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Nontraditional machining techniques with emphasis on waterjet milling

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ABSTRACT

Title of Thesis : Nontraditional Machining Techniques With Emphasis on Waterjet Milling

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The rapid growth of harder and difficult-to-machine materials over the past two decades necessitates the development of compatible nonconventional machining techniques, as detailed in this work, with special emphasis on one of the most recent machining method, the abrasive-waterjet technique(AWJ).

The feasibility of using AWJ for milling on glass is investigated. Due to the large number of parameters involved in the AWJ technique, and the multitude of machining requirements, optimization of performance is the focus. These parameters include waterjet pressure, particle size, abrasive flow rate, traverse rate and number of passes.

Surface topography is found to be a function of both cutting and abrasive parameters and the depth uniformity of the produced slot can be continually improved by increasing the traverse speed.

Nontraditional Machining Processes are typically employed when conventional methods are incapable, impractical, or uneconomical because of special material properties, workpiece complexities or lack of inherent rigidity.

NONTRADITIONAL MACHINING TECHNIQUES WITH EMPHASIS ON WATER JET MILLING

By

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To My Parents

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CHAPTER 1

INTRODUCTION TO NONTRADITIONAL MACHINING

In recent times, engineering industries have witnessed a rapid growth in the development of harder and difficult-to-machine materials such as hastalloy, nitralloy, waspalloy, nimonics, carbides, stainless steel, heat-resisting steels, and many other high-strenth-temperature-resistant alloys. These materials find wide application in aerospace, nuclear engineering, and other industries owing to their high strength-to-weight ratio, hardness, and heat-resisting qualities. For such materials, the conventional edged tool machining, in spite of recent technological advancement, is highly uneconomical and the degree of accuracy and surface finish attainable are poor. Besides, machining of these materials into complex shapes is difficult, time consuming and sometimes impossible.(1)

The designation "nontraditional machining" is applied to a wide variety of mechanical, electrical, thermal, and chemical material removal processes developed mostly after about 1940. Originally, the nontraditional machining designation was applied to emerging processes or to processes that have not been used extensively before. Today, however, this definition is misleading. Although many of the nontraditional machining processes were conceived and developed to solve special processing problems in the aerospace industry in the late 1950's and 1960's, today, many of these same processes have found wide application in varied industries over a broad range of production jobs.

Nontraditional machining, as a classification of manufacturing operations, includes literally scores of processes. Some are applied on a larger scale, while others are not much more than laboratory curiosities. The abrasive waterjet machining, on which much emphasis is placed in this thesis is an example.

In general, nontraditional machining processes are characterized by higher power consumption as a function of material removal rate as compared with traditional machining processes. Although notable exceptions exist, the stock removal rate of nontraditional processes is usually less than that attainable with conventional machining techniques.

In addition, it has been shown that many nontraditional processes can successfully contribute to special surface integrity in the areas of surface roughness, maximum depth of plastic deformation, hardness alteration, cracks, residual stresses, recrystallization, metallurgical transformations, heat affected zones etc.

Nontraditional Machining processes are typically employed when conventional methods are incapable, impractical, or uneconomical because of special material properties, workpiece complexities or lack of inherent rigidity.(2)

1.1 OBJECTIVE

The rapid growth of harder and difficult-to-machine materials over the past two decades necessitates the development of compatible machining techniques. Conventional edge tool machining methods may not be technically or economically adequate for the machining of such materials. New machining techniques have been correspondingly emerging to fill the gaps where conventional methods are inefficient. These new techniques employ different physical phenomena or energy utilization to remove material. For example, over fifteen different techniques of nontraditional machining methods use mechanical, thermal, chemical and radiation energy forms. One of the most recent machining methods is the abrasive water jet technique.

The feasibility of using abrasive waterjets for Surface milling has been investigated in this thesis. Variables impacting the process of waterjet machining had to be identified since users must still do a lot of trial-and-error cutting, as published tables are of limited value. Experienced users do not publish detailed process information.

This study also describes the cutting characteristics/machining of glass, a hard and brittle material, when cut with an abrasive jet. Although the use of a plain waterjet to cut glass is impractical owing to the frequent appearance of cracks, crack-free cutting is possible when an abrasive jet is employed.

Complete waterjet technology, its theory of operation and the instruments used for the experiments are described in detail, and to facilitate comparitive advantages of the water jet over other nontraditional methods like mechanical, electrical, thermal, and chemical, these methods are also discussed in detail.

CHAPTER 2

2.1 INTRODUCTION TO AWJC

Water jet is a flexible manufacturing tool capable of providing significant gains in terms of productivity, material utilization, quality of finished products, and overall automation of the manufacturing process. The AWJC technology is an extension of water jet cutting technology which operates by the impingement of a high-velocity abrasive-laden fluid jet against the workpiece, without producing a heat affected zone. The finished edge obtained by the process often eliminates the need for postmachining to improve surface finish.

A coherent fluid jet is formed by forcing high pressure abrasive-laden water through a tiny sapphire orifice. The accelerated jet exiting the nozzle travels at more than twice the speed of sound and cuts as it passes through the workpiece. Cuts can be initiated at any point on the workpiece and can be made in any direction of contour-linear or tangential. The narrow kerf produced by the stream results in neither delamination nor thermal or nonthermal stresses along the cutting path.(3)

In addition to applications in the machining of superalloys, armor plate, titanium, and high-nickel chromium alloys, abrasive waterjet machining can also be used to cut concrete, rock, glass, ceramics, composites, and plastics. The ability of the abrasive waterjet to cut most metals without any thermal or mechanical distortion places this innovative process on the leading edge of material cutting technology.(4)

Development of Abrasive Waterjet Technology.

In 1968, Dr. Norman Franz filed his first patents on the use of high-pressure water streams to cut materials. The first commercial application of this process in 1971, involved the cutting of 9.5mm (3/8in.) thick pressed board for manufacturing furniture forms. Waterjet cutting technology, which involves pumping a 0.08 to 0.46

mm (0.003 to 0.018in.) dia. water stream at 30 to 60 ksi was initially developed to cut or slit nonwoven materials, fiberglass building products, corrugated box materials, and plastics.

It was later found that hard or extremely dense materials such as metals and aerospace composites could be cut when particles of dry abrasives such as garnet and silica were added to the waterjet. This modification produced by the abrasive waterjet is responsible for the ability to cut advanced materials much more efficiently than with standard mechanical or thermal cutting methods. With abrasives added to the waterjet, the liquid stream itself is merely the medium that propels the abrasive instead of being the primary cutting force. Abrasive waterjet cutting is used to cut metals and composite materials, such as boron/aluminum honeycomb, aluminium /boron carbide, and graphite composites, into intricate shapes and curves with virtually no heat input into the workpiece.

Metals and advanced composites developed for use in the aerospace industry are among the most difficult to machine materials. Whether hard as steel or flexible as rubber, these materials must be able to withstand the stresses of supersonic flight. Ironically, the same properties that make space age materials invaluable for aerospace applications also make them all but impossible to machine. Reciprocating or ultrasonic knives can be used to cut uncured epoxy-base composites, but not the finished components. The cutting rates provided by lasers and plasma arc systems are adequate, but their extreme heat changes the chemical composition of the composite materials and leaves a heat-affected zone in metal-matrix materials.

Abrasive waterjet technology eliminates the problems of delamination and frayed areas, which add to the cost of machining. This elimination of secondary machining has spurred interest in this technology and has accelerated its development.

Advantages:

The advantages of waterjet/abrasive waterjet machining are summarized as follows:

- Minimal or no dust.
- High cutting speed.
- Wide range of materials can be cut.
- Ability to produce contours, shape-cutting, bevels of any angle, and three-dimensional profiling.
- No dulling of the cutting tool (the jet).
- No thermal or deformation stresses.
- No fire hazards associated with the cutting process.
- Easy integration into computer-controlled systems, optical tracers, and full-scale six-axis robots.
- Wide availability and low cost of garnet and silica, the most common abrasive materials used.
- Low water consumption (28 L/hr or 7.5 gal/hr) despite the high pressures used.

Process Limitations:

- High power levels are needed for reasonable cutting rates in many applications.
- High initial capital costs.
- Very thin ductile metals tend to suffer bending stress from an abrasive jet and show exit burrs.
- Ceramics show a decrease in their as-fired strength.
- Some types of tempered glass designed to shatter under low stress cant be cut with abrasive waterjet.

2.2 TECHNOLOGY DESCRIPTION

Considering layout and functional characteristics, the abrasive water Jet cutting (AWJC) can be described by the following major units.

1. Water preparation unit

The major components of this unit are booster pump, filter water softener, prime mover, intensifier, accumulator, and control and safety instrumentation.(fig1)

The major functions of this unit are to feed continuously pure water and to pressurize the water at required high pressure. To ensure continuous flow into the high pressure cylinder, that is to charge the water into the system, the booster pump flows the water into the low pressure water circuit (180 psi). The water must be softened to remove iron and calcium dissolved solids since they tend to come out of solution at high pressure and damage the small orifice.

To treat the water mechanically and chemically, low pressure filters (1-10 microns) and softener are used. The nozzle failure due to deposit formation or dirt and debris can be prevented. In fact the cost of water nozzle versus cost of water treatment to achieve longer orifice life should be evaluated to estimate overall process effectiveness.

A hydraulic driven (10-40 hp) oil intensifier is the most important part of the system. It develops pressure up to 60,000 psi to the water from a booster pump. There are basically two separate circuits for oil and water. An oil circuit is a closed circuit and water circuit is an open one. The oil pressure of about 3000 psi developed by a rotary pump is used to drive an intensifier. The intensifier is double acting reciprocating (6" diameter) type pump. It is operated every few seconds by an adjustable control.

The high pressure emergency damp valve is a rapid acting two way position valve used to turn the jet ON or OFF in response to control commands. Its performance is critical to control the cut geometry. When cutting speed is high the 'lag' time of the valve is a significant factor to be considered. The proper start-up and maintenance procedure should be followed.

The high pressure water from both sides of the intensifier is discharged to an accumulator where the pressure gets stabilized. Since the water at 55,000 psi is 12 percent compressible, water is not discharged uniformly from intensifier at all piston position. Thus accumulator provides uniform discharge pressure and flow. A rupture disk is provided as a safety device for the intensifier. It should be very clear that the pressure gauge mounted on oil pump indicates the pressure of oil and the gauge mounted on water line after accumulator indicates the water pressure.

2. High pressure water distribution system

The output from the accumulator, the high pressure water, is carried away to the work station (s) through a series of hard pipes, swivels, flexible joints and fittings. The different standard sizes are available in the market. Upto 20 ksi, hose can be used to eliminate the need for swivels, which greatly simplifies the plumbing. Beyond 20 ksi, hard pipes, swivels, flexible joints and fittings must be used.

The number of joints, elbows and the total pipe length, decides the line pressure drop. The chief advantage of distribution system is to centralize (isolate) the water preparation unit from one or more work station, located at different suitable places for different application. If the pressure requirement is above 55,000 psi, leakage problems should be considered while designing water distribution system.

3. Work Station

It is a place where actual cutting operation is performed. It can be of a variety of types and located at different places depending on application. It consists of following major components.

A. Nozzle Assembly

B. Abrasive Feeder

C. Work place with traverse mechanism

D. Catcher

3A. Nozzle assembly

The huge amount of pressure head is being converted into the kinetic energy in the nozzle assembly. There are two nozzles housed in the main body. A separate port for the abrasive entrance is provided.(fig 3,4)

The high pressure water supplied from water distribution line first passes through sapphire nozzle (water nozzle) of .004 to .014 inch diameter size, and accelerates to a velocity of 2000-3000 fps. In case of cutting without abrasives (pure water), the design of nozzle assembly is much simplified. However, in the case of abrasive water jet cutting, the design of nozzle assembly plays vital role over performance of the system. Diverse types of design exist today and research is also stressed to improve the design of nozzle assembly. In general, abrasives enter from the side port, after the sapphire nozzle. Water from the sapphire nozzle and entered abrasives gets mixed in a particular zone. The angle of abrasive entry, diameter of port, and vertical and horizontal distances between abrasive inlet and sapphire nozzle are the typical variables to be selected in the nozzle design. Ultimate goal is to attain the efficient mixing of water and abrasive by optimization of energy transfer from the water to the abrasive particles.

The abrasive - water mixture passes through a tube (carbide nozzle), made from Tungsten Carbide. In this nozzle the formed abrasive water particles are accelerated and final energy transformation takes place. The carbide tube length, diameter and angle of convergence are the typical design parameters to be considered in carbide nozzle design. The material of tube construction is selected considering wear due to abrasive and corrosion due to high pressure water. The consistency of jet properties depends on the rate of carbide nozzle wear.

The weight of assembly is minimized considering the use of robot or other nozzle tracing mechanisms. Flexibility is provided to use set up for AWJC or for non-abrasive jet (pure water jet) cutting by quick modification over nozzle assembly. Also to reduce down time, the means for simple changing of sapphire and carbide nozzle are provided. The method of aligning sapphire and carbide insert should be accurate and easy so that correct power is transmitted consistently. Also efforts have been made to develop multiple water jet nozzle, multi parallel jet and multi convergent jet to improve mixing and cutting performance at relatively low pressure (14,500 to 35,000 psi)(5). A pneumatically operated valve is provided for the instant (emergency) ON - OFF operation. The analysis of the work cell operations shows that it is necessary to improve nozzle design and produce most accurate and durable water and abrasive nozzles. Also an easy and fast method for an accurate alignment should be enhanced with an improved design.(4)

For several reasons, the new alignable abrasive orifice mixing assembly is a significant departure and improvement over the previous abrasive mixing assembly. The most significant among these is the adjustability of the high pressure water stream. The high pressure water stream can be adjusted such that it is concentric with the bore of the abrasive focussing tube. Consequently, the energy losses caused by the impingement of the high pressure water stream upon the abrasive focussing tube are minimized, and the tube life is significantly prolonged. Also, the wear of the abrasive focussing tube is uniform and predictable. The orifice alignment is performed off-line; thus avoiding system down time during alignment. The off-line alignment station has a self contained pump, which cannot generate the high pressure associated with the intensifier output; thereby avoiding the possibility of an injury to a person if the alignment were to be done on-line. This avoids a person accidentally coming in contact with the high pressure water. The alignable orifice abrasive mixer assembly attaches itself to the output part of the high pressure water valve and is accurately located by the cutting head support bracket which has a very high repeatability.

3B. Abrasive feeder

This unit continuously delivers abrasives into the nozzle assembly at a controlled rate. A feed hopper stores about 25-400 lbs of abrasives and an electro magnetic vibratory tray regulates and flow abrasive from hopper. The flow is regulated by changing applied voltage that in turn changes frequency of vibration. The suction created in the nozzle assembly draws abrasives from vibratory tray. Some other designs are also being used for regulation of abrasive flow. For each set up of AWJC, the calibration of an abrasive flow is required. Also for different types of abrasive the calibration of abrasive flow has to be carried out. Because of non-uniform particle size distribution and thereby fluctuation in vibration effect, it is very difficult to obtain precise flow of abrasives. The distance between abrasive feeder and nozzle should be kept minimum. The material of construction should be stainless steel or same type to resist wear. Also feeder should be protected from foreign entrained particulates.

3C. Work place

The effective use of formed jet depends on design of work place. One would need to move either the jet or the work piece. The tremendous amount of flexibility of AWJC enhanced users to built a wide variety of work stations, suitable for particular application. The level of sophistication and safety requirements also determines the design of work place. The following has been used so far.

* Robots (Articulated arm and gantry type)
* CNC controller x-y positioning tables
* Manual pinrouter stations
* Hand hold devices with catcher unit
* On line production unit.

The major components can be described as

1. Nozzle tracer or work piece tracer
2. Fixture and supports to mount work piece
3. Controller (for motion and other parameter)

To cut complicated shapes with high level of accuracy it is necessary to move work piece or nozzle at controlled and uniform rate. Robots or CNC controlled x-y positioning tables can be employed successfully .

The pin router is a very versatile tool, which can be used on a daily basis to cut every thing from composites, titanium to aluminum in any workshop manually. AWJ can be housed in a work cell, that may consist of a robot or CNC x-y table in an enclosure with shuttle feed in and out. The cutting process is isolated to prevent operator and machines from danger. The controller is kept outside the enclosure to keep it clean and easily accessible for operator control. A personal computer loaded with an Auto-CAD or similar soft- ware with proper interface can be successfully utilized for these type of work cell to make cutting cost effective. In fact the requirement of fixtures and tooling is minimal in these cases.

In certain cases water jet cutting has been set up for on-line production for continuous manufacturing process type of industries. The following are the good examples of those kind of installation.

a. Cutting Benite igniter strands

Strands are moved along by conveyer belt and cut by water jet and go for further processing continuously.(6)

b. Cutting of shoe components from multilayers of flexible sheets.(7)

c. Drilling, trimming and other multi operation cell for aerospace components.

3D. Catching, separation and drainage

In any case an effective catcher has to be developed since jet coming out of work piece still contains high amount of kinetic energy, and particulates of used abrasives and cut material. The noise level is very high (approx 105 db). Particularly in case of an AWJC, the design of catcher and drainage system requires more attention because of pollution and high accumulation problems. Approximately 1/2 to 3/4 gallons of water and 1/2 to 3 pounds of abrasive per minute is expected, however it depends on cutting requirements. This gives roughly 11 percent solids by weight in final residuals. Thus it is very important to control both noise level (as per the OSHA regulation) and residual (as per the local pollution regulations).

Different types of set up will have different types of design of catcher - drainage system. In case of the moving workpiece type work station, catcher can be a stationary, heavy duty steel tube (pipe) with an insert in it to break jet continuously and dissipate energy. But in case of moving nozzle type work station, catcher can be a tank beneath work piece support grid (frame). This type of installation produces heavy noise (90-100 db). The development of moving catcher type work station can greatly reduce the problems of noise and pollution. The operation becomes clean and safe for the operators. In the case of open tank type catcher, the operator must be remotely located. Many designs have been devised to make catching effective. Some of them use steel balls in the catching tank to break and deflect the out coming jet. The steel balls will be replaced after considerable wear. Again this is one of the area requiring design efforts.

