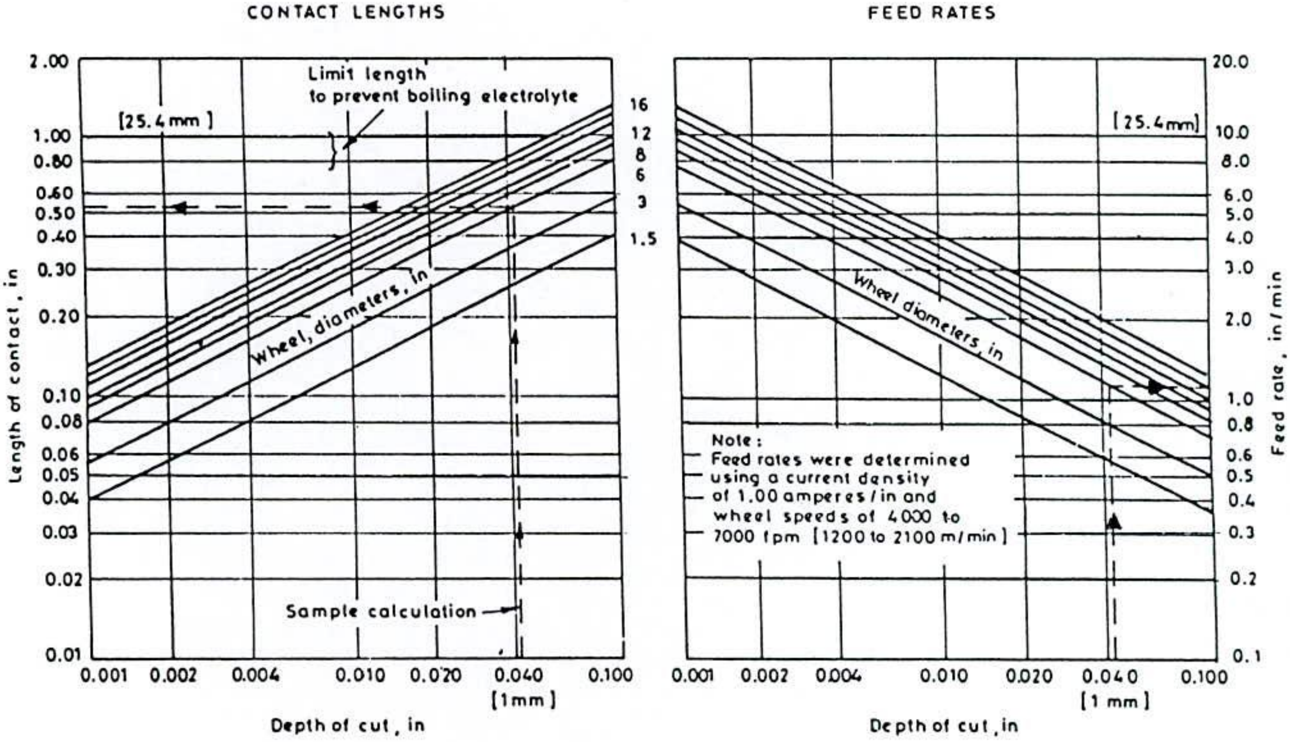

Fig. 1 The Chart for Surface ECG to Determine Contact Length and Feed Rates

2.2.4 Wheel Wear

Wheel wear comprises of wear of abrasive grits, wheel bond, micro- fracture of abrasive grains, corrosive wear etc. Mechanical contact of the grains with the workpiece results in a pressure on the surface of the wheel. This pressure in the peripheral contact area of the wheel can be seen as force components on each abrasive grit. Due to the impact of these forces, abrasive grits are broken down causing the wheel radius to change. The electrical spark and the lapping activities of metal chips also damage the wheel bond and from craters on the wheel surface. The bond metal along with the impregnated abrasive particles may be found as a "welded deposit" on the work surface which is caused by direct contact between the wheel bond and workpiece and consequent fusing of the wheel surface [26].

The wheel life in ECG is 8-10 times longer than in conventional grinding wheels. Since only 5-10% of metal removal is mechanical and the remainder is electrochemical [27]. As a result, less time is spent on wheel truing and dressing operations and important savings can be made in diamond tools used to dress grinding wheels.

An electrochemical wheel conditioning method to remove the mechanical debris, conductive bond peaks, and to expose the diamond grits on the working surface of the wheel. The method extends the wheel life and assures stable electrochemical grinding, at least when grinding tungsten carbide. Electrochemical dressing was shown to remove conductive products from the inter-grit spaces. Particularly advantageous of wheel wear characteristics were mentioned to exist during subsequent ECG use [28].

The effect of process variables on G-ratio was briefly discussed by Ranganathan. It was mentioned that G-ratio is very much sensitive to table speed and cutting fluid for the wheel speed of 30.5 m/s [29].

An analysis of power requirements in material removal due to mechanical action was explained. They presented the relationship between the selective etching occurring in the different material phases and the mechanical power requirements. The normal force component was also found to be greater in ECG than in conventional grinding due to the gasses evolved during the process [30].

2.2.5 Optimization

Process responses in ECG can be optimized either by adaptive control (on-line) optimization or parametric (off-line) optimization. A solid-state adaptive control system was introduced which explores the condition of the process in terms of fundamental behavior at speeds up to fifteen complete analytical cycles per second, and makes appropriate adjustment of the control parameters. The control system is continually searching for the optimum at operating conditions which can change very rapidly [31].

Another adaptive control scheme introduced by Lenz and Levy [32]. They incorporated a specially defined performance index that weights the improvements in the process caused by the previous control signals. The operator can also adjust the optimization criteria as desired by effecting several control constants. The relationship between the critical variables and the process responses were found to define the performance index.

Based on an empirical model that describes overcut as a function of the dominant parameters, an adaptive control system control overcut in ECG. The dominant parameters used were the voltage and the feed rate. A comparison of the results obtained with and without the adaptive control system was also presented as well as the relationship between the side and bottom overcuts [33].

A double loop adaptive control system has also been introduced by for the ECG process. The first loop's task is to modulate the process to the sparking constraint for any given adjusted voltage and then it adapts the feedrate to meet the optimal loci. It is performed continuously, automatically and on-line. The second loop is used to determine the maximum adjusted voltage that can be used for the resultant overcut to be less than the maximum permitted value [34].

Different types of fundamental material removal modes were shown by Atkinson and Noble. They have also investigated the operating settings to produce the desired mode of removal. The operating setting should provide compressive residual surface stresses together with an acceptable surface finish while ensuring that the mechanical contribution is minimized [14].

2.2.6 Influences of ECG Parameters

An experimental work was reported in Geddam and Noble [26]-which focused on peripheral electrochemical grinding of Nimonic 105 using a 10% (by weight) aqueous solution of sodium nitrite as electrolyte. Each wheel was classified according to the basis of bond type, abrasive grit size, and abrasive concentration. Diamond impregnated metal bond wheels, aluminum oxide wheels in formable conducting bond and aluminum oxide wheels in a metal bond were utilized.

An external cylindrical grinding operation with the face of a cup wheel was performed by using superhard abrasive materials such as diamond and hard face wheels. The specific consumption of diamond and surface finish were studied by considering the following process variables: electrolyte flow rate, voltage, wheel velocity, transverse feed rate, and different electrolyte type compositions (made up of aqueous solution of sodium nitrate, sodium nitrite, and potassium nitrate, sodium phosphate).

A study of independent (especially considering wheel parameters) and dependent variables was developed into a mathematical description of the electrochemical process. The mathematical description was compared with actual tests results, and a method for predicting operating parameters was also presented [9].

Influencing variables are mainly the pressure of the anode against the wheel and the size of the anodes surface. Both parameters affect the heating of the electrolyte. One interesting conclusion is that the voltage has practically no influence on the metal removal rate[15].

Some experimental results were presented by Geddam and Noble [26]- when machining a trapezoidal slot with Nimonic 105 work material by using sodium nitrate aqueous electrolyte solution and a Norelek formable wheel. The most desirable operating conditions for rough forming in single-pass plunge grinding were investigated by considering Faradaic removal conditions and limiting operating conditions in terms of metal removal rate and shape reproduction. Shape reproduction was divided into three categories such as; form angle, corner radius, and form oversize.