After catching jet, the next important requirement is to separate water and particulates and finally drain or dump them in a proper way. A continuous separation and filtering system can be designed, which will allow continuous drainage of water of quality accepted by the local pollution control agency standards. A gravity settling tank or wet cyclone can be used for course separation and series of mechanical filters can be used for final separation. Possibility of recycling the used abrasive has not been perfectly studied yet. The use of particulate waste (slurry or solid form) for construction or other purpose can be found out. A strong vacuum can be used to catch splashes during cutting to make work place pollution free or a hood or shield around the nozzle can be designed. In certain cases vacuum trucks are used intermittently to collect water and particulate slurry and subsequently dispose in to the dump yard. The noise reduction can be achieved by covering cutting cell with sound proof material (transparent) or by other means.

4. ROBOTIC MOTION EQUIPMENT

The robotic gantry motion equipment described in this specification is a CNC driven moving bridge gantry configuration. The standard configuration includes two axes of programmable motion x and y axes, and an electronically adjustable z axis. A servo driven z axis is offered as an option. The work piece support structure is a fixed grid, which in Hydro-abrasive applications, is considered sacrificial, and is located above the catcher tank and is supported by the tank structure.

The catcher tank with work support grid is adjustable to ensure that the workpiece is supported in the true X-Y plane beneath the moving bridge. The Z-axis (up &

down) movement carriage is mounted on the X-axis carriage and carries the waterjet or Hydroabrasive cutting head assembly.

The CNC control system, servomotor drives and I/O devices are located in an enclosure which is separated from the machine frame. The operator control panel is appended to the main control enclosure by a flexible metallic conduit, and is mounted upon a pedestal which enables the operators control to swivel for ease of viewing and operating. The standard control is the Allen Bradleys 8400 CNC control. All machine functions are controlled by the 8400 control.

The CNC control unit is constructed in two modules: the processor logic module which is located in the control enclosure, and the operators display and control module.

5. Polymer Mixer

The polymer mixer is composed of two parts: Polymer supplier and water supplier. For the polymer supply two pumps will be in use. When these two pumps work they suck the liquid polymer from the polymer source and carry it to the inlet of the mixing tank where a homogeneous water-polymer mixture is formed.

6. Tooling - Fixtures

One of the distinct advantage of AWJC is that no mechanical and thermal loads are directly applied to the work piece, thus the elimination of chatter, vibration, surface damage of work piece. Typically 10 lbs. of reactive force is produced at 45000 psi water pressure, 0.010 inch sapphire dia and .030 inch carbide dia. so the requirement of fixtures to hold the work piece is comparatively reduced significantly. In most cases while cutting, the jet penetrates through and through the material to be cut and any supporting materials beneath it or jet reflects back after impinging on support materials and wears the support materials very fast. So any support frame or fixture used has to be replaced periodically. The toolings are required mainly for maintenance and nozzle changing purpose.

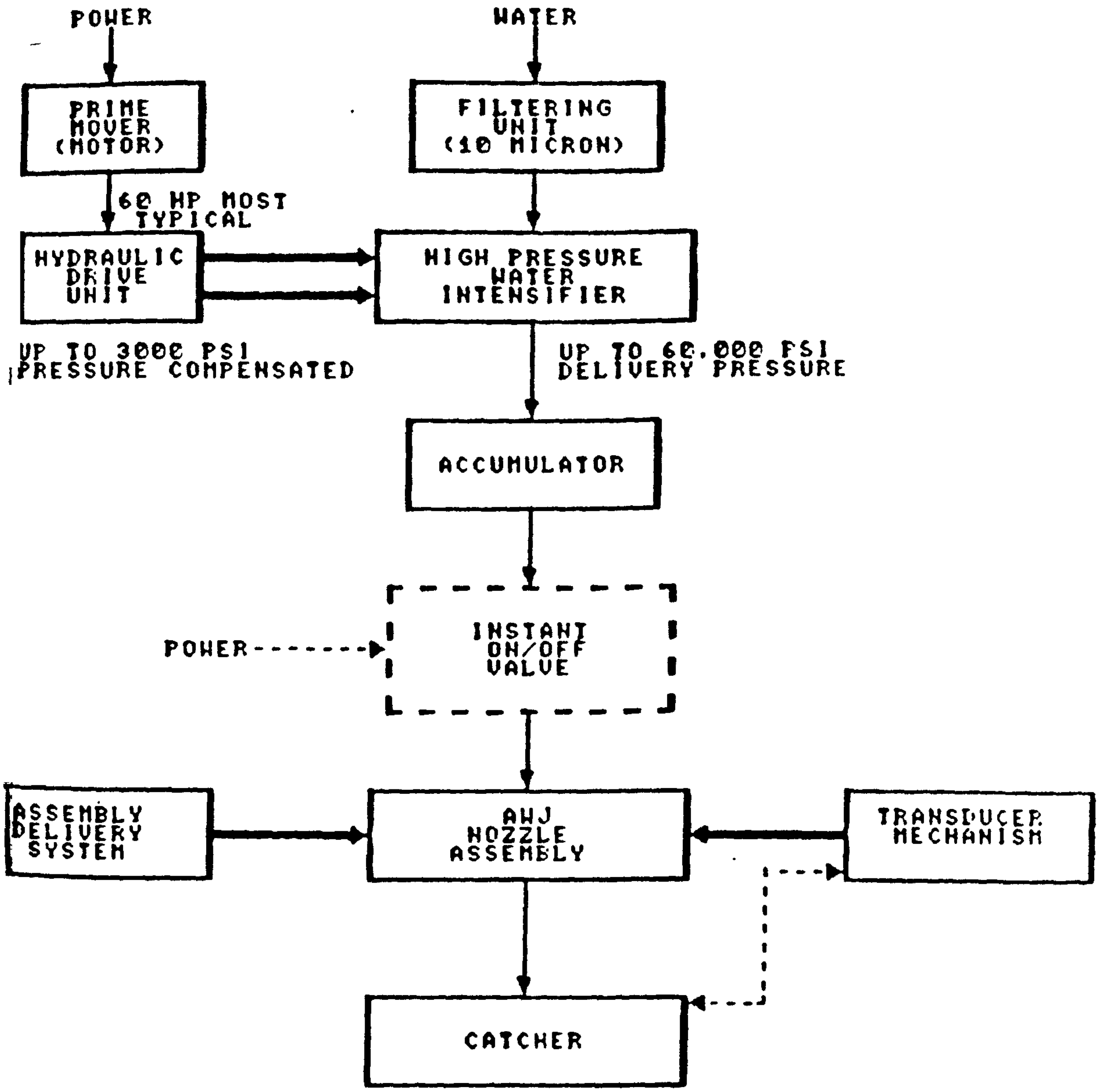


Fig: 1 Block Diagram of AWJ Components

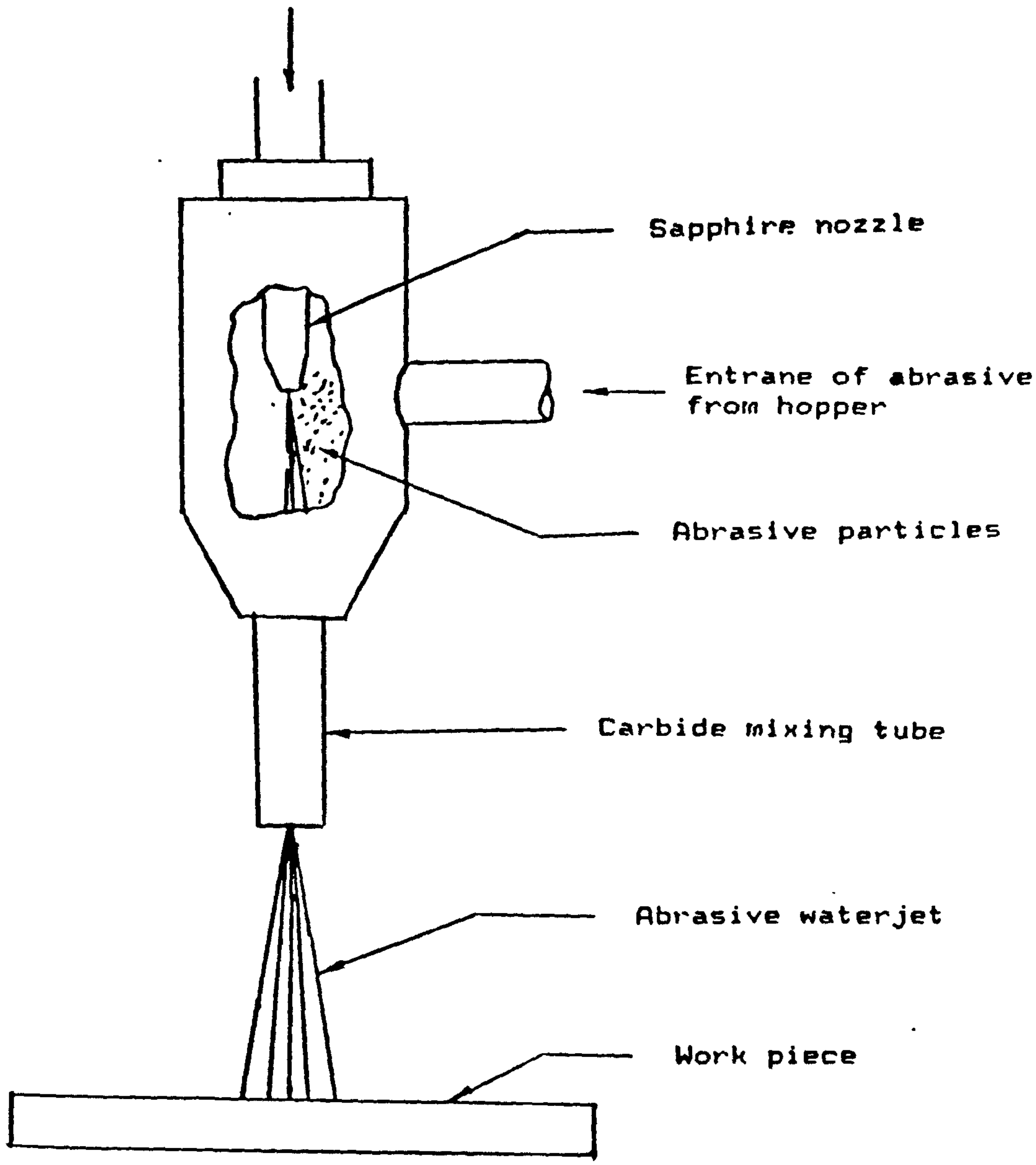


Fig: 2 Schematic of Jet-Workpiece Interaction

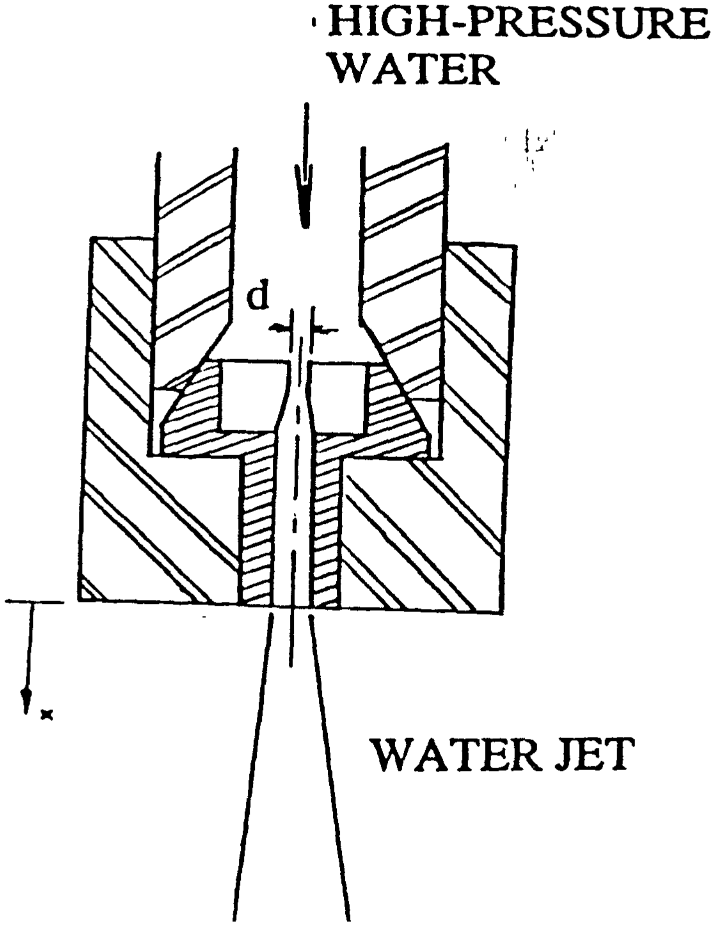


Fig: 3 Schematic of Sapphire Nozzle with Water Flow

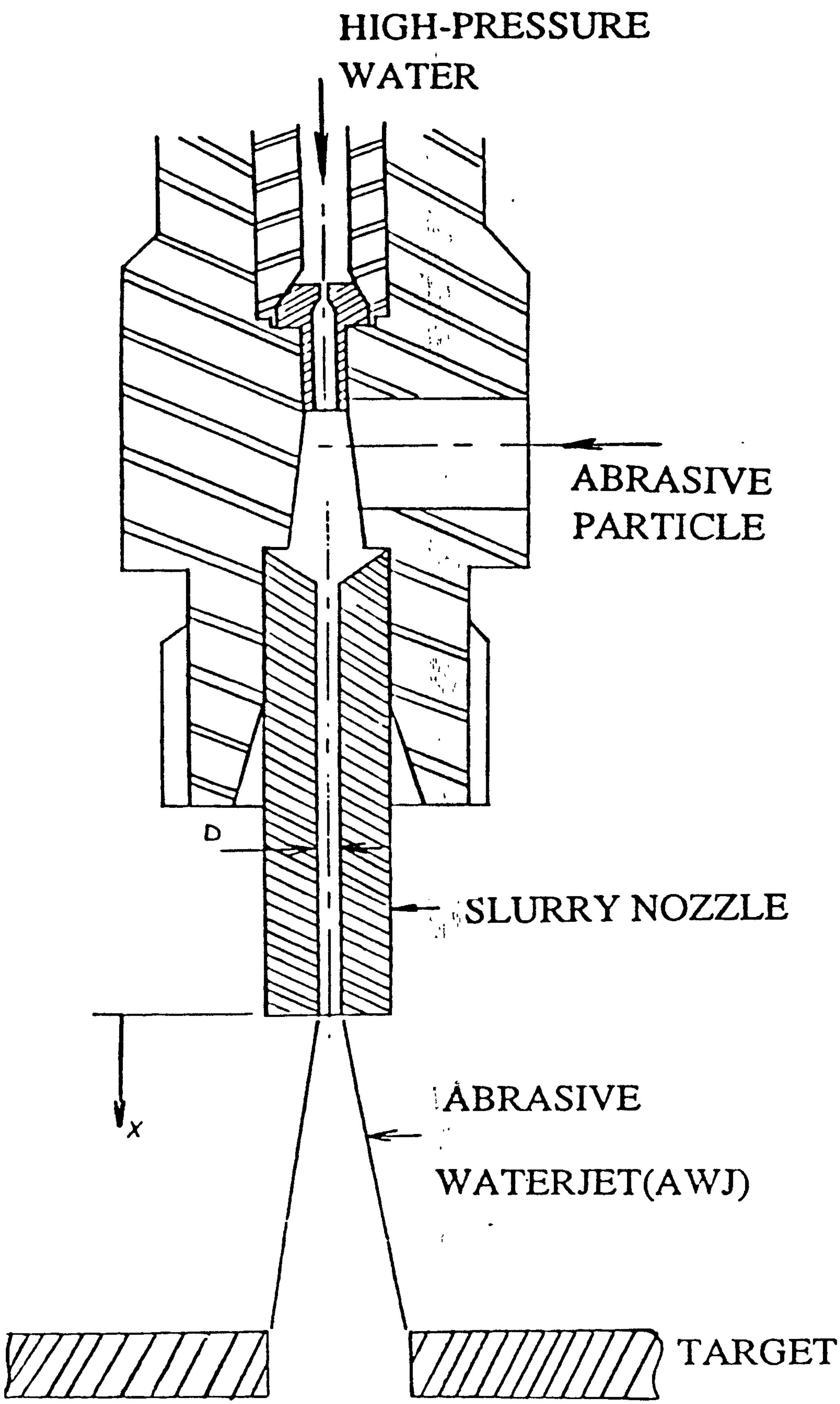


Fig: 4 Schematic of Carbide Nozzle with Flow

2.3 THEORY OF OPERATION & AWJC PARAMETERS

A. Theory of operation

As any other metal removing process, abrasive water jet cutting (AWJC) is basically an energy conversion process. The pressure head is converted into kinetic energy by a cyclindrical sapphire nozzle. The relationship between pressure developed and jet velocity can be established using Bernouli's equation(9).

v = SQRT (2p / s)

where p = pressure in psi and

s = average fluid density

The flow rate is the function of nozzle and orifice coefficient. The coefficient depends on design of nozzle. A typical pressure - flow relationship exists. The value of Cd can be obtained by water flow calibration.

Q = (pi / 4) * (D) * (D) * Cd * V

Where Q = flow of water (gallons per min)

D = Dia of sapphire nozzle (inch) and

V = velocity of fluid (ft per sec)

The significant amount of air quantity is needed to flow the abrasives pneumatically. Thus in fact, there are three flow rates at the outlet of the nozzle, which should be calculated. These are flow rate of air, water and abrasives. The velocity of air, abrasives and water are different. The pressure drop in the carbide tube might change the jet velocity. The jet physics becomes very complex in case of Abrasive Water Jet Cutting.

B. Abrasive Waterjet Parameters

In the course of cutting with abrasive water jet, there are many system parameters existing which can independently affect the cutting performance , for the sake of simplicity, most of the parameters can be categorized under the following types:

1) Hydraulic parameters,

2) Nozzle parameters,

3) Abrasive parameters,

4) Cutting parameters,

5) Work piece parameters, and

6) Others

The hydraulic parameters mainly affect the kinetic energy of the water before it passes through the nozzle assembly. The major hydraulic parameters are,

1) Fluid pressure -- psi

2) Hydraulic power -- hhp and

3) Type of fluid.

The nozzle parameters are concerned with geometry of the nozzle which affects the energy conversion process and abrasive mixing. The principal nozzle parameters are,

1) diameter of sapphire nozzle (wate nozzle) --- inches,

2) diameter of carbide tube (abrasive nozzle)--- inches,

3) length of carbide tube --- inches, and

4) Type of abrasive entry system.

The other geometrical parameters like the angle of convergence and the distances of abrasive and water entry ports can be considered as system parameters but basically those are nozzle design considerations.

The abrasive parameters are related to abrasive material and abrasive feed. These are another major part of the AWJC process parameters apart from fluid (hydraulic) parameters. The abrasive parameters are

1) Type of abrasive (material),

2) Size of abrasive (mesh size), and

3) Feed rate (lb/min)

The cutting parameters are those which are set on the cutting machine during actual cutting process. The major cutting parameters are as under.

1) Stand off distance from nozzle to work piece (inches)

2) Traverse speed (work piece or nozzle) (inch/min) and

3) Angle of cutting (degrees)

The cutting process is a very complex phenomena of wear and erosion of the material surface upon impingment of abrasive jet. Thus cutting result is affected by both jet properites and properties of material under cutting. The major work piece parameters can be considered as under:

1) Surface hardness, and

2) Brittleness of material

C. Cutting Results

The cutting results can be considered as a output of the cutting process. Considering the cutting application of AWJC, two major output are under consideration.

1) Depth of cut (inches) and

2) Surface quality, which include:

A. Surface topography

a. waviness

b. Roughness (Ra, Rz microinches)

c. Top and bottom kerf width (inch)

d. Flaw on the surface

B. Sub surface quality:

a. Microcrack in the sub surfaces

b. Hardness on the sub surface.

2.4 DESCRIPTION OF MEASUREMENTS AND INSTRUMENTATION

A: On the **surface texture:**

The surface texture is the repetitive or random deviations from nominal surface which form the three dimensional surface topography. Normally the instrument used compares between the measured and nominal profile for given surface.

American National Standard ANSI B 46.1-1978 describes, and standardizes the surface terminologies. According to Standard, surface texture includes four elements; roughness, waviness, lay and flow.(9).

a) **Roughness:** Roughness consists of the finer irregularities which generally results from the inherent action of the production process. These include traverse feed marks and other irregularities within the limits of the sampling length. The roughness component of surface texture is generally quantified by the parameter roughness average, R_a. Roughness average is the arithmetic average of the absolute values of the measured profile height taken within the sampling length and measured from the centerline. Because R_a is an arithmetic average, it only provides a general description of the actual surface. A large R_a value indicates that the actual surface is rough, and a small R_a value indicates that the actual surface is smooth.

For graphical determinations of roughness average, the height deviations are measured normal to the chart centerline. When R_a is determined from electrical averaging instruments, the cutoff selection is equivalent to the roughness sampling length. The parameter R_a is standardized throughout the world, easy to measure and useful in monitoring part roughness in established manufacturing processes. Nevertheless, two surfaces with the same R_a value may not look, feel, or function alike. The parameter accounts for the area enclosed by the surface profile about the mean line. Redistributing material above or below the mean line would not change the average because the area stays same. The ability to produce particular surface roughness on a part by a certain process depends on many factors in addition to characteristics of the material and condition of the machine tool.

Ten-point height: The ten-point height R_Z (ISO), is the average height difference between the five highest peaks and the five lowest valleys. It is measured over a single sampling length from a line parallel to the meanline and not crossing the profile. The ten-point height can be combined with R_a for a more complete characterization of surface texture. Measuring R_Z is one preferred method for analyzing short surfaces, as used in the present thesis work.

The heat in the workpiece generated by abrasive machining is the principal ingredient affecting surface integrity. The amount of heat is proportional to the intensity with which the process is applied. Thermal properties of the material and its metallurgical respond to the heating level control the degree of surface effects.

b) **Waviness:** Waviness includes all irregularities whose spacing is greater than the waviness sampling length. Waviness may result from machine or work deflections, chatter, vibration, heat treatment or cutting tool runout. Roughness may be considered superimposed on a "wavy" surface.

c) **Lay** is the direction of the predominant surface pattern, ordinarily determined by the production method used. The milling process produces the pattern that is regular and repetitive, providing an observable direction to the surface texture pattern.

d) Flaws are unintentional irregularities which occur at one place or at relatively infrequent or widely varying intervals on the surface. Flaws includes cracks, blow holes, inclusions, checks, ridges, scratches, etc. Unless otherwise specified, the effect of flaws shall not be included in the roughness average measurements. Where flaws are to be restricted or controlled, a special note as to the method of inspection should be included on the drawing or
in the specification.

Surface Finish: Surface finish is a colloquial term widely used to denote the general quality of the surface. Surface finish is not specifically tied to the texture or characteristic pattern of the surface, nor is it tied to specific roughness values, however, a "good" finish implies low roughness values and vice versa. The term surface finish is not as precisely defined as are the terminologies used in the American National Standard, nor is it necessarily expressed numerically.

Traditionally, surface texture (roughness, waviness and lay) has been accepted as the criterion which controls the quality of a surface. A 10 percent rule of thumb states that if surface roughness increased by 10 percent (in micro inches R_a or rms) or if any one of the operating parameters has been reset or "adjusted" by plus or minus 10 percent from the planned values, immediate question should be raised as to control status of process. If two or more parameters are "adjusted" by 10 percent or more, the process is no longer controlled and should be shut down until corrective action is effective.(9)

B. Instrumentations:

The matrix videometrix econoscope is a fully automatic, 3-axis videosystem. The Econoscope uses noncontact techniques to provide rapid dimensional verification of complete parts or specific features of a part. The econoscope comprises a general purpose computer, a 3-axis positioning control system, and a Digital Image Processor and Part monitor selection. Specifically designed to be easy to use, the Econoscope operates at a high speed, producing very accurate and repeatable results. The x/y/z positioning system provides the capability of moving the part to be inspected in the x/y plane and very accurately measuring the distance that the part was moved. The z plane measurements are performed by moving the camera with relation to the part (focusing on a feature) in the z axis. The x/y/z stages are moved using a very high resolution stepper motors and precision lead screws. The TOPO (Topography) function (optical surface contouring system) is selected from the main menu and then the machine is homed. The following is the information related to the measuring parameters: The surface module provides the capability to gather and view surface contour information. This process is essentially divided into two procedures: the INSPECT processing and the GRAPHICS processing. INSPECT processing provides the capability to define the configuration for collecting the data points on the surface by allowing the user to define the following parameters:

1) The number of focus points to be gathered along the length and width of the surface (the 'x' and 'y' points),

2) The magnification of the lens which will be used for gathering these points,

3) The total stage travel distance from the start point in the 'x' & 'y' directions,

4) The incremental move for the stage between each point,

5) The size of the DIP window and,

6) The intensity of the surface light.

The Graphics processing allows the user to view the collected points on a 2^d surface (on either the CRT or a hard copy). The graph may be presented from different viewing angles, amplifications or windows. Additionally, single or multiple line plots may be viewed. The Manual Measurement module is used in this work to calculate Rz (Depth of cut). The manual measurement module has many applications such as inspecting first article, verifying recorded measurements, and confirming the feasibility of making certain measurements in a program under development. The manual measurement menu consists of Title block, data capture, function, message menu's etc. The Z dimension measurement selected in this work (Depth of cut) provides a distance output in the Z axes of the part. Z distances are measured between two surfaces. An option exists which can slect either inches or millimetres as units.

C. Surface Integrity

The objective of surface integrity is the development of unimpaired or enhanced surface conditions in hardware by controlled manufacturing processes to the extent needed in specific applications. The principal causes of alterations from material removal operations are:

1) High temperature or high temperature gradients.

2) Plastic deformation

3) Chemical reactions on the nascent machined surface.

4) Excessive heating from electrical conductance.

The distortion, inaccuracies or change in material properties due to fabrication processes are of concern to the designer and the manufacturer as a reduction of quality or a source of loss and cost. Some of the effects can also contribute to the initiation of early component failures.(10)

C.1 SURFACE INTEGRITY ALTERED MATERIAL ZONES

The Zones are classified by principal energy mode.

Mechanical: Plastic deformations, tears, laps and protuberances. Hardness alterations cracks (macroscopic and microscopic). Residual stress, inbedded processing materials.

Metallurgical: Transformation of phases, grain size and distribution. Precipitate size and shape. Foreign inclusions in material, Recrystallization.

Chemical: Intergranular attack, corrosion. Contamination, Embrittlement. Pits, etch, stress corrosion.

Thermal: Heat affected zone, Recast material, Redeposited material.

Electrical: Conductivity change, Magnetic change

These effects on material properties can in turn influence the mechanical properties of which fatigue and stress corrosion resistance are of the most concern. Each material-process combination is unique and can have variable effects depending on the metallurgical state of the material and the energy intensity level used during processing. Processes are usually operated over a range of intensities. The roughing or finishing modes are reflections of these different intensities or energy densities. From a surface integrity stand point it is necessary to consider the change in effects on the workpiece material over the full range of energy levels expected to be used.

In mechanical material removal, typically abrasive in nature, the mechanical forces between the "tool" and the workpiece affect the surface integrity by introducing residual stresses, plastic deformation and sometimes hardness alterations to the surface. Both materials and processes must be controlled with equal degrees of relentlessness if the best surface integrity is to be maintained.

2.5 Glass manipulation

Cutting: The cutting of glass, for most types and forms, is achieved by creating a tensile stress at the surface at right-angles to a predetermined path. The stresses can be created either by mechanical or thermal means and the problem in both the cases is to ensure that the maximum stresses are coincidental with the cutting path required. For this reason it follows that cutting glass generally becomes increasingly difficult with increase of thickness or complexity of the shape required.(11)

Machining: The machining of glass in terms of glass removal, unlike that of metals and many other materials, is virtually limited to various forms of grinding, although surface decorative effects can also be achieved by techniques such as sand blasting or acid embossing, the terms bevelling and edgeworking being applied to hand or machine processes in which the surfaces or edges of a glass are either:

1) Ground, smoothed, and polished, or

2) Ground and smoothed, or

3) Ground only

Selection of these processes depends upon the amount of glass to be removed and the surface finish required. "Arising" is the term applied to the process of removing the sharp edges of cut glass, equivalent to chamfering. Machining or removal of glass by grinding can be achieved either by hand or by machine using one of the following methods:

1) Cast-iron mills fed with loose abrasive such as silicon carbide and water;

2) Silicon-carbide wheels or coated belts which produce a surface finish related to the grit size of the abrasive;

3)Aluminium oxide wheels or belts which give a slower stock removal than silicon carbide but a smoother finish;

4) Tungsten-carbide-coated discs;

5) Diamond-plated wheels and tools; and

6) Impregnated diamond wheels.

The polished finish subsequent to grinding is obtained by one of the following methods:

1) Various rouges used with felt or cork pads or wheels;

2) Pumice powder used with willow wood wheels, particularly in bevelling;

3) Pumice powder used with rubber and canvas wheels for edge polishing; and

4) Aluminium-oxide wheels bonded with rubber for edge polishing.

It will now be appreciated that the machining of glass has many practical difficulties.

2.5.1 Machining & Processing of Glass

1) Deep cutting: Glass is ground away by holding the article against the upper edge of a large abrasive wheel. Marking, rough grinding, smooth grinding, and polishing constitute the stages. Formal, geometrically based designs, usually polished are the usual types of decoration. Typical products include Domestic glassware, especially full lead crystal, flat glass, decorative mirrors, etc.

2) Intaglio cutting: Lighter grinding by holding the upper surface of the article against the lower edge of a small abrasive wheel. The stages involved are Marking, grinding, and polishing. Freer designs, eg. scrolls, but with a definite rhythm, often unpolished are the usual types of decoration. Typical products include Domestic glassware, especially full lead crystal.

3) Copper-wheel engraving: Light grinding by holding the article against the lower edge of a copper wheel on to which an abrasive is fed, a variety of sizes of wheel are used for different depths and widths of pattern. Marking and grinding are the only stages involved. Pictorial treatments, lettering, seldom polished. Domestic glassware, especially full lead crystal, generally for individual pieces, commemorative and special glassware are some typical products.

4) Diamond point engraving: Scratching on surface of glass with a diamond or tungsten carbide pointed stylus - the latter is more usual now. Marking, often on guide chart, and scratching or stippling are the stages involved. Pictorial treatment and lettering are seldom polished. Typical products are full lead crystal, and commemorative and special glasses.

5) Grinding: Flat glass surfaces are pressed on to a revolving grinding table; curved surfaces are ground on a lathe. Typical products are dessicator lids, jar stoppers, and ground-glass joints for laboratory ware.

6) Sandbasting: Surface of the glass is removed by blowing a jet of abrasive against it by compressed air and portion of the glass to be left plain is covered with a resistant material. Small articles are held in a sandblasting cabinet which protects the operator and flat glass is blasted with a spray gun, the operator wearing a mask, goggles, gloves and other protective clothing. The usual types of decoration are labels for containers, especially chemical, which are often enamelled afterwards, domestic and catering glassware and decorated and lettered flat glass, including mirrors.

7) Acid etching: Immersion in solutions contains hydrofluoric acid and patterns obtained by covering the glass with a wax resist to protect areas from being etched. The stages involved are a) Flat glass is dipped in acid and electric lamp bulbs are filled with acid which is then drained off. b) Application of wax resist and immersion in acid wash. The usual types of decoration are total and partial translucency. Typical products are flat and hollow glassware like lighting shades, pearl electric lamp bulbs,

and domestic glassware.

2.6 Experimental Procedure (Milling on glass)

Waterjet system made by Ingersoll Rand equipped with a 3-axis robot has been used for the experiments. Glass is used to conduct linear milling tests. Hydraulic, abrasive and cutting parameters are varied to generate a data matrix on the effect of the material on the depth of cut. The main objectives of generating this data matrix are to observe the geometrical quality of the cuts, roughness of produced surface , and variation of depth of cut along traverse.

A CNC program is written and keyed into the controller of the machine.

Initial experiments are conducted with high pressure (50000 psi) and changing speeds which have resulted in a deep and irregular slot depth. The lateral profile of the slot produced is also nonuniform.

Pressure is reduced gradually with increased traverse speeds to produce a better finish and controlled depth of cut.

Cutting parameters are varied, like, traverse rate and standoff distance. Abrasive parameters like size, flow rate, abrasive condition (dry or slurry) are also considered at low pressures and high speeds. The goal is to change parameters to maximize material removal rates and produce minimal surface irregularities. Standoff distance is optimised for maximum material removal.

Pressure and speed are kept constant and standoff distance is gradually increased and the results are recorded.

The experiments have resulted in a data base much needed since very little work is carried in this area. All the samples are analysed thoroughly on the videometrix to analyse the surface topography. Programs are written to compute Rz and depth of cut.

Submerged waterjet cutting is also explored wherein the glass sample is fixed on a machine vise and the vise was submerged in a pan of water/abrasive. The waterjet is aimed at the piece and the whole unit covered to prevent sp- lashing of water. However, the experiment is a failure with all the samples breaking at high pressure of water, and with low pressure, not impacting at all.

2.7 Results

Increasing the traverse rate, lowering the pressure and optimizing the stand-off distance for maximum volume removal

is the approach adopted for milling in this thesis. The low pressure of 15,000 Psi & traverse speed 1000 ipm was found to be very ideally suited since high pressures increase the rate of nozzle wear and increased pump maintenance frequency. Higher pressures are usually associated with lower volumetrix efficiencies, reduced coefficients of discharge and generally reduced hydraulic efficiencies.

Surface topography is found to be a function of both cutting and abrasive parameters.

Optimization of the traverse rate is found to be the most important factor in affecting experimental results since the traverse rate affects the cutting mechanism i.e cutting wear may occur more often at low traverse rates and deformation wear at high traverse rates. A given material may be very sensitive to one form of wear and relatively insensitive to the other and hence the depth-of-cut versus traverse-rate curves which are enclosed are of a very complex nature. At a pressure of 15,000 Psi, the depth of cut is found to gradually decrease as the traverse speed increases. (Fig 6, P 46)

However, at 12,000 Pressure, the depth of cut was more or less constant for speeds greater than 1200 ipm. (Fig 8)

(Fig 9) shows the relation for 25,000 Pressure. At high pressure and low speed of 120 ipm, the sample was found to break.

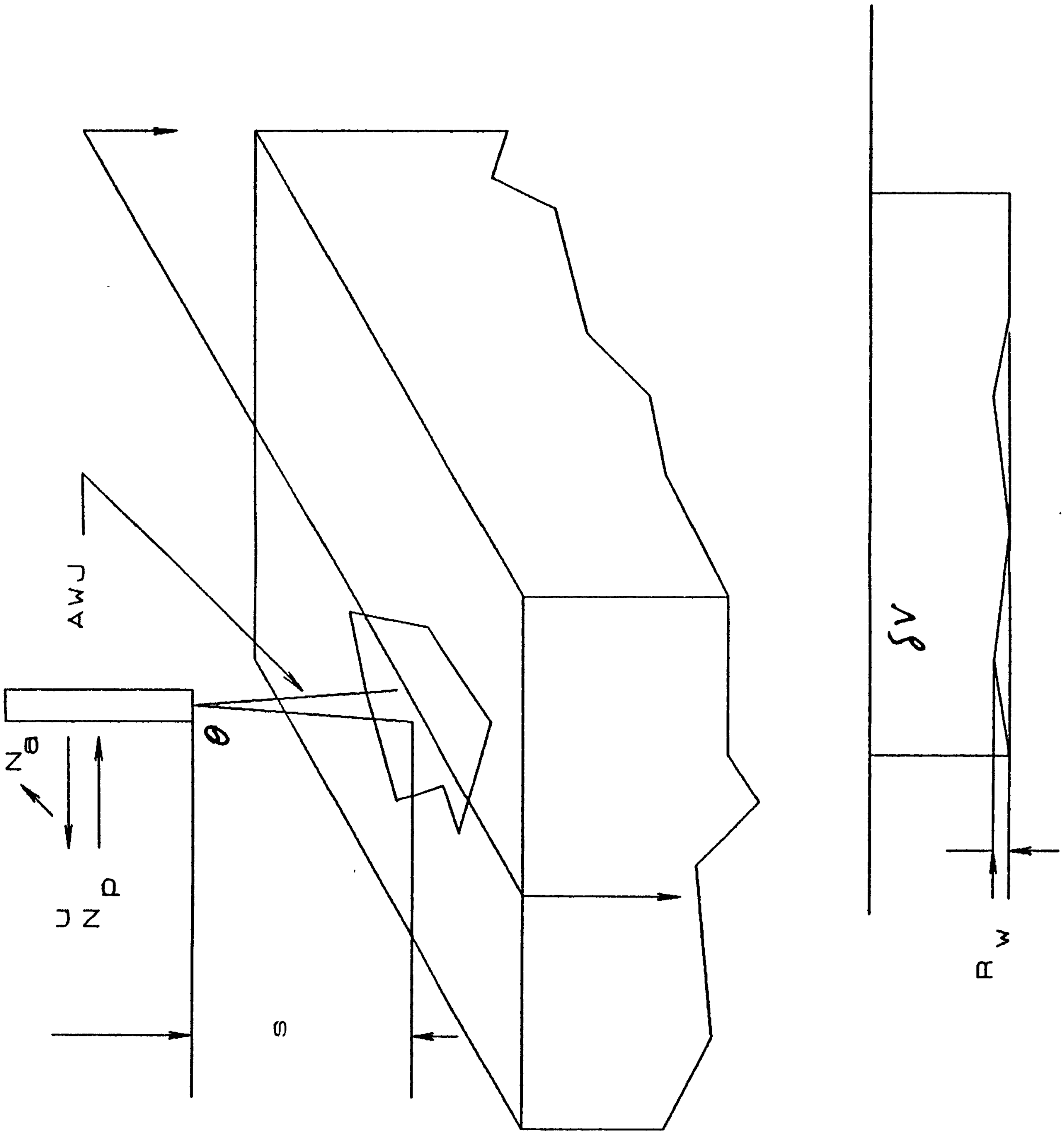
(Fig 10) reveals that, for a constant speed of 120 ipm, as the pressure increased gradually and reached 25,000 psi, the sample broke.