The electrochemical gap was shown as a critical parameter in ECG and four main factor influenced this gap when surface grinding with a vertical spindle configuration: the principle of operation, the grinding wheel conditioning, the geometrical accuracy of the machine tool, and the forced vibration level. This study combined a short fundamental analysis and related experimental work to establish the contributing role of the factors for process control [35].

Wheel parameters along with the effect of magnetic field was analyzed. Magnetic field showed no advantageous effect in metal removal with aluminum oxide wheels. However, it decreased the specific energy consumption with diamond and silicon carbide wheels [36].

2.3 Electrochemical Grinding Wheels

The ECG wheels consist of an abrasive in an electrically conductive bonding agent. Copper, brass, and nickel are the most commonly used materials for metal-bond wheels. Soft, copper-impregnated resins are used when wheels are fabricated for form-grinding applications. These wheels are all dressed in the traditional manner using diamond dressing tools. Various techniques are used to expose the abrasive grains and provide the proper gap after dressing. Metal-bond wheels can be prepared either by reversing the current and grinding into a scrap piece of metal (to deplate the metal bond), or a metal braid ground strap may be rubbed against the wheel under power for a few minutes. Resin-bond wheels are prepared by simply prerunning on a scrap part. The operation of exposing the abrasive grains must be performed every time the wheel is dressed.

The most common abrasive is aluminum oxide in grit sizes of 60-80 mesh. In special applications, a solid metal disk with a thin layer of diamond particles in a nickel matrix may be used [2].

Most of the material is removed electrochemically from the. workpiece, although some is ground away in the conventional manner as the protruding abrasive grain move across the surface of the workpiece. The main functions of the abrasive particles are: (1) to provide insulation and to determine the effective gap thickness between anode and cathode, (2) to remove continually any passive layer that may be formed on the surface of the workplace by electrochemical action, (3) to determine the shape and size of the cut.

2.4 Electrochemical Grinding Machine

The ECG systems appear so similar to conventional grinders that if it were not for the power supply and the electrolyte system, it would be difficult to distinguish between the two. In fact, many ECG systems are conventional grinders that have been converted to ECG units. The major differences to the machine tool itself are the addition of non-corrosive materials in the work area and the insulation of a device that will deliver power through the spindle.
Two methods are currently used to carry power through the spindle: brushes and mercury couplings. Most ECG machines use heavy metal wire brushes to provide a sliding electrical connection; however this method is limited in its ability to carry extremely high current. The most effective method for delivering high current is the mercury coupling. Five different grinding methods can be performed with various ECG equipment. The five methods are face grinding, surface grinding, internal grinding, form grinding and cylindrical grinding.

The machines should be equipped with two independently operating fixtures with semi-automatic forward and reverse movement to keep waiting times as short as possible.

The D.C. power supply provide voltage control from 0-15 volt. Standard amperage ratings are 300, 600 and 1000 but higher amperages are available. Amperage adjusts automatically with change in contact area between wheel and the workpiece to maintain this constant current density, therefore, constant metal removal rates are provided. The feed rate is slow and must be absolutely steady, with less than 1% variation in set speed. Slip-stick conditions can not be tolerated. There must be adequate provision for removal of the electrolyte mist and the nitrous gases that develop, as these are harmful to the human body. Although common table salt, sodium chloride, is an excellent electrolyte from an ionization standpoint, it is highly corrosive by nature. The less corrosive electrolytes exhibit lower ionization rates and because electrochemical metal removal is a function of ionization rates, the ECG rate of metal removal rate is slower with the noncorosive electrolytes. Often, sodium chloride is combined with other salts in the electrolyte solution for optimum metal removal rate and current density [23].

CHAPTER 3

DEVELOPMENT OF THE MATHEMATICAL MODELING FOR METAL REMOVAL RATE

CHAPTER 3

DEVELOPMENT OF THE MATHEMATICAL MODELING FOR METAL REMOVAL RATE

3.1 Introduction

Electrochemical Grinding (ECG) is a non-conventional machining process where material removal results from a combination of electrochemical action and mechanical action. That occurs when an electric current is passed through the electrolyte. The removal in this process has a low work feed rate and a large depth of cut, is mainly performed by electrochemical action. With increasing feed rate, materials are removed mainly by mechanical abrasive action of abrasive grains. The cutting phenomena are very complicated both experimentally and theoretically as they are accompanied by electrochemical action [7].

The mechanically assisted electrochemical machining process yields through a combination of the controlled electrochemical anodic dissolution of the workpiece and the mechanical action of the abrasive wheel. In this process, the rotating metal bonded abrasive grinding wheel is made the cathode and the workpiece serves as the anode of the electrolytic cell. The electrolytic usually a neutral salt solution (i.e. KNO_3, $NaNO_3$ or $NaNO_2$ etc) is passed through the small machining gap between the electrodes i.e. the conducting grinding wheel and the workpiece, in order to complete the electrical bridge between the anode and the cathode. The electrolyte solution with high velocity is used to remove the material particles from the machining gap resulting from the electrochemical and chemical reactions due to metal or conducting wheel bonding. The abrasives in the grinding wheel are insulating in nature. These abrasive particles may be diamond, aluminum oxide or silicon carbide [37].

The process exhibits material removal rate that goes up to ten times faster than conventional grinding on materials harder than HRc 60. The average value of metal removal rate is $1.6cm^3/min/1000A$[2]. The D.C. power supply provides voltage control from 0 to 15 volts and standard amperage ratings are 300,600 and 1000A but higher amperage are available. With proper application tolerance of 0.05mm can be achieved but with the extreme control of electrochemical grinding parameters, tolerances as close as 0.003mm are possible [7].

Current densities range $2A/cm^2$ in grinding tungsten carbide to about $3A/cm^2$ in grinding steel. The surface finish is affected by the metallurgy of work piece. When electrochemical grinding is performed perfectly, the resulting surface is a microstructure of workpiece crystalline structure. On tungsten carbide this generally provides a surface finish in the range of 0.4 to 0.5 micron for surface grinding and 0.2 to 0.4 micron for plunge grinding. In case of steels and various alloys, it ranges from 0.4 to 0.6 micron [4].

Wheel speeds are most often found between 22 and 35 m/sec. The temperature of the electrolyte is usually maintained between 32 - 43^0C, pressure used to pump the fluid is about (35-70 kpa) [38]. The longitudinal feed rate should not exceed 6m/min [15]. Atkinson and Noble [14] investigated that in peripheral electrochemical grinding, there are three fundamental removal modes involving mechanical abrasion and one mode which has no mechanical contribution.

In ECG process, the burr-free, stress free and metallurgical damage free workpiece surface can be produced and higher metal removal rate (MRR) as much as 5 to 10 times that of traditional method of grinding can be achieved. In mechanical assisted electrochemical grinding process, 90-95 % of the metal is removed by electrochemical action and rest 5-10 % by the mechanical action as a result the wheel life is 8 to 10 times that of a conventional grinding wheel during the grinding of tough material [39].

Analyzing the above characteristic features of the ECG process, the object is to formulate the mathematical modeling for metal removal rate (MRR) of the process and to analyze the parametric effects of the various process variables such as applied voltage, feed rate, the machining gap, set depth of cut on metal removal rate (MRR).

3.2 Mathematical Modeling for Metal Removal Rate of Electrochemical Grinding Process

Materials subject to electrochemical grinding are removed by both mechanical and electrolytic actions. The mathematical modeling for the metal removal rate has been developed considering the involvement of the electrochemical dissolution component and mechanical abrasive grinding component.

Thus, the total material removal rate can be evaluated as:

$$W = W_1 + W_2 \qquad \dots\dots (1)$$

Where, W = total material removal rate

W_1 = material removal rate due to electrochemical dissolution

W_2 = material removal rate due to mechanical action of the abrasive grinding wheel.

Material Removal Rate due to Electrochemical Action

The rate of dissolution (material removed) can be analysed from the basic fundamentals of electrochemistry given by Michael Faraday in his laws [40].