Videometrix analysis (Fig 11) shows that optimum stand-off distance exists and increased stand-off only produces an irregular surface. Graphics file: Shiv 24 had a pressure of 15,000 psi & speed 1000 ipm.

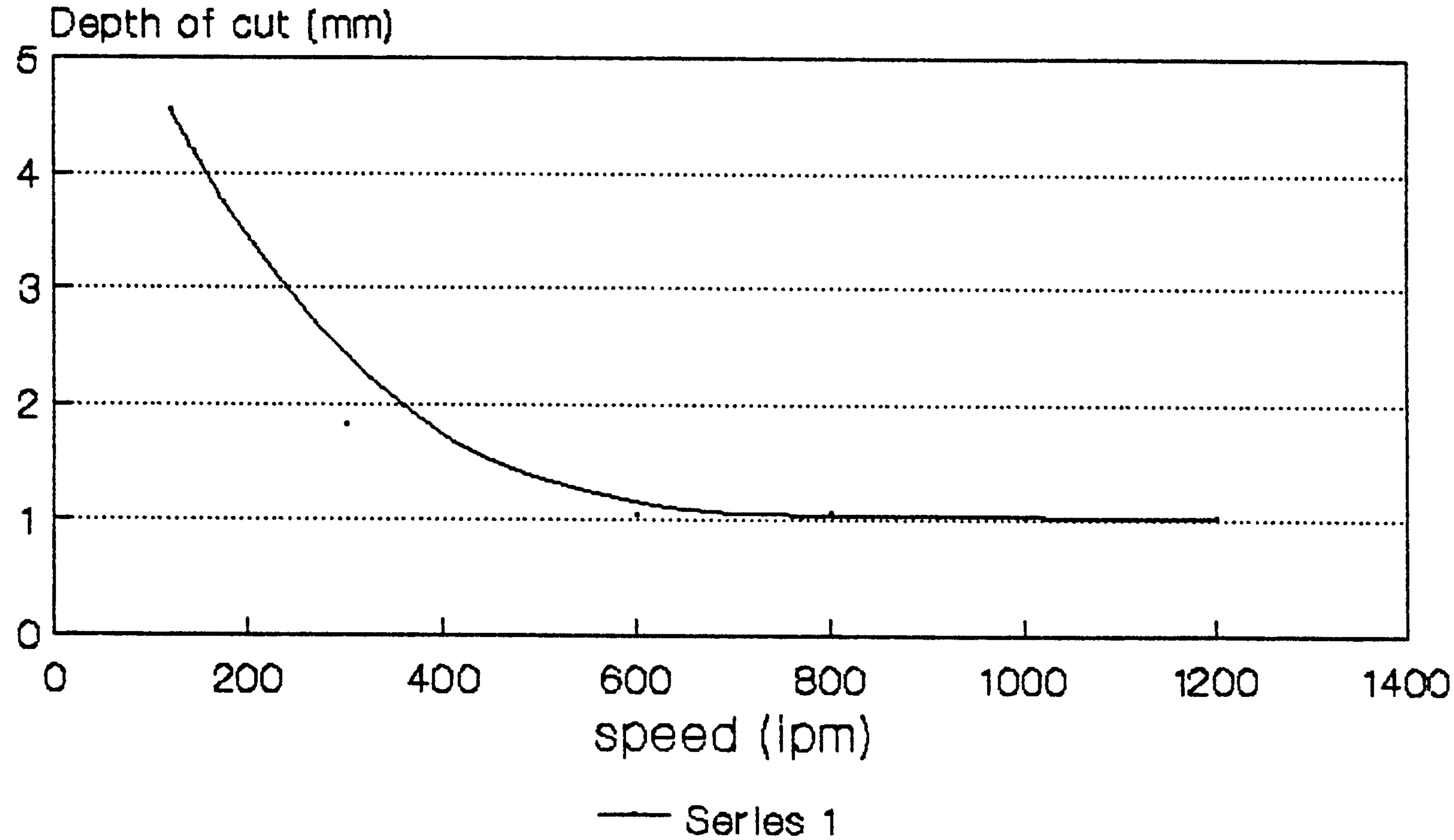
In comparison, the stand-off was increased to 30mm and the surface was irregular as also indicated by an Rz value of .1846 mm, in comparison to .1665 mm for a low stand-off distance.

Videometrix analysis (Fig 12) shows that at low pressure, uniform surface is acieved at gradually increasing speeds as also indicated by relative Rz values of .1990 mm, .1422 mm and .1353mm.

Videometrix analysis (Fig 13) shows that as pressure increases, at same constant speed, sample is found to break eventually.


AWJ
θ
S
δV

feed rate vs depth of cut
pressure = 15000 psi



stand off = 2mm

Fig 6

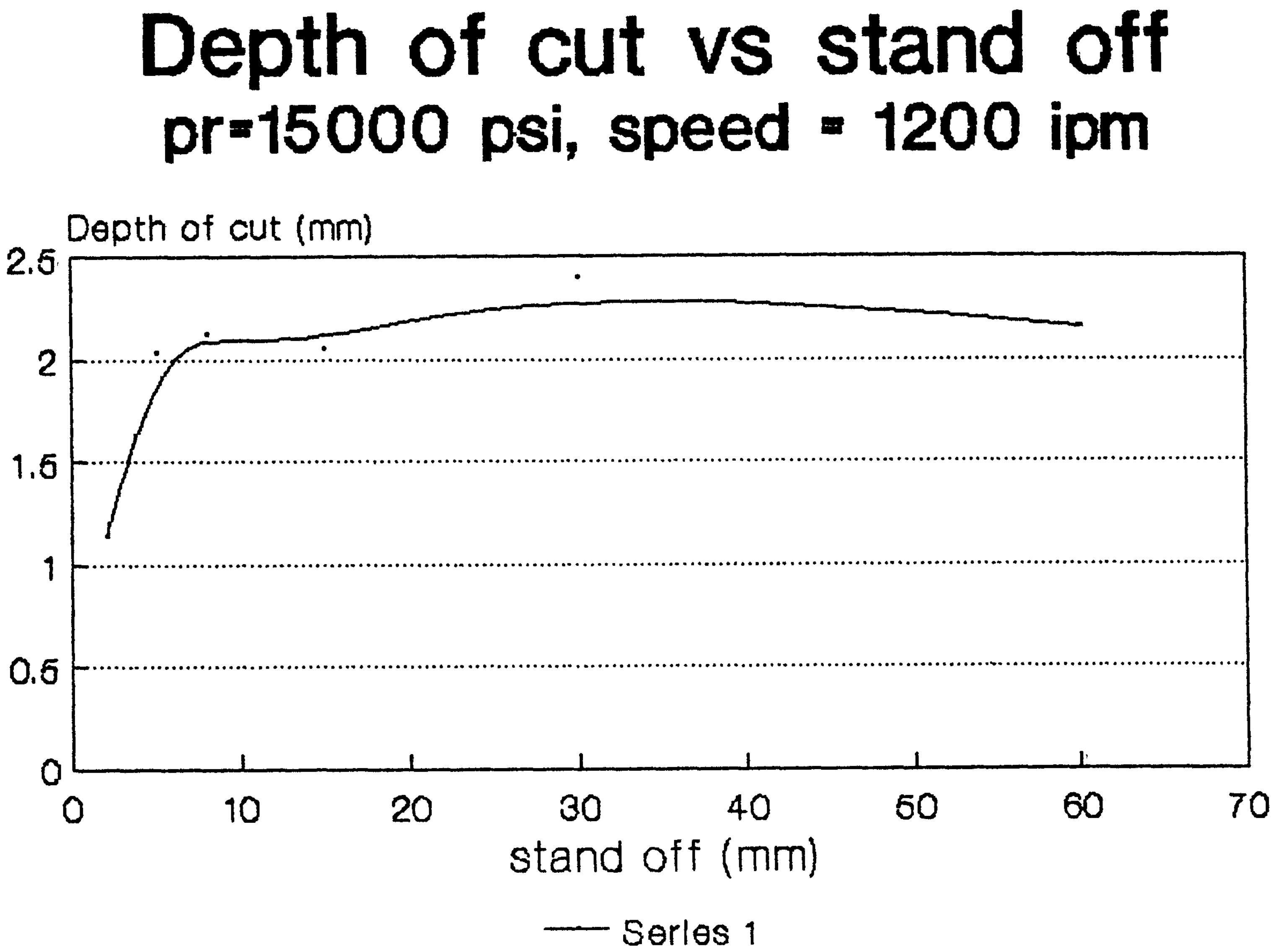
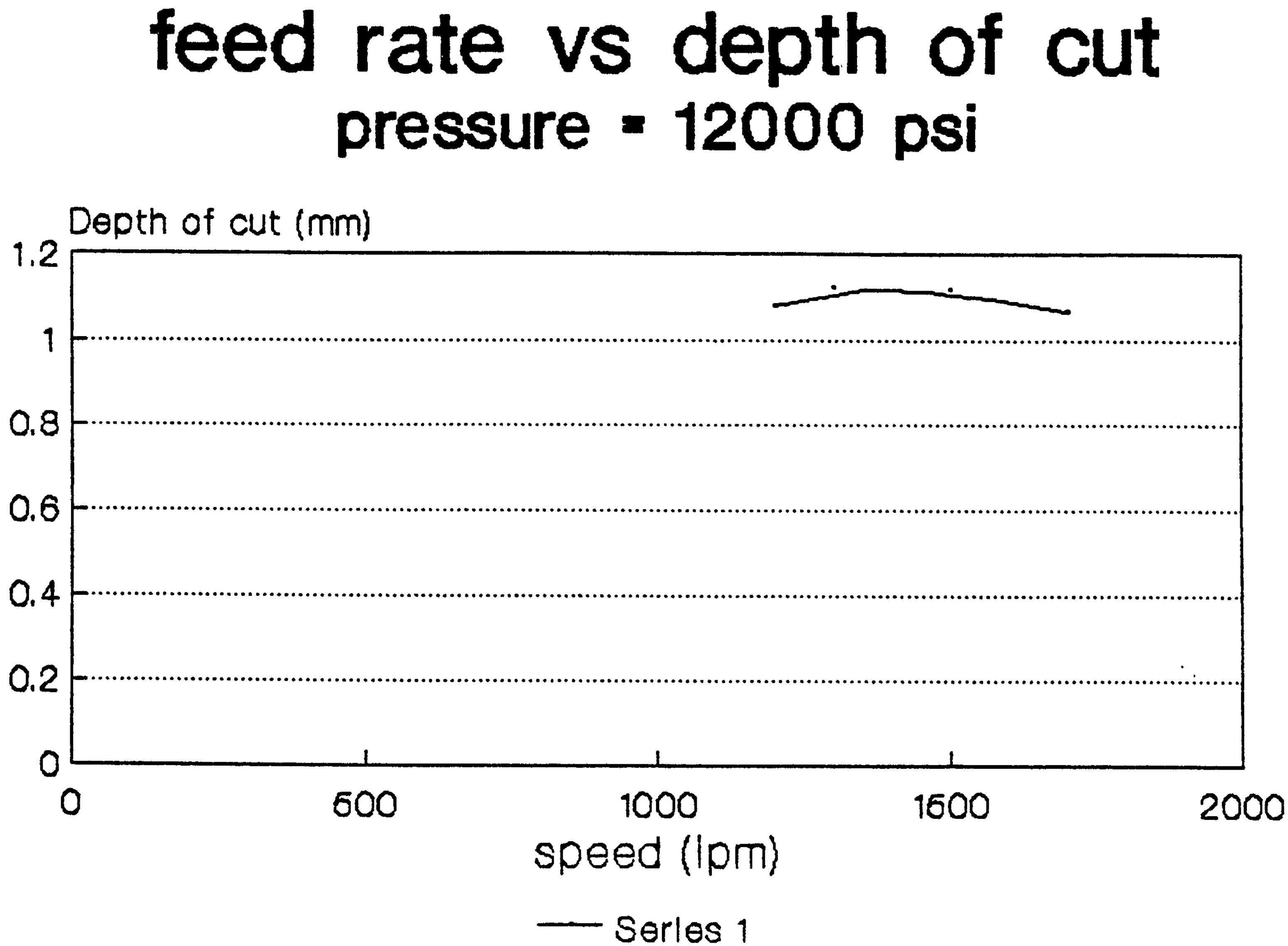
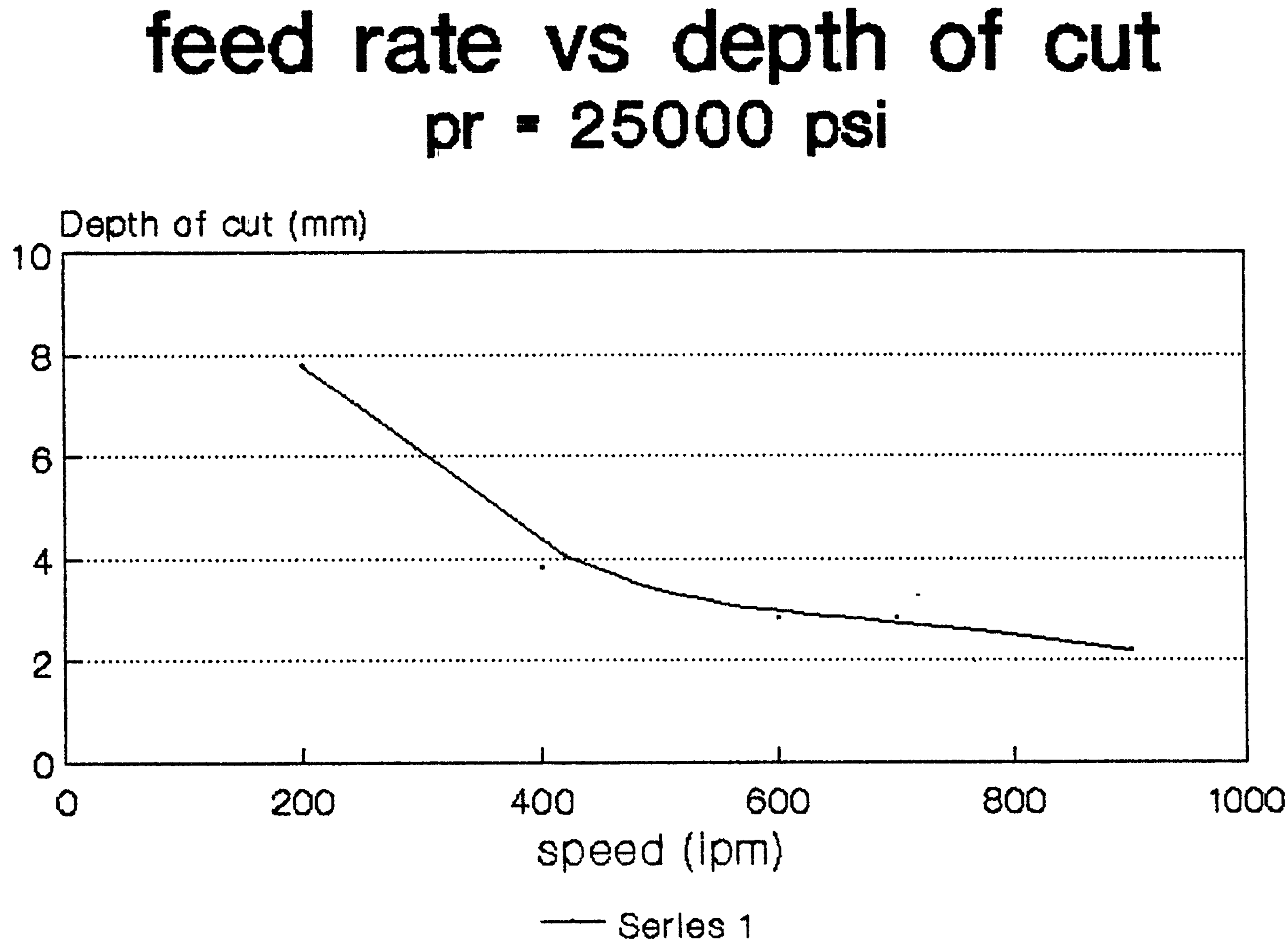

Depth of cut vs stand off
pr=15000 psi, speed = 1200 ipm
Depth of cut (mm)
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
stand off (mm)
Series 1

Fig 7



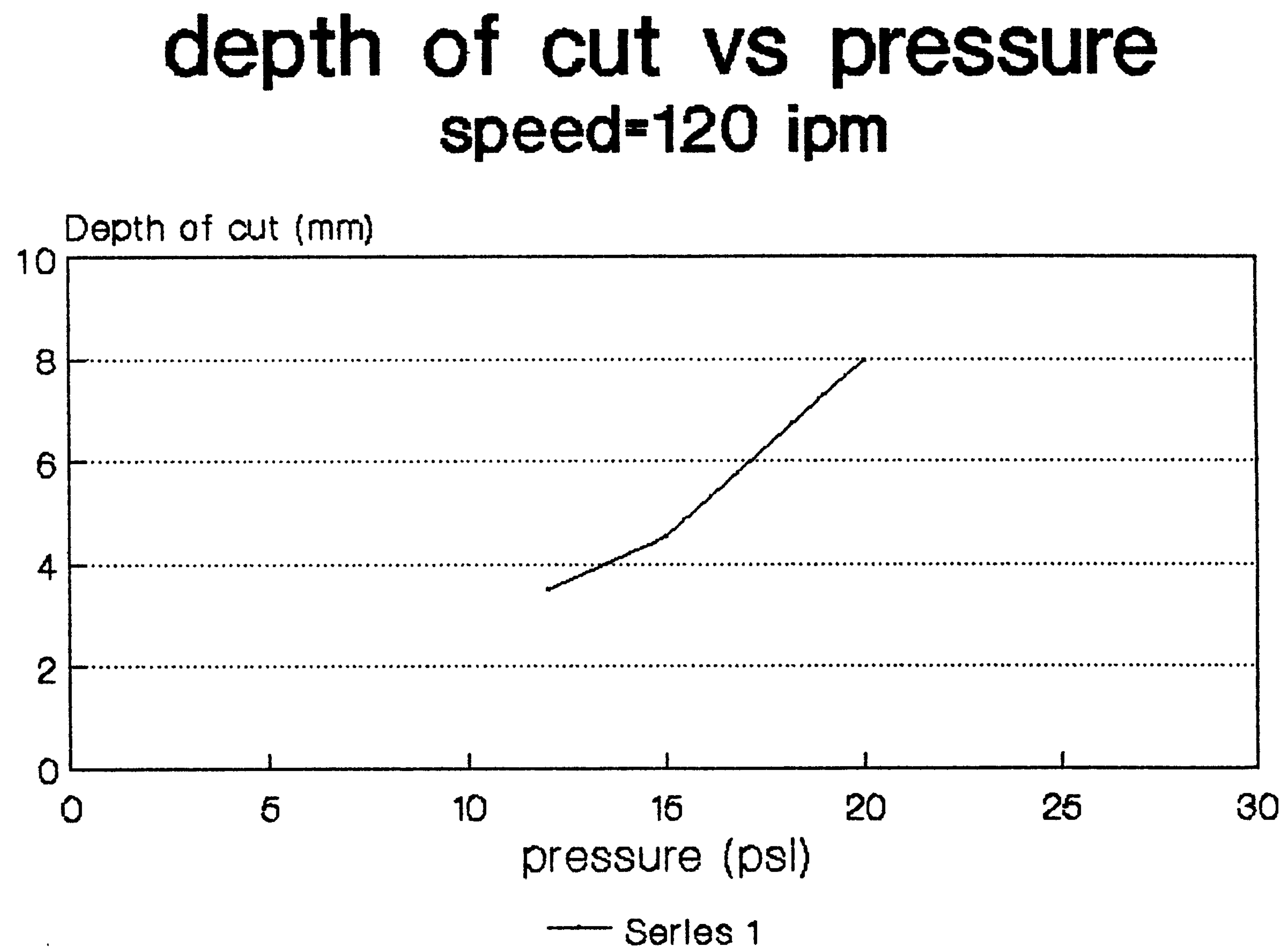
stand off = 2mm

Fig 8



stand off = 2mm

Fig 9



stand off = 2mm

Fig 10

MATRIX VIDEOMETRIX

TOPO TM

TOPO Summary

Report Date: 13 Mar 1991 Report Time: 14:51:13

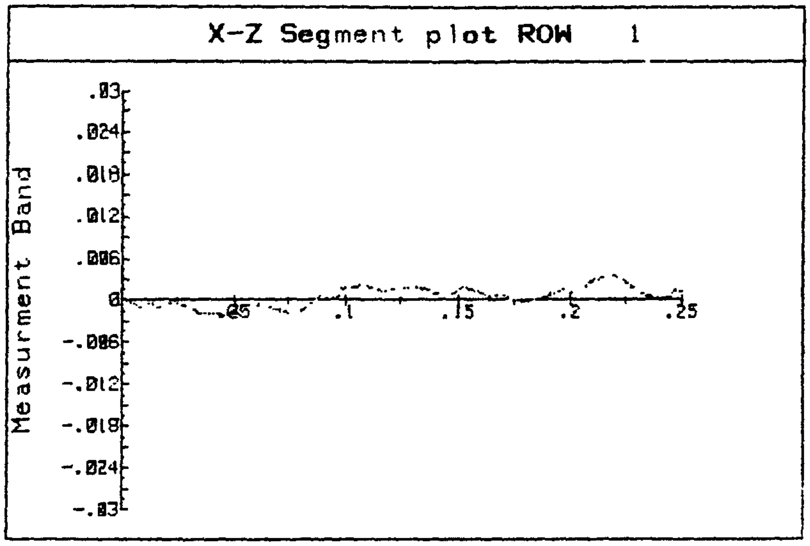
Program Name: SHIV

TOPO Date: 6 Mar 1991

TOPO Time (START): 10:16:47
(STOP): 15:15:52
(ELAPSED): 04:59:04

TOPO Objective: 5X
Units: IN

	X	Y	Z
Total axis travel :	.20000	.20000	
# of focus points :	60.00000	60.00000	
Step Increments :	.00339	.00339	
Z point (MIN) :	.14915	.04407	-.00941
(MAX) :	.04746	.09153	.00559
(MEAN) :			.00005


X-Z Segment plot ROW 1
Measurment Band
.03
.024
.018
.012
.006
0
-.006
-.012
-.018
-.024
-.03
.05
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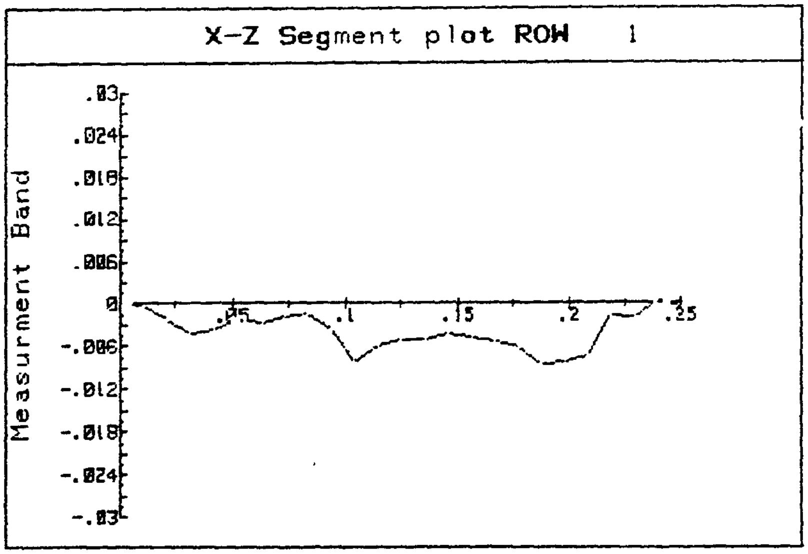
X-Z Segment plot ROW 1
Measurment Band
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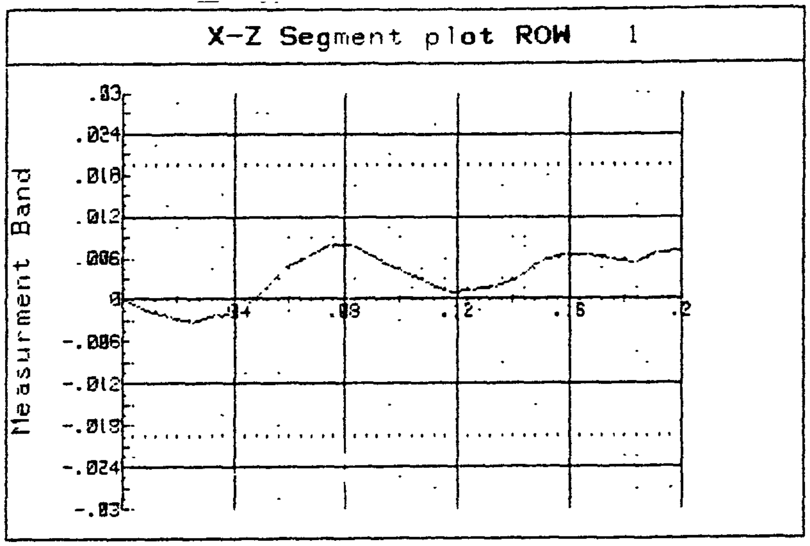
0
-.006
-.012
-.018
-.024
-.03
.05
.1
.15
.2
.25

Fig 11


X-Z Segment plot ROW 1
Measurment Band
.03
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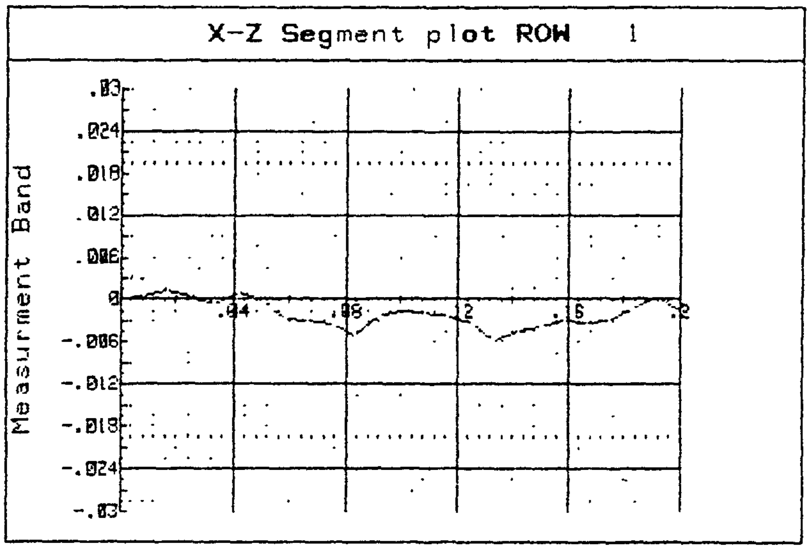
.012
.006
0
-.006
-.012
-.018
-.024
-.03
.04
.08
.12
.16
.2


X-Z Segment plot ROW 1
Measurment Band
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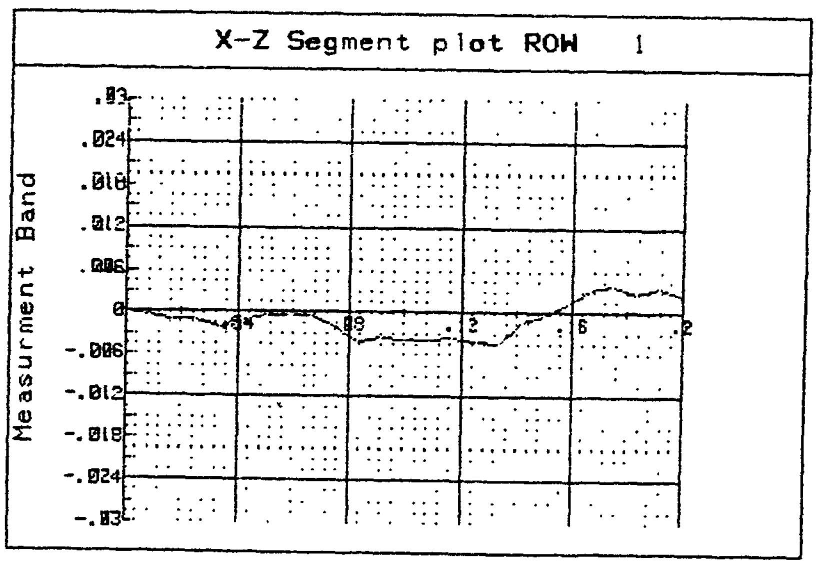
X-Z Segment plot ROW 1
Measurment Band
.03
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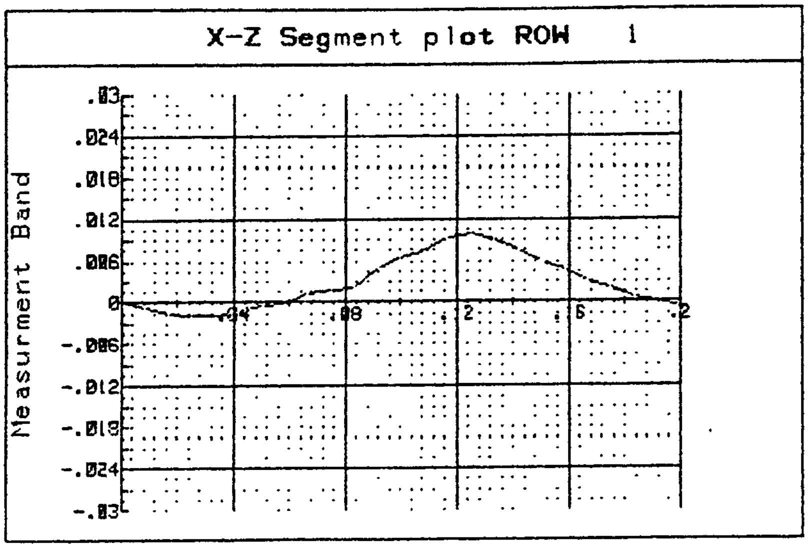
.006
0
-.006
-.012
-.018
-.024
-.03
.04
.08
.12
.16
.2

Fig 12


X-Z Segment plot ROW 1
Measurment Band
.03
.024
.018
.012
.006
0
-.006
-.012
-.018
-.024
-.03
.04
.08
.12
.16
.2

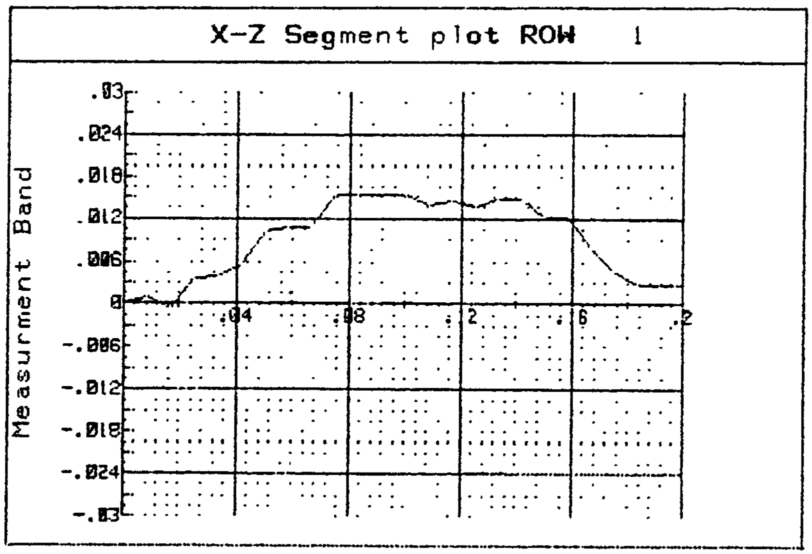

X-Z Segment plot ROW 1
Measurment Band
.03
.024
.018
.012
.006
0
-.006
-.012
-.018
-.024
-.03
.04
.08
.12
.16
.2