(a) The first law states that the amount of chemical changes W_1 produced (i.e. dissolved or deposited) is proportional to the amount of charge Q passed through the electrolyte, i.e.

$$W_1 \,\alpha\, Q$$

(b) The second law proposes that the amount of change produced in the material is proportional to its electrochemical equivalent, ECE of the material, i.e.

$$W_1 \,\alpha\, ECE, \text{ but } ECE = \frac{M_x}{n}$$

Where, M_x = atomic wt. of anodic material, gm

n = valency of anodic material

From the two laws it can be written

$$W_1 = \frac{1}{F}\,(\text{ECE}).Q$$

$$= \frac{1}{F}\,\frac{M_x}{n}.Q$$

$$W_1 = \frac{1}{F}\,\frac{M_x}{n}.\,I.t$$

Where, F = Faraday's constant =96500 amp.sec, I = the current that passes through the machining gap, amps and t = dissolution period

The mass material removal rate, W_l (gm/min) becomes

$$W_1 = \frac{\mathrm{M}_x.\eta_c}{nF} I \times 60 \qquad \text{... ... (2)}$$

Where, η_c = the current efficiency (%), n = valency of anodic material

Hence volumetric material removal rate, V_m (mm/min)^3 can be represented as:

$$V_m = \frac{M_x.I.60.\eta_c}{n.F.\rho} \qquad \text{... ... (3)}$$

Where, ρ = density of the workpiece material, gm/mm^3

From the Ohm's law, if the over potential that includes activation and concentration over potential at the electrodes, is ΔV and the applied voltage is V, then the current passes through the gap between the electrodes is represented as:

$$I = \frac{V - \Delta V}{R} \qquad \text{... ... (4)}$$

Where, R = the resistance in the working gap of the electrochemical grinding, ohms.

The resistance, R consists of two components as:

$$R = R_e + R_p \qquad \text{... ... (5)}$$

Where, R_e = ohmic resistance of the layer of electrolyte between the interelectrode gap, and

R_p = ohmic resistance of the oxydo-saltic polarized layer on the anode surface whose value is less compared to Re.

Then the total resistance, R can be expressed as:

$$R = K_p.R_e \qquad \text{... ... (6)}$$

Where, K_p = the co-efficient that define the degree in which the process occurs without polarization phenomenon.

This co-efficient can also be regarded as the loss of energy because the electrochemical dissolution rate decreases with the decrease in current density in the working gap due to the disturbance resulting from the polarization effects on the electrodes.

The electrolytic resistance, R_e can be written as:

$$R_e = \frac{h}{K_e.A} \qquad \text{... ... (7)}$$

Where, h = effective interelectrode machining gap, mm

A = machining area, mm^2

K_e = conductivity of the electrolyte, ohm mm

The current density i.e. the current passing through machining gap per unit area of machining is

$$J = \frac{I}{A} = \frac{(V - \Delta V).K_e}{K_p.h} \qquad \text{... ... (8)}$$

Where , K_p = the co-efficient that define the degree in which the process occurs without polarization phenomenon.

The velocity, u_l electrochemical penetration of the anode towards the cathode under steady state conditions of grinding can be evaluated as:

$$u_l = \frac{M_x.60.\eta_c}{n.F.\rho}\frac{I}{A} \qquad \text{... ... (9)}$$

$$= \frac{M_x.60.\eta_c.J}{n.F.\rho} \qquad \text{... ... (10)}$$

Substituting the value of J in equation (10), the velocity of electrochemical penetration, u_l can be represented as:

$$u_1 = \frac{60.M_x.(V - \Delta V).K_e.\eta_c}{nF.\rho.K_p.h} \qquad \text{... ... (11)}$$

The workpiece is fed towards the grinding wheel as a rate of $f\cos\theta$ in the opposite direction, then the rate of change of position of the gap is given by:

$$\frac{dh}{dt} = \frac{60.M_x.K_e\eta_c(V - \Delta V)}{n.h.\rho.F.K_p} - f\cos\theta \qquad \text{... ... (12)}$$

Where, f = linear feed rate of the workpiece, mm/min

In a peripheral grinding configuration, the gap at the leading edge (at $\theta = \theta_o$) will be the least for any set of operating condition, and therefore, the stable conditions will be determined by the minimum gap requirements corresponding to this position. Under steady conditions,

$$\frac{dh}{dt} = 0$$

$$\text{i.e}\ \frac{60.M_x.K_e.\eta_c.(V - \Delta V)}{n.h_o.\rho.F.K_p} = f.\cos\theta_0 \qquad \text{... ... (13)}$$

where, h_o = Interelectrode steady state gap at the leading edge

If θ_o is such that the gap formed at the leading edge, h_o then becomes

$$\cos\theta_0 \sim \left(\frac{2ds}{R}\right)^{1/2} \qquad \text{... ... (14)}$$

Where, ds = Set depth of cut, mm, R = radius of the grinding wheel, mm

Substituting the value of $\cos\theta_o$ in equation (13), then it becomes

$$\frac{60.M_x.K_e.\eta_c.(V - \Delta V)}{n.h_o.\rho.F.K_p} = f.\left(\frac{2ds}{R}\right)^{1/2}$$

$$\text{or,}\ \left\{\frac{60.M_x.K_e.\eta_c.(V - \Delta V)}{n.h_o.\rho.F.K_p}\right\}^2 = f^2.\left(\frac{2ds}{R}\right)$$

$$\text{or,}\ ds = \frac{R}{2}\left\{\frac{60.(V - \Delta V).M_x.\eta_c.K_e}{h_o.\rho.F.K_p.n}\right\}^2.f^{-2} \qquad \text{... ... (15)}$$

From equation (11), used the value of u_t and the set depth of cut becomes

$$ds = \frac{R}{2}\{u_t\}^2.f^{-2} \qquad \text{... ... (16)}$$

The metal removal rate, W_1 (gm/min) can be expressed as:

$$W_1 = u_t.\rho\mathrm{A} = f.\rho\mathrm{A}.\sqrt{\frac{2ds}{R}} \qquad \text{... ... (17)}$$

Hence, for constant area of machining and for a particular size of grinding wheel the metal removal rate depends on the linear feed rate of the workpiece and set depth of cut.

The metal removal rate due to electrochemical dissolution, W_1 can also be represented as:

$$W_1 = \frac{60.(V - \Delta V).M_x.\eta_c.K_e.A}{n.F.h_0.K_p} \quad \ldots \ldots (18)$$

The equation implies that the metal removal rate depends on supply voltage, the working gap at steady state condition, type of the workpiece material and electrolytic solution etc.

Material Removal Rate due to Mechanical Action

The grinding wheel has a rotational motion about its own axis as well as linear motion relative to workpiece. The metal removal rate by mechanical grinding is proportional to the machining area and velocity of penetration of the materials which can be expressed as:

$$W_2 = \rho.ds.B.f \quad \ldots \ldots (19)$$

Where, B = width of cut, mm

f = velocity of penetration into the materials, mm/min

The penetration velocity, f due to mechanical action of grinding can be evaluated as:

$$f = Z_t \,.\, t_z \quad \ldots \ldots (20)$$

Where, Z_t = Number of grains participating in the mechanical grinding process during 1 min. contact interval of the wheel with the material.

t_z = mean thickness of the layer removed by one cutting point for a given pressure, mm

Hence, the mechanical metal removal rate due to mechanical action, W_2 (m/min) can be obtained as:

$$W_2 = \rho.ds.B.Z_t.t_z \quad \ldots \ldots (21)$$

Total material removal rate

As electrochemical grinding is considered as a process compounded of electrochemical dissolution and mechanical grinding, Eqn. 18, and Eqn. 21 may be combined to give the total metal removal rate as :

$$W = W_1 + W_2$$

$$W = \frac{6o.(V - \Delta V).M_x.\eta_c.K_e.A}{nF.h_o.K_p} + \rho.ds.B.Z_t.t_z \qquad \dots\dots(22)$$

The equation implies that the metal removal rate is a function of the supply voltage, steady state gap, type of workpiece material, type of electrolyte, set depth of cut etc.

3. 3 INFLUENCE OF PROCESS PARAMETERS ON MRR

The material removal rate in electrochemical surface grinding depends on the combined effect of electromechanical dissolution and mechanical action rate. The process parameters that affect the mechanical metal removal mechanism are:

- type of bond and abrasive gain size and concentration and wheel profile of the grinding wheel.
- structure, pretreatments and shape of nature and
- different machining conditions such as feed rate, wheel speed and depth of cut

The main aim of adopting this process is to achieve higher material removal rate and grinding ratio coupled with better dimensional control and surface integrity. In electrochemical surface grinding, major portion of the material removal is due to electrochemical action. The following parameters influence the material removal rate very significantly

- the voltage input across the two electrodes
- the automatic weight and valency of work material and its constituents
- the conductivity and strength of the electrolyte
- the width of the machining gap
- the degree of polarization or passivation
- the presence of the gas in the machining gap

An increase in input voltage increases the current causing higher electrolytic action which means it increasing in MRR but excessive increase in voltage will cause rise in gas pressure and electric sparking will occur. The effect of decreasing volts is to reduce the electrolyte action thus reducing overall metal removal rate. It is found from different literature that total removal depends mainly on electrochemical removal rate. Material removed due to mechanical action is very low compare to that due to electrochemical action. Material removal rate is found to increase with current density. With the increase depth of cut MRR also increases. The mechanical action is directly controlled by the force applied between the grinding wheel and the workpiece thus increases MRR, but excessive feed force will result intensive mechanical rubbing which shortens the process efficiency [41]. The interrelationship among the process parameters has been illustrated in **Fig. 2.**

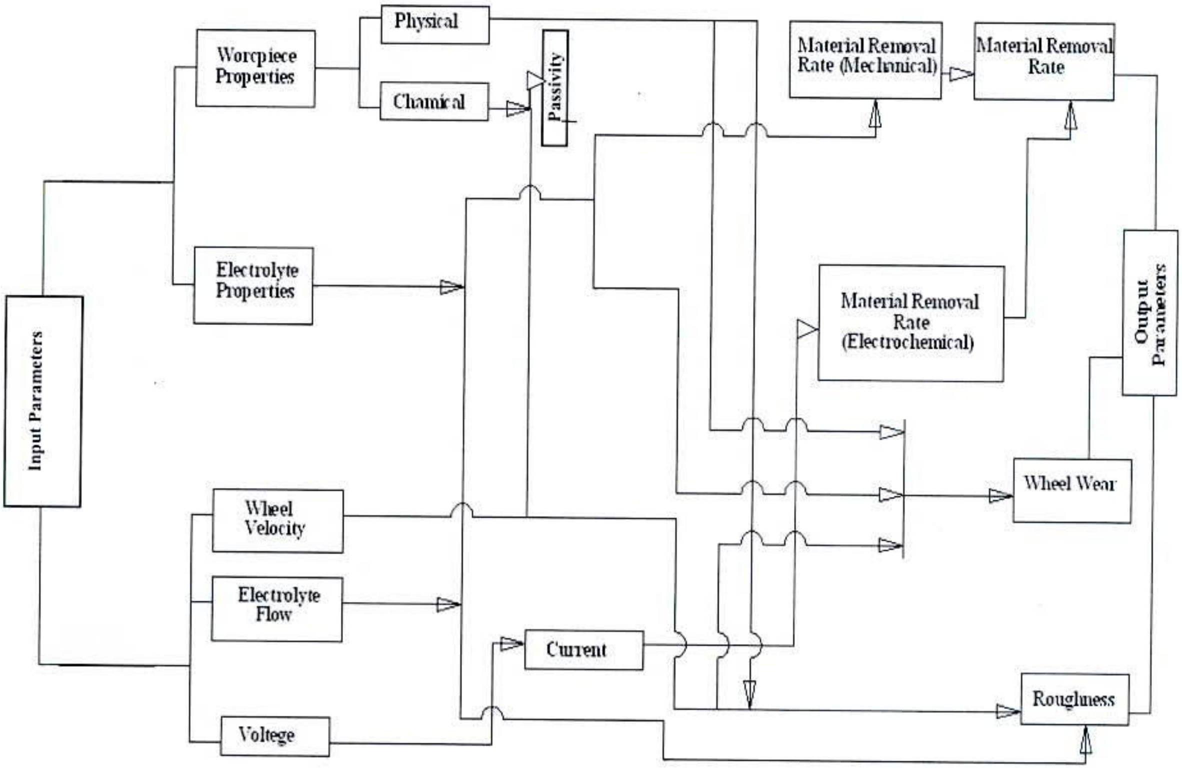

Fig. 2 Inter-relationship Amongst ECE Process Parameter

3.4 Suitability of Mathematical Modeling for Metal Removal Rate

Many investigators have investigated electrochemical and mechanical actions on MRR of grinding hard metals by experimentation since long time. This analysis aimed at finding the suitability of the theoretical models with the experimental results of the past investigators. Recently T.P. Bhowmick and P.K. Mishra have carried out an investigation on it [42].

The metal removal rate due to electrochemical dissolution, W_1 has been found out as:

$$W_1 = ut.\rho \mathrm{A} = f.\rho \mathrm{A}.\sqrt{\frac{2ds}{R}}$$

Where,

f = linear feed rate of the workpiece, mm/s = 2.67 mm/s

ρ = density of the workpiece material, gm/mm^3 = 2.67 gm/mm^3

A = machining area, mm^2 = (25.4 x 4.712) mm^2 = 119.68 mm^2

ds = set depth of cut, mm = 5μm

R = radius of the grinding wheel, mm = 75 mm

The value of MRR due to electrochemical action becomes,

$$W_1 = 2.67 \times 2.67 \times 119.68 \times \sqrt{\left(\frac{2x5x10^{-3}}{75}\right)}$$

$$= 9.774 \text{ gm/s}$$

$$= 3.69 \text{ mm}^3\text{/s}$$

The metal removal rate due to mechanical action has also been calculated by the following developed formula:

$W_2 = \rho.ds.B.Z_t.t_z$

Where, ρ = density of the workpiece material, gm/mm^3 = 2.67 gm/mm^3

ds = set depth of cut, mm = 5μm

B = width of cut, mm = 25.4 mm

Z_t = number of grains participating in the mechanical grinding process per unit time = 23333

t_z = mean thickness of the layer removed by one cutting point for a given pressure, mm = 0.2 μm [38]

Hence,

$$W_2 = \rho . ds . B . Z_t . t_z$$

$$= 2.67 \text{ x } 5\text{x}10^{-3} \text{ x } 23333 \text{ x } 0.2 \text{ x } 10^{-3} \text{ x } 25.4$$

$$= 1.582 \text{ gm/s}$$

$$= 0.5926 \text{ mm}^3\text{/s}$$

Whereas the experimental result was 0.51 mm^3/s. Hence the theoretical result is nearer to the experimental result.

The total metal removal rate is found as:

$$W = W_1 + W_2$$

$$= (3.69 + 0.5926)$$

$$= 4.28 \text{ mm}^3\text{/s},$$

Which is near to the experimental value [42].

Similarly, using different values of different parameters, the various result of theoretical MRR would be obtained according to those parameters.

Now, comparison of metal removal rates from mathematical modeling has been shown in Table 3.1.

Table 3.1 Comparison of Metal Removal Rates

Depth of Cut, µm	Current Density, amp/mm^2	Theoretical Metal-removal Rate, mm^3/s			Experimental Metal-removal Rate, mm^3/s	
		Mech	Electrochemical	Total	Mech	Total
5	16.95	0.59	3.69	4.28	0.51	4.02
10	17.86	1.18	5.21	6.39	0.68	4.43
15	19.58	1.77	6.39	8.16	0.72	5.20
20	21.28	2.37	7.37	9.74	0.82	6.02

For which it can be easily mentioned here that the mathematical models developed for MRR is quite acceptable.

CHAPTER 4

THE BEHAVIOR OF THE METAL REMOVAL MECHANISM AND THE PARAMETRIC EFFECTS OF THE VARIOUS PROCESS PARAMETERS ON METAL REMOVAL RATE

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THE BEHAVIOR OF THE METAL REMOVAL MECHANISM AND THE PARAMETRIC EFFECTS OF THE VARIOUS PROCESS PARAMETERS ON METAL REMOVAL RATE

4.1 Introduction

Electrochemical grinding (ECG) process employs a grinding wheel in which an insulating abrasive is set in a conducting bonding material. The D.C. power is connected to the port and the conductive bond of the grinding wheel in such a way that the latter is at negative potential with respect to the component part. Brushes are used on the grinder spindle for the supply of current into the spindle, from which it then flows to the grinding wheel. The region between the wheel and workpiece is flooded with electrolyte [4].