Fig 13

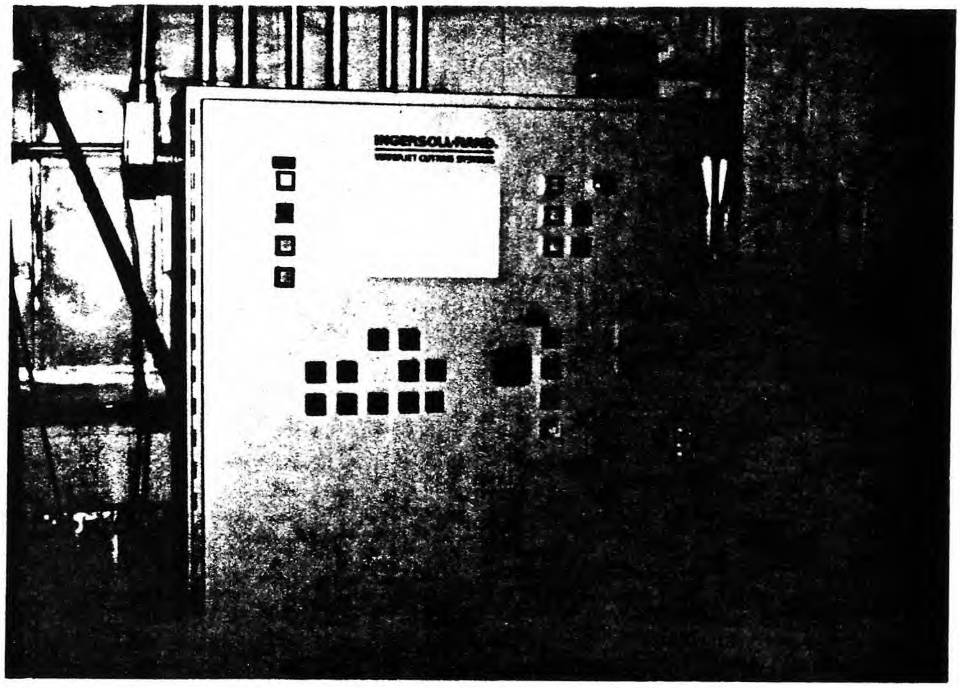


Fig: 14 Controls of Waterjet System

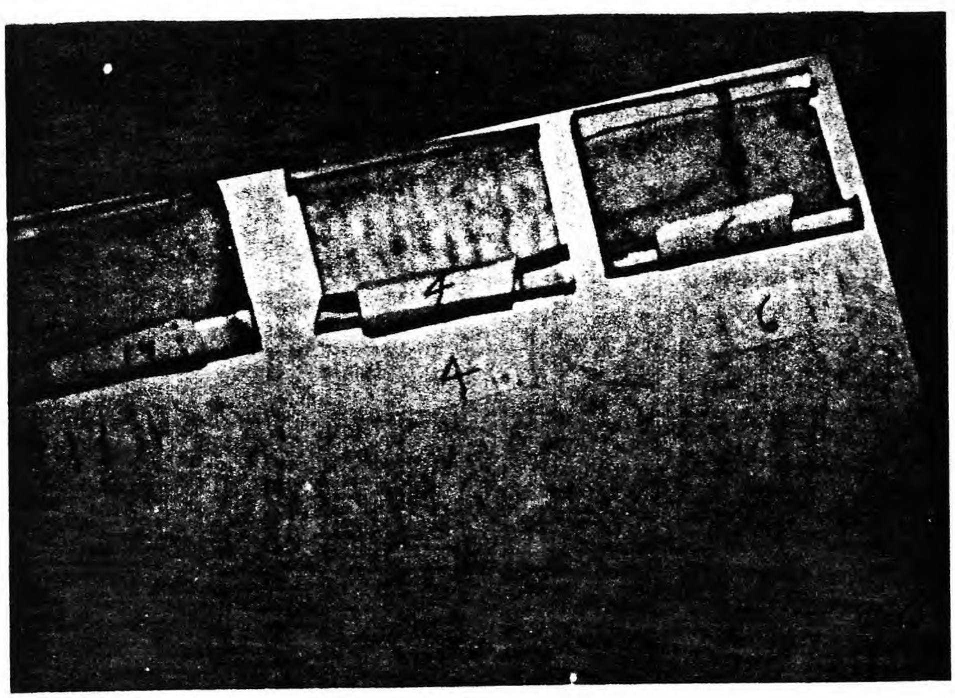


Fig: 15 Glass Samples in Experiment

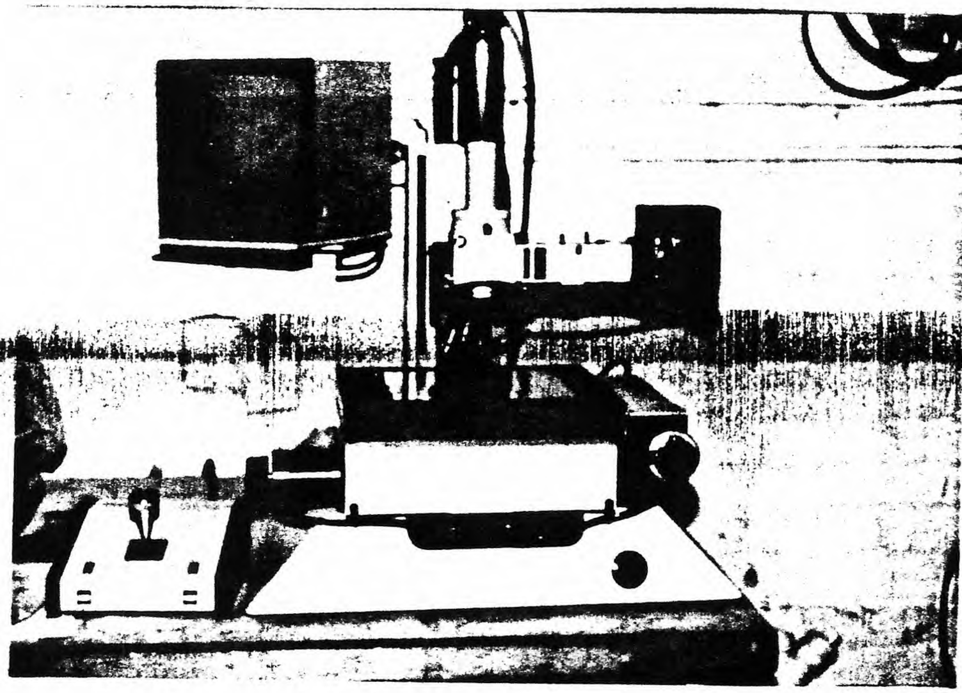


Fig 16. 3 Dimensional Videometrix Econoscope

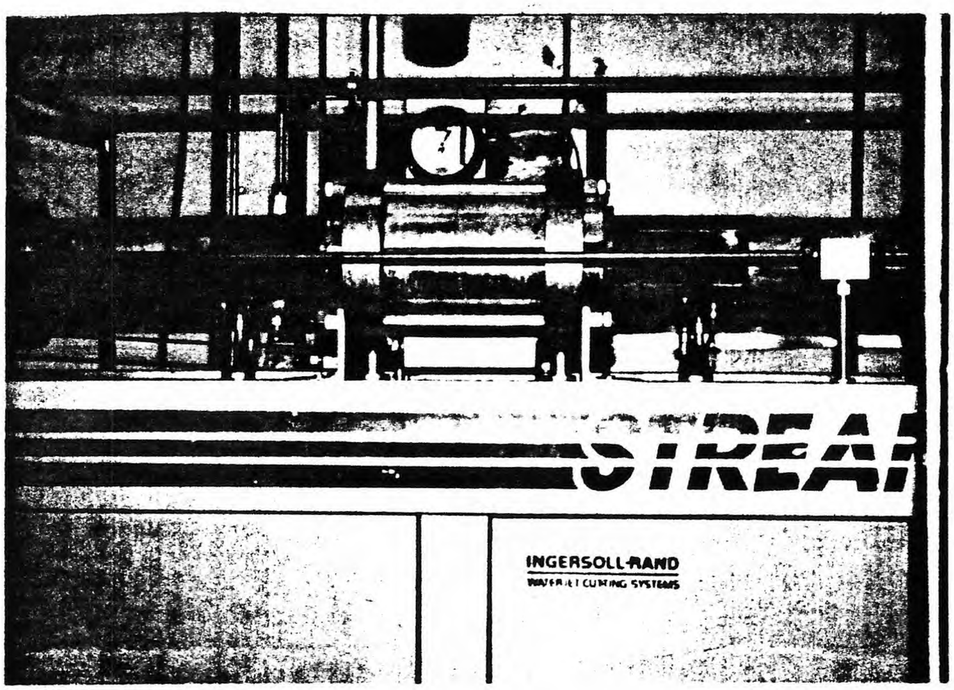


Fig 17. Reciprocating Intensifier / Pressure Unit

CHAPTER 3

DIAMOND MACHINING

Diamond Machining is usually applied to the productions requiring high precision and low roughness surface finish so a tight quality control is always needed. Diamond machining of non-ferrous and plastic materials is finding increasing applications to the situations requiring high precision and low roughness surface finish production, eg. aluminium substrate of computer memory disks, laser optics, etc. The optimization of the machining process may involve two aspects. The first is finding the operating parameters to reduce cutting related surface defects and tool chatter. The second is the monitoring of tool wear to offset tool geometry change during machining. The effect of this optimization can improve the surface finish and part accuracy during the life of a cutting tool.(12)

Diamond Versus Conventional Machining

Diamond machining is characterized by the high precision geometries and surfaces which it can produce. The process is generally performed on a machine tool featuring the following components and accessories: (fig 18)

1) Single-point, gem-quality diamond tools with precise geometric characteristic (i.e free angle, rake angle, face radius)

2) Air bearing spindles and slides

3) A massive granite machine base

4) Vibration isolation mounts

5) Special controls like laser alignments systems, inprocess interferometers, piezoelectric transducers, etc (13).

In addition, machines are normally located in a stable, temperature and humidity controlled environment.

Single crystal and natural diamond cutting tools possess a number of unique properties which enable them to cut surfaces to optical quality finishes. These properties include:

1) extremely high hardness and thus an extremely low wear rate,

2) single crystal structure, which permits sharpening of the cutting edge to a fineness unattainable with multicrystalline or sintered materials,

3) high thermal conductivity, which enables heat to be dissipated away from the tool tip,

4) chemical inertness, which is manifested in the nonerosion characterisitics that retard chip build up common in carbide and other cutting tools,

5) low coefficient of expansion, which ensures the stability of the tool geometry. If the tool geometry were unstable, the surface quality would be adversely affected.

Cost advantages

The diamond machining offers significant cost advantages over other fabrication techniques. Geometry of the part and the number of pieces required is an important factor.

The diamond machining of an aspheric surface involves
three basic steps:

1) Fixture design to properly hold and orient the part to optimize the surface finish and figure accuracy,

2) Preparation of a computer program to accept feedback position signals and provide both tool and part movements which contour or generate the desired surface figure, and

3) The actual micromachining and subsequent inspection of the component.

The following materials are compatible with the diamond machining process: Aluminium, Brass, Zinc, Nylon, Lead, Gold, Silver, Tin, Germanium, Silicon, Magnesium, Bronze etc.

The inability to cut ferrous metals results from a chemical reaction between the diamond and carbon. This reaction causes graphitization and subsequent destruction of the diamond cutting tool. Surface finish and figure accuracy are normally a function of the material being processed and the machine configuration used.

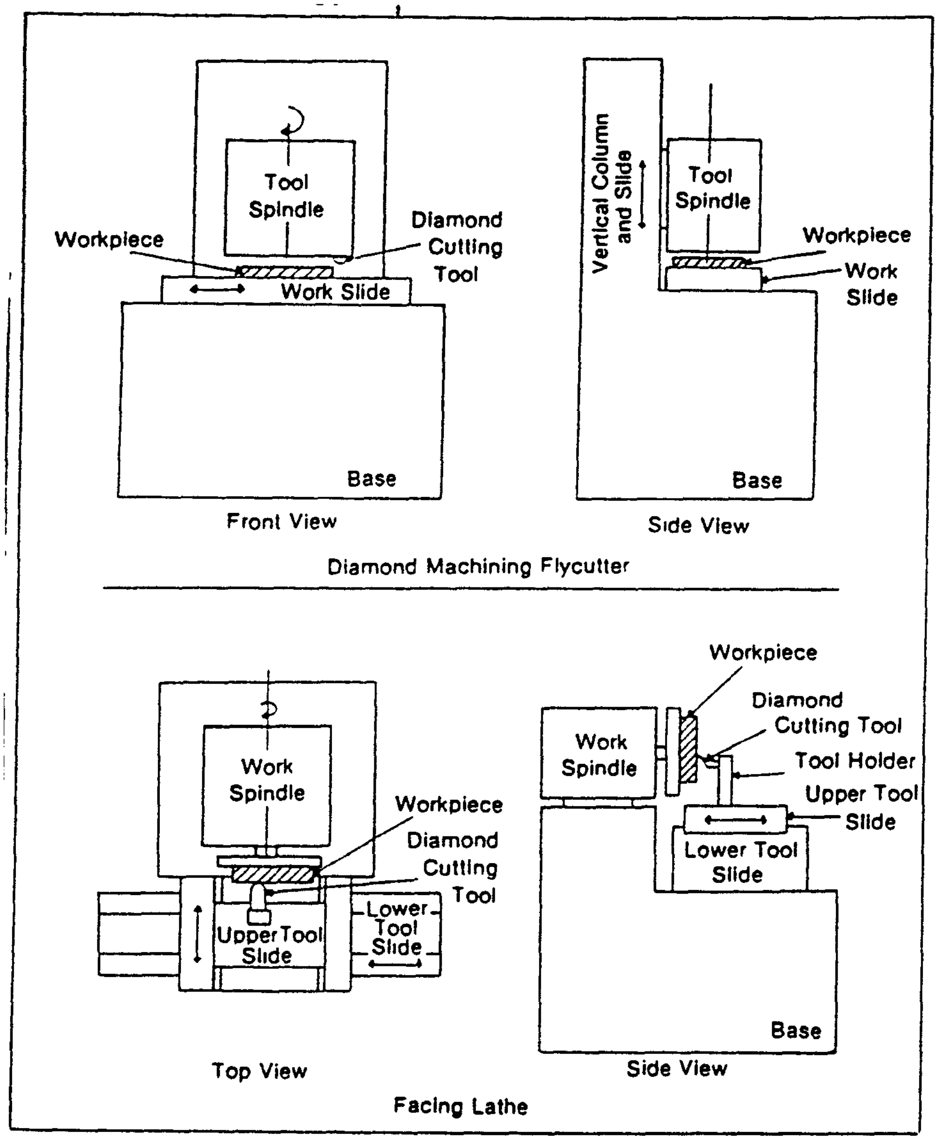


Fig 18

TYPICAL DIAMOND MACHINE CONFIGURATIONS

(Tool & Manufacturing Hand Book)

CHAPTER 4.0

THERMAL METHODS

4.1 ELECTRIC DISCHARGE MACHINING- EDM

Electric discharge machining, sometimes referred to as spark machining is a nontraditional method of removing metal by a series of rapidly recurring electrical discharges between an electrode (the cutting tool) and the workpiece in the presence of a dielectric fluid. Minute particles of metal or chips, generally in the form of hollow spheres, are removed by melting and vaporization and are washed from the gap by the dielectric fluid which is continuously flushed between the tool and workpiece.(1)

The workpiece which constitutes one of the electrodes between which the sparks occur, must be of electrically conductive materials. The other electrode (tool) which also must be made of electrically conductive material is located in close proximity to but not in contact with the workpiece during cutting.(fig 19)

Principles of Operation

The removal of material in electrical discharge machining is based upon the erosion effect of electric sparks occurring between two electrodes. The theory best supported by experimental evidence suggests that metal removal in EDM operations takes place as a result of the generation of extremely high temperature generated by the high intensity of the discharge current. The discharge mechanism can be explained by diving it into different phases and stages. The first phase, known as the preparatory phase, lasts only a very limited time . During this phase, the powerful electric fluid ionizes the dielectric medium and thus forms a high conductivity channel. The second phase is characterized by the discharge itself in the form of a heavy flow of current similar to an avalanche of electrons. The third phase is the ejection of the eroded metal which may start during the second phase and may continue even after the end of discharge.

Dielectric Fluids

A dielectric fluid must meet the following three requirements to ensure optimum performance in an EDM operation:

1) The fluid must insulate until the required conditions are achieved between the electrode and workpiece, and then it must act as a conductor,

2) The fluid must cool the workpiece, electrode, and chips, and

3) The fluid must flush the particles out of the spark gap.

Method of dielectric distribution: The several methods of introducing dielectric fluid to the arc gap fall into four broad classifications:

1) Normal flow,

2) Reverse flow,

3) Jet flushing, and

4) Immersion flushing.

Typical dielectric fluids:

Petroleum based hydrocarbon mineral oils are used as the dielectric fluid for most EDM applications. The oils should have a high flash point and very low viscosity.

Spark gap and overcut. Typical spark gap used in EDM operations is usually between 0.0005-0.005". Overcuts range between 0.0002-0.020"/side. Overcut, the distance by which the machined hole in a workpiece exceeds the electrode size, is determined by the initiating voltage discharge energy and clarity of the dielectric fluid. As discharge energy is increased, the overcut increases.

Material removal rate. Stock removal rate varies from as little as 0.001 in 3/hr or less for precision machining with smooth surface finishes to 15 in 3/hr or more for rough machining with coarser surface finishes. Metal removal rates are nearly a direct function of current amperage, higher amperage removes more stock but produces rougher surface finishes.

Equipment and Tools

Electrode materials: the EDM tool electrode is the means by which electric current is transported to the workpiece.

1) Graphite electrodes: graphite has become the predominant material for EDM electrodes.

2) Copper electrodes: Copper works well as an electrode material. The materials is normally pure copper or an electrolytic grade copper. While copper machines quite easily, problems do occur with regard to wheel loading when grinding operations are required. Copper is most often used when the smoothest surface finishes are required.

Electrode rotating and Orbiting EDM

The need for improved flushing techniques in certain EDM applications contributes to the development of electrode rotating and electrode orbiting devices. Electrode rotating is generally used for small hole work while electrode orbiting is most useful for contoured cavities and for fine finishing.(19)

Product Applications

With the increasing use of hard, difficult to machine space age metals, EDM's ability to machine burr free, intricate configurations, narrow slots, and blind cavities or holes into these materials, at close tolerance, becomes more important. Since EDM does not set up the high cutting forces and mechanical strains often associated with conventional machining, the process is well suited for cutting tubing, honeycomb, and other thin wall, fragile structures.(16)

One well established application of EDM is in machining die cavities and molds used for die casting, plastic molding, wiredrawing, extrusion, compacting, cold-heading, and forging. Another important application of EDM is in the metal forming field to produce punch, trim, or stamping dies. Another use of EDM which has proved to be economical in many companies, is for salvage work on worn forging dies.(14)

Surface quality damage or deterioration due to machining operations is directly related to the amount of force used to remove the material and the time allowed for the process. The greater the amount of material removed and the shorter the time allowed for the cut, the more extensive the damage. The more stringent the required surface integrity, the longer the operation will take, be it on an EDM unit or by a more traditional method. The resultant surface integrity that can be produced by a modern EDM die sinking unit is a direct result of proper use of the sophisticated power controls and making necessary preparations to assure that damaged material is removed and reliable workpieces created.(15)

Submerged wire cutting: All of the Japanese EDM builders are now offering submerged cutting on wire machines. The primary advantage of submerged cutting is enhanced accuracy although cutting speed and surface finish may show significant improvement at the same time. As the term suggests, the wire guides and workpiece fixturing are contained in a tank filled with dielectric fluid and cutting occurs under the fluids surface. By cutting under water, flushing tends to be more uniform and thermal stability is easier to achieve. However, it is considerably more expensive.

Advantages: Extremely high popularity of the EDM process is due to the following advantages:

1) The process can be applied to all electrically conducting metals and alloys irrespective of their melting points, hardness, toughness or brittleness.

2) Any complicated shape that can be made on the tool can be reproduced on the workpiece.

3) Highly complicated shapes can be made by fabricating the tool with split sectioned shapes, by welding, brazing or by applying quick setting conductive epoxy adhesives.

4) Time of machining is less than conventional machining processes.

5) EDM can be employed for extremely hardened workpiece. Hence, the distortion of the workpiece arising out of the heat treatment process can be eliminated.

6) No mechanical stress is present in the process. It is due to the fact that the physical contact between the tool and the workpiece is eliminated. Thus, fragile and slender workpieces can be machined without distortion.

7) Cratering type of surface finish automatically creates accommodation for lubricants causing the die life to improve.