4.2 Behavior of the metal removal mechanism

Electrochemical grinding (ECG) is a process that combines both electrochemical and mechanical action to remove hard or fragile electrically conductive materials. Because of the electrochemical nature of the process, the workpiece material is “ground” without producing burrs and without generating heat, distortion or stress [2].

Many similarities between ECG and conventional grinding make this one of the easiest ECM-based processes to both understand and implement. The ECG grinding wheels closely resemble their conventional counterparts with the exception that ECG wheels use an electrically conductive abrasive bonding agent. The ECG electrolyte is introduced to the work area in the same manner that coolant is introduced in conventional wet grinding. The abrasive particles in an ECG wheel protrude beyond the conductive bond surface. This establishes a small gap between the wheel and workpiece. Electrolytic action begins when the gap is filled with an electrolyte and the wheel is electrically charged. The wheel is charged negatively and acts as the cathode, the workpiece performs as the anode. Material is removed through a combination of electrochemical action and conventional mechanical grinding. Approximately 90% of the material is removed through electrochemical action and

10% by mechanical grinding. Because only a small amount of material is removed by grinding action. ECG wheel life is typically 10 times longer than the life of a conventional grinding wheel. An additional factor contributing to the long life of ECG wheels is the contact arc. **Fig. 3** illustrates that the mechanical contact arc for the ECG process is only a fraction of that used for conventional grinding [2].

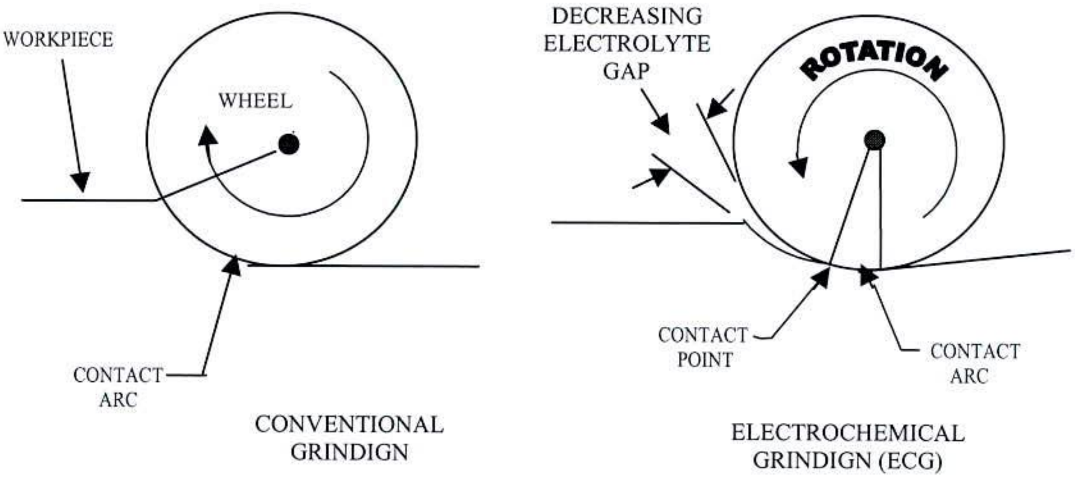

Fig. 3 A small mechanical contact arc is partly responsible for the long wheel life experienced by ECG users.

The mechanical contact arc of an ECG wheel is smaller than that of a conventional grinding wheel because ECG material removal occurs in three phases corresponding to three zones on the wheel. Phase 1 is entirely electrochemical and as indicated in **Fig. 4** takes place within a zone at the leading edge of the ECG wheel. In this phase, oxides form on the workpiece surface at a rate faster than they can dissolve into solution (this is in contrast to the ECM process in which it is desirable to have oxides dissolve into solution before a build up can occur)

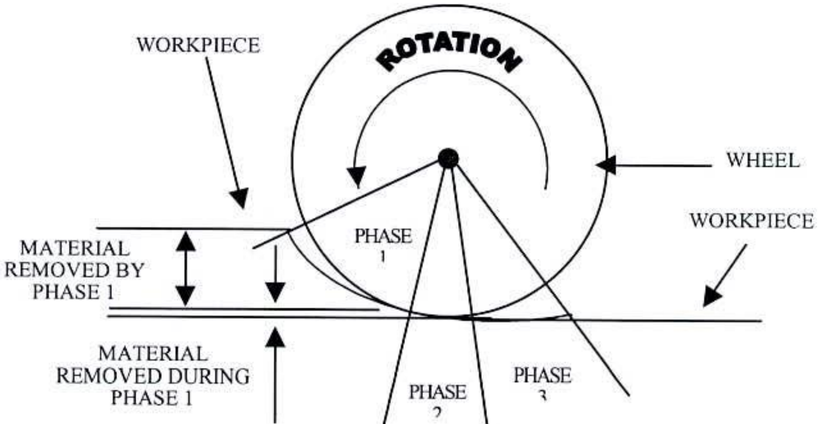

Fig. 4 The three phases of ECG material removal

The ECG wheel rotation acts to draw fresh electrolyte from the delivery nozzle and move it into and through the wheel workpiece interaction zone. As electrolyte passes through the phase 1 zone and moves toward the phase 2 zone, oxides, evolved gases and numerous other process by product contaminate the electrolyte and decrease its conductivity. As the conductivity decreases, less and less of the workpiece is depleted, causing the gap to decrease, until finally the wheel comes into contact with the workpiece. At this point on the wheel contact arc, phase 1 material removal ends and phase 2 begins.

Phase 2 material removal begins at the point where the abrasives in the ECG wheel are in direct contact with the workpiece. This traps the electrolyte between the protruding abrasive grains, thus forming tiny electrolytic cells where the deplating occurs. In addition, because the electrolyte is being forced deep into the contact arc by the rotational motion of the wheel, the local electrolyte pressure in the gap increases. For example, a wheel rotating at 1675 surface meters per minute (5500 SFPM) produces electrolyte pressure in the phase 2 region of approximately 1 MPa Increasing the electrolyte pressure acts to suppress the formation of gas bubbles in the gap, which in turn increases the material removal rate.

The abrasive grains that are in contact with the workpieces surface during phase 2 act to remove the soft, non reactive oxide layer, thus exposing fresh metal to further electrolytic action. Unlike phase 1 in which no mechanically formed chip is created, phase 2 produces a combination of small grind chips and partially dissolved metal oxides that resemble a soft, puttylike solid. Phase 2 cutting ends at the point where the wheel lifts off the work surface.

Phase 3 material removal is again totally electrochemical. As the contaminated electrolyte exits the rear of the wheel, it continues to slowly deplete the workpiece. This phase removes very little material but tends to electrolytically remove any scratches or burrs that may have formed on the workpiece [2].

4.3 Process Parameters

The removal rate for ECG is governed by the current density, just as in ECM. Standard machines are available with current ratings ranging from 50 to 3000 amp. The current density most often used depends upon the material being processed and can range from 77 to

620 amp/cm^2. As with ECM, the higher the current density, the faster the removal rate and the better the resulting surface finish.

The voltage used for ECG can range from 4 to 15 VDC depending upon the application and is usually set as high as possible to maximize the removal rate. Of course, this maximum limit must not be so high that it degrades the quality of the machined surface, and it must be consistent with surface finish and tool requirements. Typically, voltage is adjusted by increasing it until fine red sparks become visible at the exit side of the wheel. Too much voltage is indicated by the formation of bright blue, audible sparks at the front of the wheel. The ECG electrolyte is maintained at a temperature between 15 to 32^{o}c and is filtered in other ECM processes. The electrolyte being forced through the gap generates a wheel pressure. In practice, this pressure can range from 0.3 to 1.4 MPa and is held constant by either a constant feed rate or a hydraulic cylinder that allows the wheel to either give or feed depending upon the dissolution rate [2].

Once a feed rate has been established for a particular application, it can be varied by as much as 4mm/sec without detrimentally affecting the process. If the feed rate is running too slowly for the application, a large over cut will be produced that will result in poor surface finishes and tolerances. If the feed rate is too fast, the abrasive particles will be prematurely forced into the workpiece, resulting in excessive wheel wear.

The gap between the work surface and the conductive wheel-bonding agent is normally 0.25mm on a freshly dressed wheel. Wheel speeds are usually between 1200 and 1800 surface meters per minute [2].

The maximum depth of cut for a single ECG wheel pass is usually considered to be about 2.5mm but can be extended with care. The limiting factor for this is the wheel contact arc, which should never exceed 19 mm. When the wheel contact arc extends beyond this limit, the electrolyte becomes in effective because of high concentrations of hydrogen bubbles and dissolved metal oxides [2].

4.4 Analysis of the Process Parameters that Influences on Metal Removal Rate (MRR)

An experimental study was conducted to analyze the effects of the various process parameters through the developed mathematical models of the electrochemical grinding process by Mitra et al [37]. For the purpose of analysis, the workpiece, tool and electrolyte combination have been chosen as C-20 steel, conducting diamond grinding wheel and Na NO_3 solution respectively.

The metal removal rate in ECG linearly increases with the machining gap voltage as exhibited through **Fig. 5**. This is because of the fact that for constant value of feed rate, set depth of cut, higher current will flow through the machining gap due to increase in machining voltage and hence the metal removal rate will be enhanced.

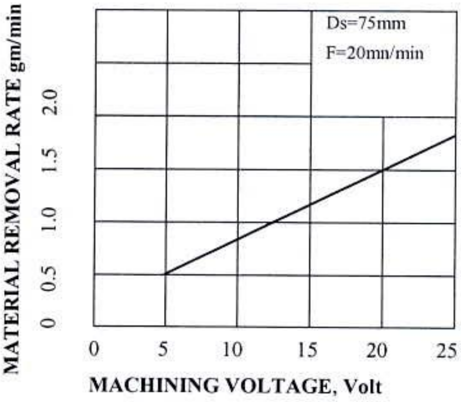

Fig. 5 Variation of MRR with machining voltage.

Fig. 6 shows that with the increase in feed rate of the workpiece, the metal removal rate linearly increases because that higher material removal takes place at a lower machining gap condition [37].

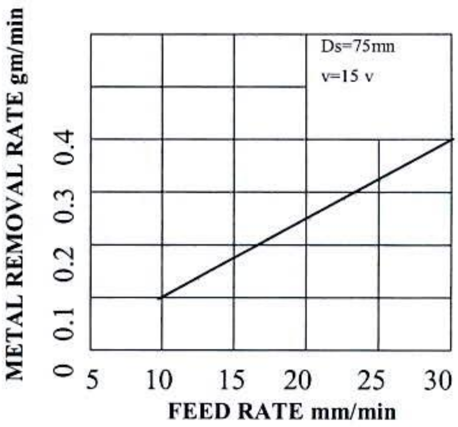

Fig. 6 Effects of feed rate on MRR.

The higher material removal rate can be obtained with setting higher depth of cut as shown in **Fig. 7**. At the initial stage of ECG, the mechanical grinding rate will also be enhanced with higher set depth of cut. The metal removal due to electrochemical dissolution takes place at a higher rate with reduce machining gap justifying the characteristic features of such system and the strength of the mathematical model developed for the purpose [37].

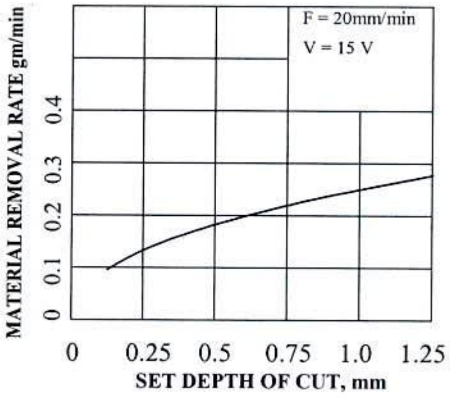

Fig. 7 Dependence of MRR upon Set Depth of Cut

CHAPTER 5

DESIGN OF AN EXPERIMENTAL SET UP FOR ELECTROCHEMICAL GRINDING PROCESS

CHAPTER 5

DESIGN OF AN EXPERIMENTAL SET-UP FOR ELECTROCHEMICAL GRINDING PROCESS

5.1 Introduction

The ECG system appears so similar to conventional grinders that if it were not for the power supply and the electrolyte system, it would be difficult to distinguish between the two. In fact, many ECG systems are conventional grinders that have been converted to ECG units. The major differences to the machine tool itself are the addition of non-corrosive materials in the work area and the installation of a device that will deliver power through the spindle [2].

5.2 Schematic Layout of the Experimental Set-Up

While designing, it was planned to provide arrangements for varying the principal parameters desirably within suitable ranges. Arrangement was also thought of for monitoring the main responses. The layout of the machine is schematically shown in the **Fig. 8**. The machine layout is comprised mainly of the following major units:

- Grinding wheel mounting.
- Drive for wheel rotation.
- Mounting and loading of job (Carbide Tools).
- Hydraulic unit for electrolyte flow.
- Hydraulic drive circuit for reciprocating motion of work table.
- Main D.C. supply for ECG.

Provisions are made to vary and control speed, feed-force, flow rate, voltage and change of specimen.

At the time of designing it was borne in mind that mechanical, hydraulic and electrical circuits do not hamper each other but can work simultaneously in desired way. As for example, at the time of designing the mechanical system proper cognizance, should have been given on interactions between the mechanical circuit and hydraulic circuit as well as between mechanical circuit and electrical circuit in addition to the mechanical circuit as such. This can be represented by the following matrix form:

[Mechanical system] = [Mechanical circuit] + [Mechanical circuit] X [Hydraulic circuit] + [Mechanical circuit] X [Electrical circuit].

Similarly considerations were also made for hydraulic system and electrical system. The whole planning is represented by a Design Matrix.

DESIGN MATRIX

$$\begin{array}{ccccc}
\underline{\textbf{Parameters}} & & \underline{\textbf{Restrictions}} & & \underline{\textbf{Objectives}} \\
\begin{bmatrix} 1 & \text{Mechanical Circuit} & \text{Mechanical Circuit} \\ \text{Hydraulic Circuit} & 1 & \text{Hydraulic Circuit} \\ \text{Electrical Circuit} & \text{Electrical Circuit} & 1 \end{bmatrix} & \text{X} & \begin{bmatrix} \text{Mechanical Circuit} \\ \text{Hydraulic Circuit} \\ \text{Electrical Circuit} \end{bmatrix} & = & \begin{bmatrix} \text{Mechanical System} \\ \text{Hydraulic System} \\ \text{Electrical System} \end{bmatrix}
\end{array}$$