8) Hard and corrosion resistant surfaces, essentially needed for die making can be developed.(17)

Disadvantages: The following disadvantages of the process limit its application:

1) Profile machining of complex contours is not possible at required tolerances,

2) Machining times are too long,

3) Machining heats the workpiece considerably and hence causes change in surface and metallurgical properties,

4) Excessive tool wear, and

5) High specific power consumption.(2)

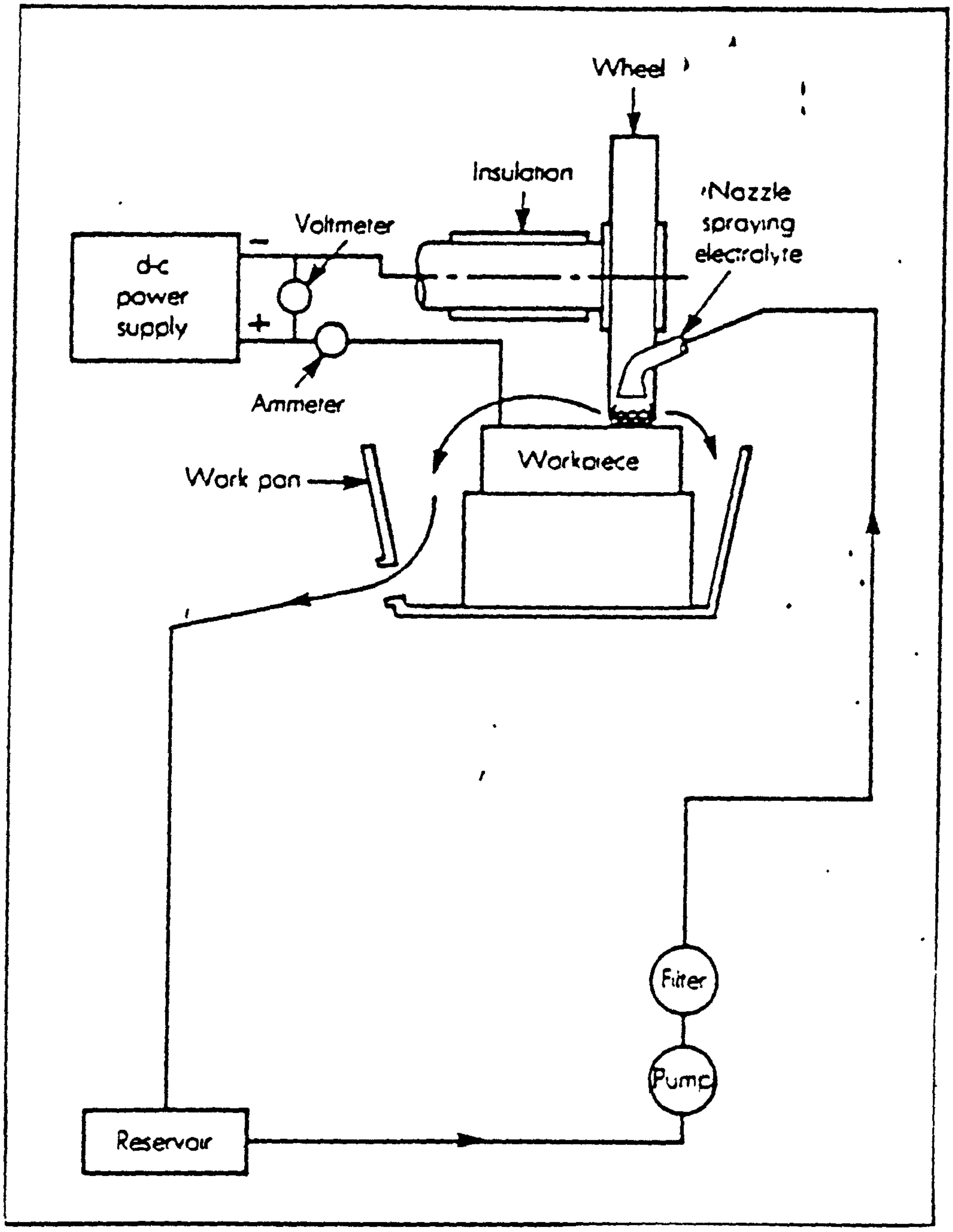


Fig 19

Fig: Components of an Electrical Discharge Machine (EDM)

(Tool & Manufacturing Hand Book)

4.2 ELECTRON BEAM MACHINING - EBM

Electron beam Machining uses electrical energy to generate thermal energy for removing material. A pulsating stream of high speed electrons produced by a generator is focused by electrostatic and electromagnetic fields to concentrate energy on a very small area of work. High power beams are used with electron velocities exceeding half the speed of light. As the electrons impinge on the work, their kinetic energy is transformed into thermal energy and melts or evaporates the materials locally.

Electron beams are concentrated on spots as small as 0.0002 diam. The process is usually performed in a vacuum as shown schematically in figure 20. A vacuum is used both to prevent collisions of electrons with gas molecules which would scatter or diffuse the beam, and to protect the workpiece from oxidation and other atmospheric contamination. Lead shielding is required to protect the operator from X-ray radiation produced by the electron beam.(1)

Principles of Operation: When electrons impinge upon a solid material at a certain speed, their kinetic energy is immediately translated into thermal energy. The material can be heated, melted or vaporized. In removing material by electron beam machining one of two different mechanisms is employed. The material is either totally evaporated, or it is simply melted. Then the liquid phase is taken away by additional forces such as centrifugal forces. In general, a combination of melting and evaporation is used in such a way that generated vapor pressure acts as additional force that assists in ejecting the liquid material. As in the case of electron beam welding the pulsed beam also creates a highly dynamic cylindrical zone of molten material. Because of the high power density in a beam such as this, the vapor pressure within the column of molten material increases so much that the material is ejected in a sudden burst.

Applications:

Any known material, metal or nonmetal, which will exist in high vacuum can be cut, although experience has shown that diamonds do not cut well. Holes with depth to diameter ratios up to 100:1 can be cut. Limitations include high equipment costs and the need for a vacuum, which usually necessitates batch processing and restricts workpiece size. The process is generally economical only for small cuts in thin parts.

Typical applications of EBM include:

1. Drilling gas orifices for pressure differential devices, in which closely dimensioned holes must be drilled through the part. These holes regulate the amount of gas that flows in a given amount of time.

2. Producing wire drawing dies, light ray orifices, and spinnerets to produce synthetic fibers.

3. Producing metering holes, either round or profile shaped, to be used as flow holes on sleeve valves, rocket fuel injectors or injection nozzles on diesel engines.(20)

Operating parameters: Power EBM operations are performed at voltages ranging from 50-150 KV. The beam current is usually between 0.1-1.0 MA. Power requirements are on the order of 0.5-60 KW.

Cut characteristics: The narrowest cut attainable with EBM operations is on the order of 0.001" when cutting material of 0.0001" thickness. The maximum depth of cut is usually about 0.25".

Tolerances: Electron beam machining is capable of holding tolerances on hole size to about 0.0001" although in special cases, tolerances of 0.0002 can be held.

Advantages and limitations: EBM is an excellent method for micro finishing. It can drill holes or cut slots which otherwise cannot be made. It is possible to cut any known material, metal cannot be made. It is possible to cut any known material, metal or nonmetal that can exist in vacuum. Besides there is no cutting tool pressure or wear. As a result, distortion free machining having precise dimensions can be achieved. The biggest disadvantage is the high equipment cost and employment of high skill operator. Besides, only small cuts are possible. Further, requirements of vacuum restrict the size of specimens that can be machined.(2)

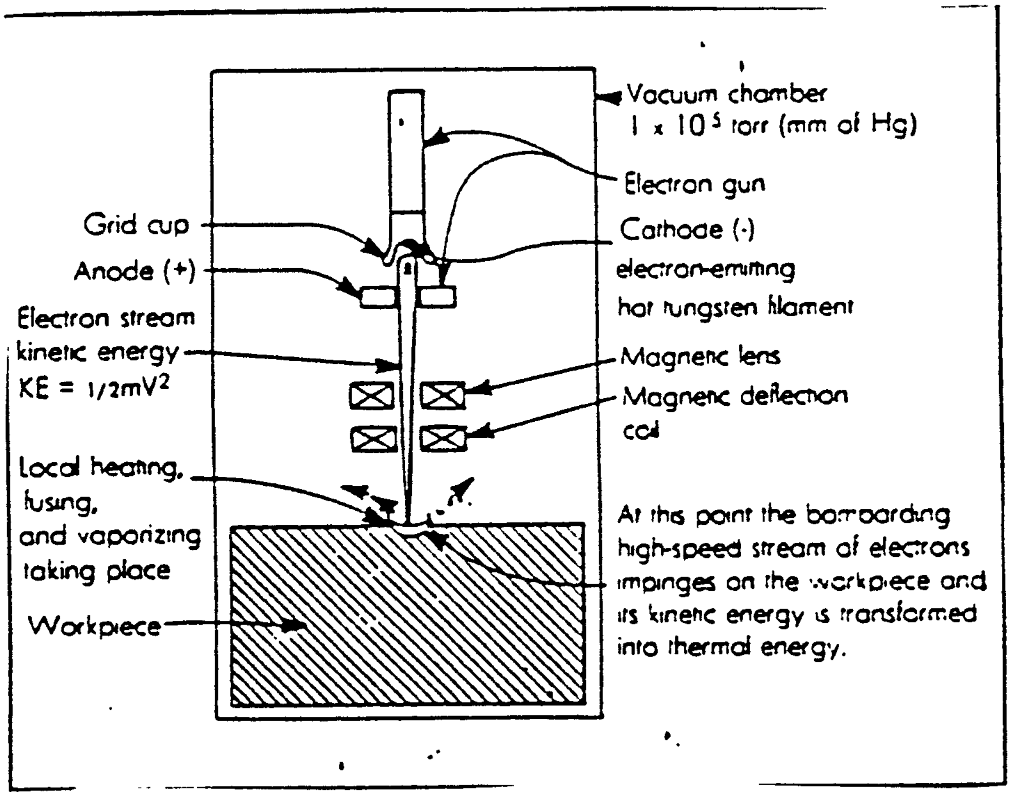


Fig: 20 Elements of an Electron Beam Machine (EBM)

(Tool & Manufacturing Hand Book)

4.3 LASER BEAM MACHINING

The increased power output of lasers has opened up growing number of applications where the technology could represent a productivity and/or product quality advantage over conventional processing techniques. There are 15,000 materials processing lasers in use worldwide. Currently, they are being installed at the rate of approximately 3000 per year for applications such as cutting, welding, drilling, surface modification, marking, soldering, and sealing.(ref.18)

The word LASER is an acronym: Light amplification by stimulated emmission of radiation.

A device that generates a beam of coherent radiation in the infrared, visible or ultraviolet part of the electromagnetic spectrum by means of a quantum mechanical process called Stimulated Emission.

Principles of Operation: Laser beam machining is based on the conversion of electrical energy into light energy and then into thermal energy. Although several types of lasers exist, all lasers produce an intense, coherent, highly collimated beam of single wavelength light. In material processing applications, this narrow beam is focused by an optical lens to produce a small, intense spot of light on the workpiece surface. Optical energy is converted into heat energy upon impact, and temperatures generated can be high enough to melt and/or vaporize any material. (fig 21). Lasers can be classified as solid state, gas, or liquid lasers. In a typical laser system, electrical energy is converted into light via excitation of a lasing medium. Solid state and liquid lasers are excited by xenon, krypton, or tungsten-halogen flashlamps which illuminate the lasing medium as shown in fig x. Gas lasers are driven by direct electrical (d-c,a-c, or RF) excitation of the gas, usually at low pressure.

In the case of a CO2 laser, the lasing medium is a mixture of CO2, N, and He gases; (ref.1)

Cutting a material with a laser generally is done by intiating a hole through the material and then moving either the focused beam or the workpiece as the laser is operated.

Lasers are being employed to drill holes in stainless steel tubing. Typical product applications are as under:

1) In the garment industry: the cutting of patterns from single-ply or multilayer stacks of fabrics can be fully automated and accomplished at a rate of upto 2,400 in. per minute.

2) Dynamic balancing of gyrorotors, watch or clock balance wheels, or precision rotating parts: high-speed balancing is accomplished by vaporizing away excess metal as the part rotates on the balancing machine.

3) Marking or engraving: numerically controlled or computer-controlled data in the form of coded information or special numbers may be applied to various workpiece materials.(17)

Dimensional accuracy in the order of $\pm$ 0.0254 mm. can be obtained under closely controlled conditions.

The advantages of Laser beam machining are:

1) Any solid material which can be melted without decomposition can be cut with the laser beam,

2) Heat affected zone is small because of the collimated beam, and

3) Extremely small holes can be machined.

The limitations of this process are:

1) Cannot cut metals that have high heat conductivity or high reflectivity, eg., Al, Cu, and their alloys,

2) Life of the flash lamp is short,

3) Low material removal rate, and

4) Process limited to thin sheets.(2)

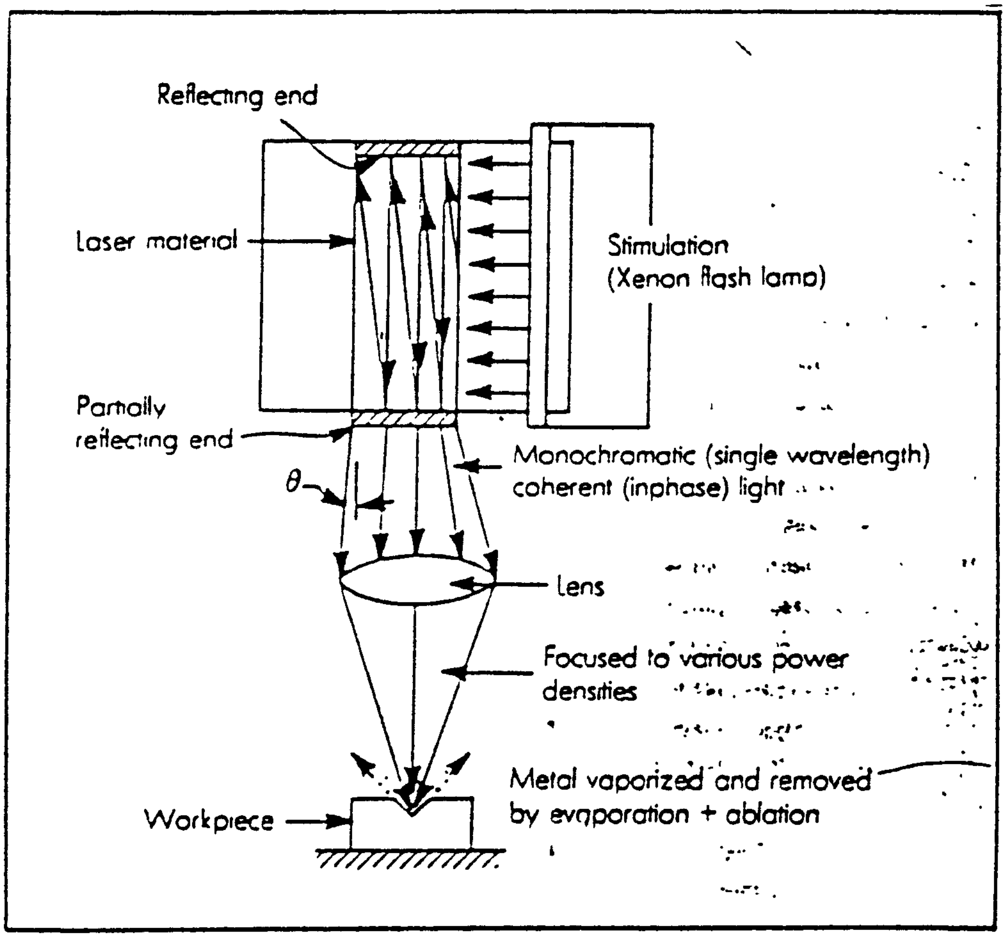


Fig:21 Setup of Pulsed solid state Laser Beam Machining

(Tool & Manufacturing Hand Book)

Selected Laser Applications	
Type of Process	**Typically Used Lasers**
METAL CUTTING	PULSED AND CONTINUOUS-WAVE CO_2, RUBY, ND:YAG
METAL WELDING	PULSED AND CONTINUOUS-WAVE CO_2, ND:YAG, ND:GLASS, RUBY
METAL DRILLING	PULSED CO_2, ND:YAG, ND:GLASS, RUBY
METAL ANNEALING/HEAT TREATING	CONTINUOUS-WAVE CO_2
PLASTIC CUTTING	CONTINUOUS-WAVE CO_2
CERAMIC CUTTING	PULSED CO_2
SOLDERING	PULSED ND:YAG
CERAMIC SCRIBING	PULSED CO_2
METAL MARKING	PULSED CO_2, ND:YAG
PLASTIC SEALING	CONTINUOUS-WAVE CO_2
PHOTORESIST REMOVAL	EXCIMER
METAL SURFACE ALLOYING	CONTINUOUS-WAVE CO_2, ND:YAG
TRANSFORMATION HARDENING	CONTINUOUS-WAVE CO_2
METAL SURFACE TEXTURIZING	PULSED CO_2
RESISTOR TRIMMING	ND:YAG, CO_2
SEMICONDUCTOR FABRICATION	EXCIMER, ND:YAG
PLASTIC DRILLING	EXCIMER
PLASTIC/CERAMIC MARKING	EXCIMER

4.4 PLASMA ARC MACHINING

Plasma is defined as a gas that has been heated to a sufficiently high temperature to become partially ionized and therefore electrically conductive. The term Plasma, as employed in physics, means ionized particles. This phenomenon may be likened to a streak of lightning which ionizes the gases of the atmosphere and heats them to incandescence. The temperature of plasma may reach as high as 50,000 F. Various devices utilizing an electric arc to heat gas to the plasma state have been in existence since the early 1900's. However, the development of such apparatus into commercial plasma arc equipment for metalcutting applications dates back to only about 1955.

The plasma arc produced by modern equipment is generated by a plasma torch that is constructed in such a manner as to provide an electric arc between an electrode and workpiece as shown in fig 22. A typical plasma torch consists of an electrode holder, an electrode, a device to swirl the gas, and a water-cooled nozzle. The "swirler" which may be ceramic, encircles the lower portion of the electrode, serving to stabilize the gas flow and thus preventing gas turbulence. The geometry of the torch nozzle is such that the hot gases are constricted in a narrow column.

Primary gases, such as nitrogen, argon-hydrogen, or air, are forced through the nozzle and arc and become heated and ionized. Secondary gases or water flow are often used to help clean the kerf of molten metal during cutting.(1)

The stream of ionized particles from the nozzle can be used to perform a variety of industrial jobs. The plasma arc as an industrial tool is most heavily employed ref.in sheet and plate cutting operations as an alternative to more conventional oxyfuel torches. Plasma arc is routinely used as an integral component of some modern punching machines.

Operating Parameters

Cutting: Quality of cut and metal removal rate are largely dependent upon proper attention to operating variables. Several factors contribute to the quality and speed of cuts made by the plasma arc process, including cutting-tip nozzle selection, power level, gas type and mixture, gas flow rate, traverse speed, standoff distance, thickness of material, type of material, impingement angle, and equipment design.

Nozzle size: The highest quality plasma cut is usually obtained when maximum thermal intensity is used. To achieve this, the smallest, or next to the smallest, nozzle size that is capable of operating at a power level suitable for the speed and thickness involved is used.

Power: Direct current up to 200 KW and 50-1000 A is employed in plasma arc cutting operations.