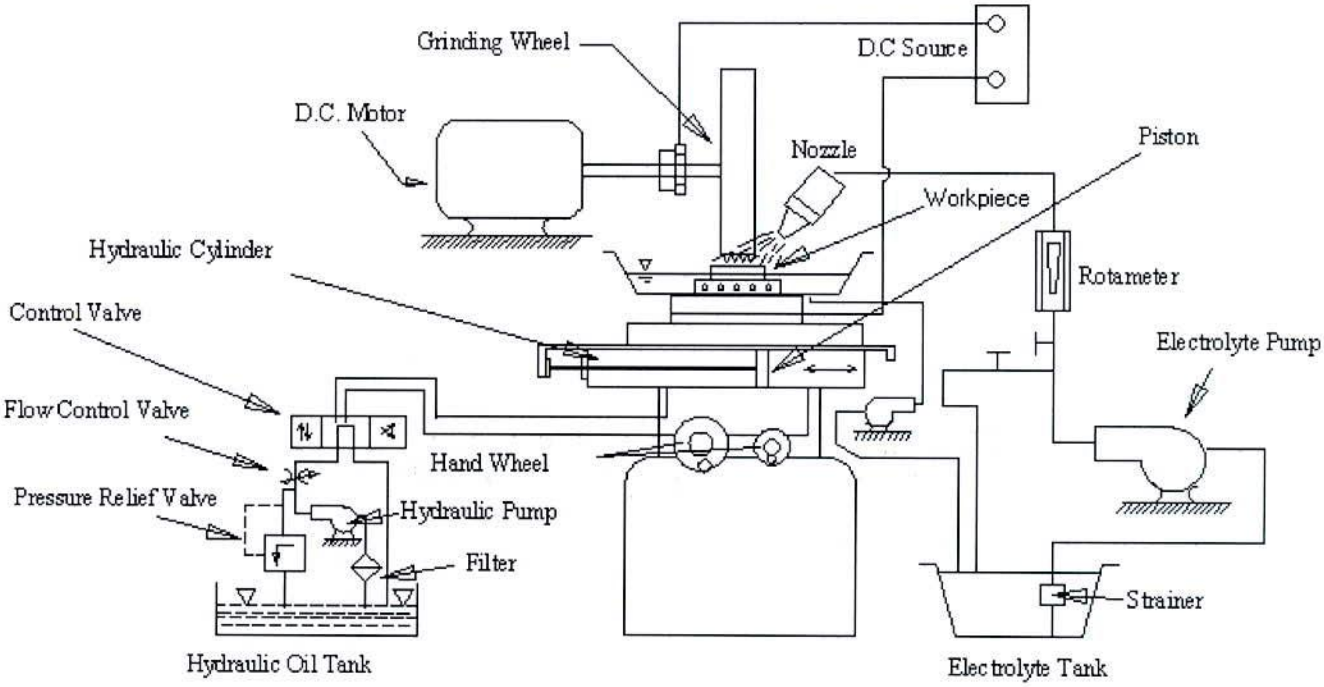

Fig. 8 Schematic layout of the experimental set-up for ECG

5.3 Main D.C. Supply

To cause anodic dissolution, the ECG needs a low voltage and high current D.C. supply. The power supply is designed for the ECG machine to provide the following characteristics-

i) A D.C. voltage of about 5-15v as desired between the work piece and grinding wheel.

ii) When the voltage is set, the amperage can automatically vary so that current density remains constant.

iii) The current should have a minimum of ripple. [5].

Ripple is a residual A.C. component of the output voltage (the variation in the current) supplied by D.C. voltage generator.

5.4 Electrolyte Flow System

A hydraulic system using a centrifugal pump –motor set suitable for the purpose has been designed to provide continuous flow of electrolyte at desirable rates at the working area of the ECG process. Flow rate is controlled by two valves, set one on the by pass line and the other on the infeed line. For monitoring the flow rate, two pressure gauges properly calibrated were mounted at suitable position.

5.5 ECG Wheels

ECG wheels are made of abrasive material, bonding agent and a conductive medium. Generally aluminum oxides are used as abrasives and copper impregnated resigns oxide as conductive medium. For very hard materials, such as tungsten carbide the preferred abrasives are diamond or borazon (CBN). The purpose of the abrasives is to increase the effacing and permit the continuance of the process. The grinding wheels generally used are:

1) Metal bonded diamond wheels in surface grinding where high material removal rate is anticipated.

2) Aluminum oxide wheels with a bond consisting of mixed of resin and copper powder, or of graphite used for form grinding, and

3) Non-grit graphite wheels for both surface and form grinding.

The wheel produces an electrolyte pressure and creates the flow velocity in the machining gap. When the wheel runs very slowly, the electrolyte can not reach the machining gap. On the other hand, when the wheel rotates with too high speed, it will through the electrolyte off the wheel before coming in contact with the wheel workpiece interface [5].

Grinding Wheel

The grinding wheel generally used at present is metal bonded diamond wheel in surface grinding where high material removal rate is anticipated.

5.6 Hydraulic Drive Circuit

Hydraulic drives possess certain advantages those have made them popular for straight line and reciprocating motion. The advantages of hydraulic drives are:

1. A hydraulic drive is smooth and reverses without shock. Thus, hydraulic drives are found on most reciprocating grinding machine tables because they contribute to good surface finish.

2. Faster reverse and acceleration rates are possible with hydraulic drives because of less inertia and cushioning effect of the fluid.

3. A hydraulic drive eliminates the gears and moving parts rendering quietness of the operation.

4. A hydraulic drive is infinitely variable for speed and feed with its range. It is also self-lubricate by transmission fluid.

For the ECG machine, the driving mechanism of work table movement can be accomplished by the hydraulic pump, motor and piston-cylinder. Feed motion in the machine is achieved by pump and piston-cylinder unites. The output fluid of the pump when injected into the cylinder, the piston displaced. For the controlling of the rate of feed in machine, two systems are available:

i) By controlling the output of a fixed delivery pump by throttles, or

ii) By variable delivery pump.

Two types of hydraulic circuits are most commonly used a) open type and b) close type. In an open circuit there is a reservoir where from the pump draws the fluid oil which after passing the whole circuit returns in the tanks from the exhaust of the cylinder. This arrangement is simpler and temperature rise is negligible [43]. The hydraulic fluid flow circuit enables to reciprocate the work table as shown in **Fig. 9**.

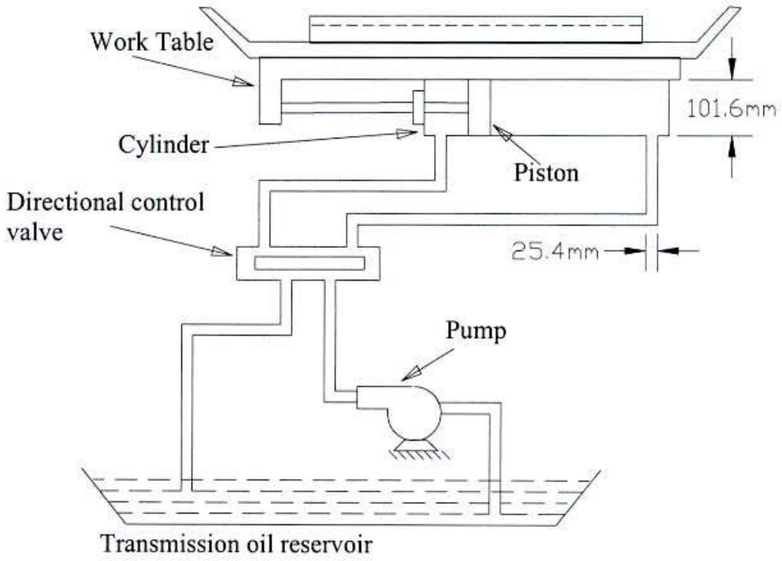

Fig. 9 Schematic feature of the hydraulic drive circuit

5.7 Design Calculations

The design calculations of various parts of the electrochemical grinding machine are shown below:

Hydraulic drive unit: The hydraulic drive consists of several parts such as piston-cylinder, pump, directional control valve, transmission oil etc.

Transmission oil:

We choose the oil for transmission is Hy- Grade™ Hydraulic/transmission oil, which,

Density = 0.89 g/cm^3 = 890kg/m^3

Viscosity index = 140

Pour point = -40°c

Flash point = 227°c

Hydraulic cylinder and piston:

The inside diameter of cylinder is 101.6 mm and piston diameter is 101.6 mm. The diameter of the transmission oil pipe is 25.4 mm.

Pump for Hydraulic drive:

Assuming

Weight of table = 40 kg =392.4 N,

Cutting force due to grinding operation = 30 kg =294.3 N,

Total load = (392.4 + 294.3) = 686.7 = 687 N.

Considering the factor of safety as 2 for design load,

Design load = total load × F.S

$=687 \times 2 = 1374$ N.

Coefficient of friction (μ) is assumed to be maximum, that is $\mu=1$,

Then resistance load for the movement of table = 1374 N.

Pressure, P = Force (F)/Area (A),

$P = 1374/\{(\pi/4)\times(4\times25.4)^2/1000\}$

$= 169476.48\ \mathrm{Nm}^2$.

This pressure is delivery pressure for the pump.

For pump, Power = $(\gamma\times Q\times H_m) / \eta$

Where,

γ = Specific gravity, Q = Discharge, H_m = Manometric height.

If suction and delivery velocity is same,

$H_m = (P_d/\gamma - P_s/\gamma)$,

Here, $P_d/\gamma = 169476.48 / 8730.9 = 19.41$m

$P_s/\gamma = -19.41$m, where (-) ve sign for suction side

$H_m = \{19.41-(-19.41)\} = 38.82$ m

Discharge, Q = AV, for centrifugal pump, V=3.5m/s.

$Q = \{(\pi/4)\times(4\times25.4)^2/1000\}\times 3.5 = .001773\mathrm{m}^3/\mathrm{s}$

Power = $(8730.9 \times 0.001773 \times 38.82) / 746$

$=0.805$ hp $\approx$ 1hp

Grinding wheel Shaft:

Assuming the material used for the shaft is carbon steel 30C8

Yield point strength, S_y = 300MPa

Yield point shear strength, S_{ys} = 150MPa [43].

Taking factor of safety, F.S = 4

$\tau = S_{ys} / F.S = 150/4 = 37.5$MPa

Torque, T = power/ revolution = $P/\omega = (F \times v) / \omega = (F \times \omega \times r) / \omega = F.r$

$T = (1.5 \times 1000) / (2 \times \pi \times 3000/ 60)$

$= (1.5 \times 1000 \times 60) / (2 \times \pi \times 3000)$

= 4.7746 N.m = 4774.6 N.mm

For a shaft subjected only to torque T

$T = (\pi / 16) \times d^3 \times \tau$

$4774.6 = (\pi / 16) \times d^3 \times 37.5$

d = 8.355 mm modified to 10 mm.

The diameter of shaft is 10 mm.

Electrolyte unit:

Pump:

Stainless steel has been considered as the material of the pipe, friction loss and bend loss of the pipe is neglected.

50% of velocity of flow is lost by filter

Assuming the required discharge is 30 liter per minute.

Nozzle diameter 10 mm and net head of pipe is 30 m,

Density range of fluid is $\rho = 0.12 - 0.36$ kg/l of water. $\rho = 0.3$ kg/l of water,

Then $\gamma = 9.81 \times 0.3 \times \frac{1}{10^{-3}}$ kg/m^3 = 2943 kg/m^3

$$Q = 30\frac{l}{\min} = \frac{30 \times 10^{-3}}{60}$$

$= 5 \times 10^{-4}$ m^3/s

h = 30m

Assuming the overall efficiency as 0.70, The power of centrifugal pump becomes

$P = (\gamma \times Q \times h)/\eta$

$= (2943 \times 5 \times 10^{-4} \times 30)/0.70$

$= 63.10$ Watt

$= 0.085$ hp

Considering the factor of safely as 2

Power = 0.17 hp $\approx$ 0.2 hp

5.8 Electrolyte Solution

In electrochemical grinding, a suitable electrolyte solution is used depending upon the properties of workpiece material, type of wheel and environmental condition. Generally, any salt such as sodium nitrate, potassium nitrate, sodium or potassium carbonate etc. mixed with water are used as electrolytes. Strong electrolytes like NaCl solution are used as the main electrolytes in the process. Strong electrolyte means the electrolyte that becomes greatly dissociated for concentrations. The concentration may be varied as desired. Some additives may be added to main electrolyte to increase the material removal rate or to inhibit rust formation. The most efficient electrolyte for ferrous, nickel, and cobalt alloys is sodium chloride solution [11].

This NaCl solution is a very good electrolyte but it is highly corrosive in nature even though it is used. The concentration and pH value of the electrolyte can be varied by adding water or chemicals to it. The electrolyte flow distribution in the machining gap is not uniform, so the acidity level on the anode material is not constant. As a result, the electrochemical reaction rate and oxide film thickness vary on the workpiece surface. Also the temperature affects the chemical activity of the electrical resistivity of the electrolyte.

Electrolyte:

The electrolyte solution contains the following

Type- Sodium choloride

Concentration- 2 to 10% W/W

5.9 Estimated Cost of the Set-up

An experimental set-up can be developed through the modification of an obsolete mechanically operated surface grinder. Otherwise; a new set up can be built up. The table movement due to mechanical action can be modified for hydraulic control. The driving mechanism of work table movement can be accomplished by the hydraulic pump, motor and piston-cylinder. The approximate cost of the complete set up for electrochemical grinding along with other components and accessories are furnished here under-

Table 5.1 Estimated Cost for Experimental Set-up

Sl. No.	Items with Specification	Cost (Tk.)
1.	Motor 2 HP, 1500 RPM DC	25000.00
2.	Metal bonded diamond wheel Diameter 150mm, width 12.4mm, diamond about 200 mesh	3000.00
3.	Centrifugal pump for electrolyte unit 0.2 –0.5 HP	15000.00
4.	Centrifugal pump for hydraulic unit (1 HP)	30000.00
5.	Hydraulic cylinder and piston Inside diameter of cylinder is 100 mm	45000.00
6.	Hydraulic unit and its accessories:	100000.00
7.	Rotameter	10000.00
8.	Nozzle, strainer, pipe etc.	20000.00
9.	Workpiece holding table, vise and its accessories	100000.00
10.	Electrical unit and its accessories	50000.00
11.	Hydraulic oil, valve etc.	15000.00
	Total: Tk.	**4,40000.00**

CHAPTER 6

DISCUSSION AND CONCLUSION

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6.1 Introduction

The theoretical model developed for the metal removal rate is mostly based on the different actions and viscous effect of electrolyte. Besides the above, the size, shape, and the arrangement of abrasive in the wheel are also responsible for the contribution of feed force which involves many unknown terms in the final expression. These unknown terms are to put carefully to obtain an acceptable value. This also bears some finite series and analysis is in order of micron level. It is true that all the abrasive grains can not be identical, that means there is a great possibility of deviation of theoretical steps with the experimental results. Prior to the above limitations a rigorous study named out to reach a final expression. In the theoretical analysis, some factors are left to be considered (specifically in electrochemical action for example, the study of the constituting elements in workpiece material are mostly not known for the exact valencies displayed by elements during electrochemical dissolution), the theoretical machining rates can only be considered as a rough guide. In is assumed that the gap between wheel and anode material is constant. During the machining process different actions such as activation polarisation, concentration polarisation, ohmic over voltage, passivity activity etc. will also be present, for which Faradic efficiency can not be calculated accurately. In ECG operation, there is also a chance of sparking and/or short circuiting, would lead to flow more current than the expected value.

The anode material may be attacked by certain solutions, fails by corroding at individual spots, known as ‘pit’ corrosion. The presence of dents, rough spots, foreign particles deposited on the metal surface can increase this formation of pits. At the time of severe electrical arcing and sparking, the process suddenly changes from electrochemical grinding to electrodischarge machining as well and results in severe pitting.

6.2 Construction of Machine

Some parts of the machine like metal bonded Grinding wheel, Rotameter etc. are not available here. If the time and all the parts of Electrochemical Grinding machine are available then the experimental set- up can be build in the following way-

The experimental set-up may be built up through the modification of an obsolete mechanically operated surface grinder. The table movement due to mechanical action can be modified for hydraulic control. The existing electrical connections except the motor connection should be removed. The hydraulic cylinder-piston arrangement will be fitted to the frame. The connecting rod of the piston will fasten with the working table with the help of bracket and adjustable nuts so that the table can move along with the movement of the piston rod. The table fed will design so that there will no slip stick effect on the table or slides when slow motion. The PVC high pressure pipies will connect with the different operating valves of the system. Direction control valves will employ to determine the routine of fluid in the hydraulic system. The NaCl solution is a very good electrolyte but it is highly corrosive in nature even though it will use. For the experimental work stainless steel specimen will use and fit to a vice within a container made of perspex. A 10 KVA D.C power supply (Input 440 V AC 3 phase 50 Hz and output 50 V D.C 200 A max)will use for experimentation and voltage will control by a variac.

6.3 Conclusion

The developed mathematical models are quite powerful to analyse the contribution of electrochemical dissolution and mechanical grinding in ECG and the studies of parametric effects on metal removal rate criteria will be quite useful to signify the fact that optimal control of the various process parameters.

Conclusions are drawn on the basis of theoretical analyses. The main features of the present work are concerned with the mechanical and electrochemical aspects of the process. The theoretical analysis for material removal rate has been done in generalized form applicable to all situations. Electrochemical grinding geometry and kinematics are analized, and different aspects of the process have been extensively studied. Different process parameters and their interrelations are made. An attempt has been made to design an experimental set up for the electrochemical grinding process.

6.4 Scope of Further Work

Since the present work deals with the theoretical analysis for the development of mathematical models for material removal rate due to both electrochemical and mechanical actions, it creates a knowledge for any further analysis in such machining process.

The experimental set up for ECG process, that has also been designed which will help developing creative idea to build up such a machine.

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