Accuracy: This is a roughing operation to an accuracy of about 1.5 mm with corresponding surface finish. Accuracy on the width of slots and diameter of holes is ordinarily from $\pm$ 0.8 mm on 6 to 30 mm thick plates, and $\pm$ 3.0 mm on 100 to 150 mm thick plates.

Advantages and Limitations: The principal advantage of this process is that it is almost equally effective on any metal, regardless of its hardness or refractory nature. There is no contact between the tool and workpiece and only a simply supported workpiece structure is enough.(21) The main disadvantages of this process are the metallurgical change of the surface. Safety precautions are necessary for the operator and those in near-by areas. This adds additional cost.(17)

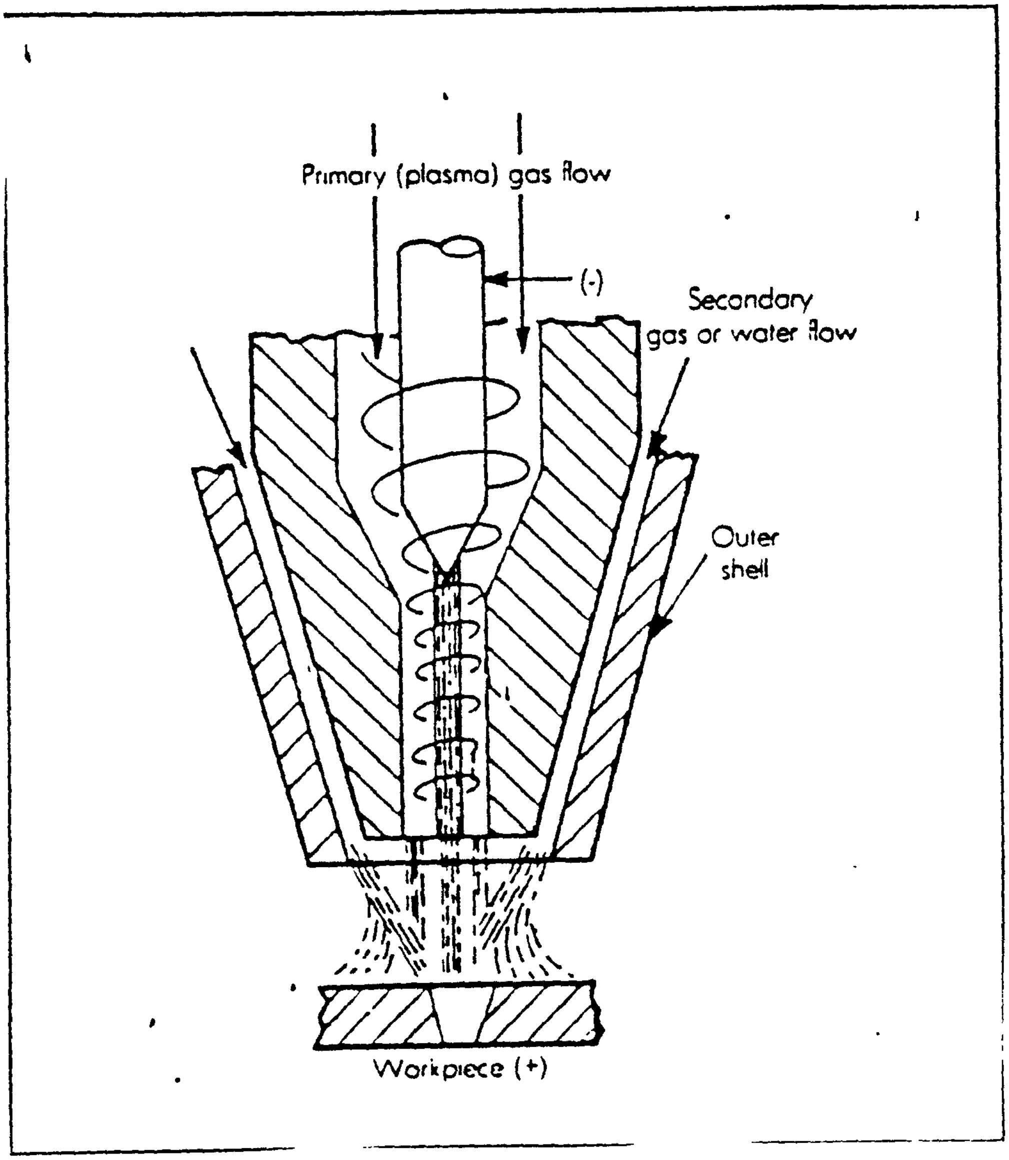


Fig:22 Configuration of a Plasma Arc Torch

Tool & Manufacturing Hand Book)

CHAPTER 5

MECHANICAL METHODS

5.1 ULTRASONIC MACHINING

Ultrasonic machining, sometimes called ultrasonic abrasive machining, is a mechanical nontraditional machining process by which workpiece material is removed and an exact shape is imparted to the workpiece surface via the cutting action of an abrasive slurry that is driven by a tool vibrating at high frequency in line with its longitudinal axis. As shown in fig 23, the cutting tool is attached to a vibrating horn. The tool is shaped in the exact configuration to be ground in the workpiece. In this way, the vibration of the tool forces the cutting action of the abrasive grits in the slurry. The slurry is recirculated in the space between the tool and workpiece. In most applications, the slurry is automatically cooled in the recirculation cycle.(1)

Workpiece Materials

USM employs a "chipping" mechanism to remove material. For this reason, materials which succumb to brittle fracture are the best candidates. However, the process is effective on both hard and soft materials. Harder materials are cut by brittle fracture due to the action of the abrasive and the vibrating tool. Softer materials are cut effectively because of a tendency of the abrasive grit to become imbedded in the material by plastic deformation.

Typical applications: USM is used to produce blind and through holes, slots, and irregular shapes, limited in complexity only by the configuration of the tooling. However, in some applications, tool wear and/or taper in the cut may discount the process's effectiveness.

Process Selection Factors

Surface Finish: The process can produce finishes of 10u in. depending upon the workpiece material, size of the abrasive particles, tool amplitude, and finish of the tool face.

Tolerances: precision depends to a large extent upon the size and finish of the tool that is used. Tolerances within $\pm$ 0.0005 in. can be obtained using special precautions.

Sharp corners: A finishing tool must be used if sharp corners are required. Corners have a tendency to chip at the exit end of holes unless the workpiece is cemented to a backing material.

Removal Rate: Important factors that affect the volume of material removed per unit of time are the size and nature of the abrasive grit used, and the hardness density and brittleness of the workpiece material.

Hole Sizes: Drilling operations can be accomplished on workpieces in sizes ranging from 1.02 to 38.1 mm in diameter, but holes as small as 0.08 to 0.15 mm in diameter have been successfully produced on experimental work.

Possible Limitations

Removal Rate: USM is not competetive with conventional machining operations on the basis of stock removal rates.

Sidewall Taper: It is not possible to ultrasonically machine parallel walls in deep holes or cavities. As an example, the taper may exceed 0.005 in./in. of depth on some operations. Sidewall taper exists because of two conditions: first, there is tool wear, which is greatest at the lower end and along the sides of the tool face. Second, a condition known as "secondary" impact occurs in the gap between the tool and the workpiece. The amount of taper associated with a given operation may generally be determined by trial runs. In most cases, taper may be almost entirely eliminated by using a finishing tool.(25)

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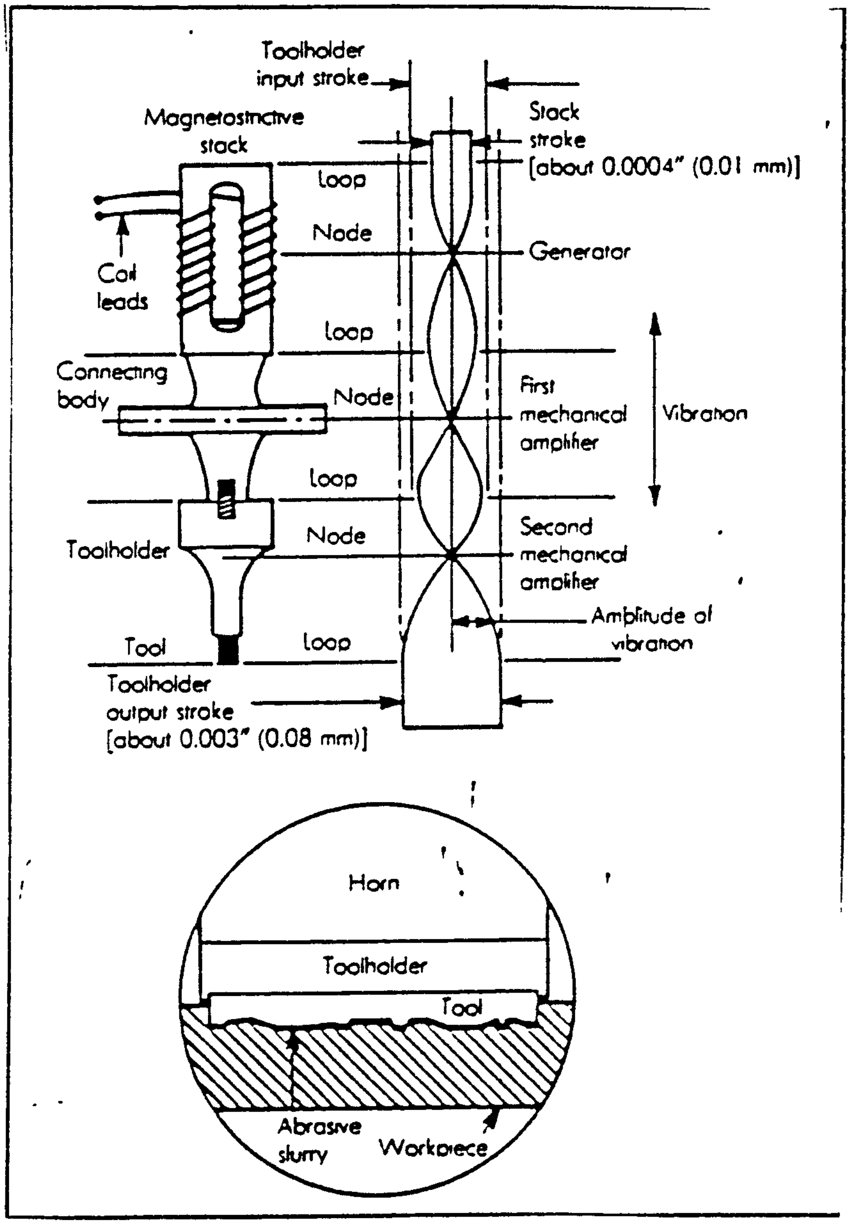

Fig:23 Ultrasonic Machining Setup

(Tool & Manufacturing Hand Book)

5.2 ELECTROMECHANICAL MACHINING

Electromechanical machining is an experimental nontraditional process that enhances the capabilities of traditional machining operations such as drilling and turning. Metal removal is effected in a conventional manner using standard equipment and tooling except that the workpiece is electrochemically polarized. A controlled voltage is applied across the interface of the workpiece and an electrolyte. In drilling operations, the workpiece is submerged in a bath of electrolyte; in turning operations, the surface of the workpiece is flooded with electrolyte.

The principle of EMM is that when the applied voltage is closely controlled and the electrolytic solution is matched to the workpiece material, the surface of the workpiece can be changed to achieve favorable characteristics which will enhance machining performance. When the variables in the process are controlled, the workpiece surface can be changed from passive (oxide film on the surface) to active dissolution (surface being slowly dissolved) to hydrogen reduction (surface is discharging hydrogen ions).

The theory behind EMM is that relatively soft and work harenable materials are more easily cut when the work surface is passive. In this state, the workpiece suface is hardened by the presence of oxide film which also minimizes cutting friction. On the other hand, hard materials are more easily cut when the workpiece surface is in the active dissolution region in which the material is softened.
EMM is considered to be in the early stages of development. The limited feasibility of electromechanical turning and electromechanical drilling has been demonstrated in both laboratory and plant settings. The limited testing conducted to date indicates advantages of surface finish, tool wear, hole tolerance, and chip configuration. However, maximum improvement is tied closely to the optimization of electrolytes,

and it has been shown that the electrolytes should be modified through the use of inhibitors to minimize corrosion of machine tool components.(24)

CHAPTER 6

ELECTRICAL METHODS:

6.1 ELECTOCHEMICAL MACHINING

The term electrochemical machining is often used to describe a broad classification of nontraditional machining and finishing metal removal processes that employ electrolytic action.

Electrochemical machining is a widely employed method of removing metal without the use of mechanical or thermal energy. Electric energy is combined with a chemical to form a reaction of reverse plating. Direct current at a relatively high amperage and low voltage is continously passed between the anodic workpiece and cathodic tool (electrode) through a conductive electrolyte. At the anode surface, electrons are removed by the current flow, and the metallic bonds of the molecular structure of the surface are broken. These surface atoms go into solution as metal ions.(1)

Simultaneously, positive hydrogen ions are attracted to the negatively charged surface and emitted at the cathode surface to form hydrogen atoms, which combine to form hydrogen molecules. Dissolved material is removed from the gap between the work and tool by the flow of electrolyte, which also aids in carrying away the heat and hydrogen formed. Exposure of the workpiece to hydrogen is thus reduced. As shown schematically, in fig 24, ECM operations require:

1) A cathode tool prepared with an approximate mirror image of the configuration to be machined into the workpiece.

2) A workpiece and means to hold and locate it in close proximity to the tool.

3) A means of supplying the gap between the tool and workpiece with pressurized, flowing, conductive liquid (electrolyte).

The overall machining rate is governed by faraday's laws of electrolysis which state (i) that the amount of chemical change produced by current is proportional to the quantity of electricity that is passed through the electrolyte, and (ii) that the amount of metal from an electrode or deposited on to an electrode by the flow of the same quantity of electricity, e.g., one Faraday is equal to one gram equivalent weight of the metal.

Accuracy of ECM: On a good machine, tolerance can be maintained on a production basis in the region of $\pm$ 0.02 to 0.04 mm.

Applications: ECM is used in a wide variety of industries to machine many different metals. Typically, the process is used to machine hard metals, but theoritically it can be used on any electrically conductive metal. Nearly any external shape can be generated with ECM; however, the tooling may be difficult to develop. e.g., Production of turbine blades from a solid disc. The preferred electrode technology for generating internal shapes is forward-flow electrode technology. Electrochemical machining is sometimes used as a sawing process for cutting large billets of hard-to-machine alloys. ECM is used in a wire cutting model.(26)

Advantages:

1) Metal removal rate is quite high for high-strength-temperature-resistant materials,

2) Residual stress is low; depth of work-hardened layer is lower by one-hundredth compared to turning, and

3) Surface finish is in the order of 0.2-0.8 microns.

Limitations:

1) Specific power consumption in this process is nearly 100 times more than in turning or milling steel, and

2) Non conducting materials cannot be machined.

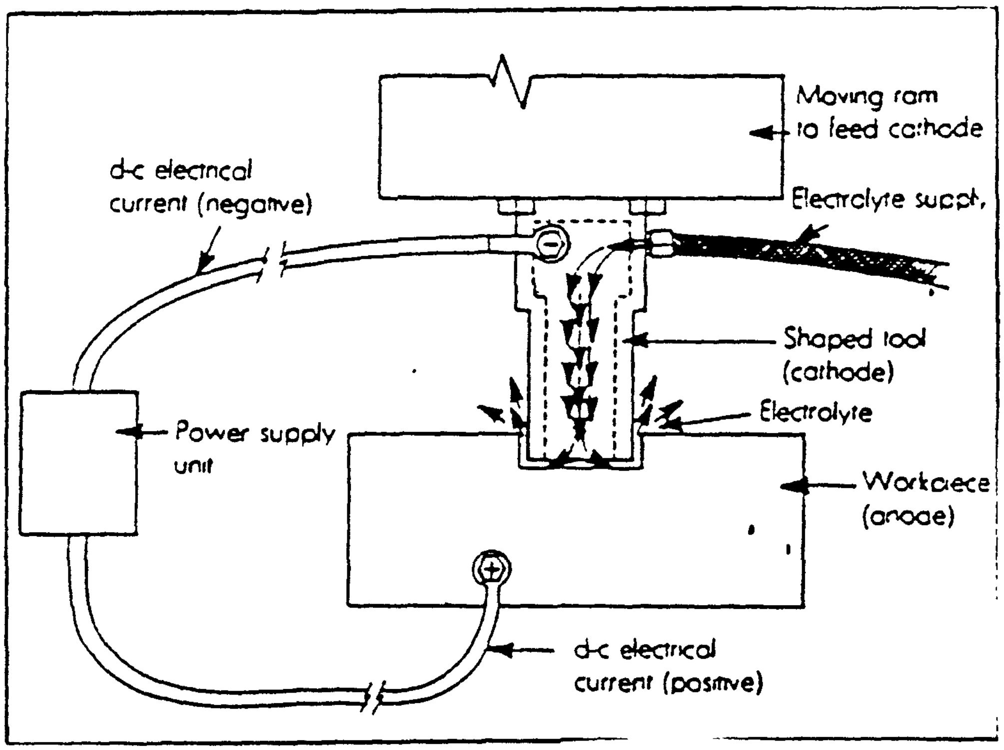

Fig: 24 Schematic of Electrochemical Machining

(Tool & Manufacturing Hand Book)

6.2 ELECTROCHEMICAL GRINDING:

A specific form of electrochemical machining, electrochemical grinding employs the combined actions of electrochemical attack and abrasion to rapidly remove material from electrically conductive workpieces, usually hard, tough materials.

The operating principles of ECG are the same as those of ECM except that ECG employs a rotating grinding wheel. Direct current is passed through an electrolyte which is pumped in a small gap, about 0.03 mm, between the wheel (cathode) and workpiece (anode). In ECG, the majority (98%) of the material is removed by electrochemical attack; significantly less (2%) of the workpiece material is removed by the abrasive action of the wheel. The protruding abrasive particles in the wheel serve to remove electrochemical oxidation on the workpiece surface.(1) (fig 25)

Accuracy: Tolerances of about ± 0.02 are held on rather complex grinding operations. The surface finish is held in the range of 0.2 microns on carbide and 0.4 microns on steel.

Applications: Any material which is electrically conductive may be ground by the electrolytic process, but its most useful application is concerned with hardened steel, cemented carbides, and similar materials. This is mainly applied to resharpening and reconditioning of carbide tools and other materials that are difficult to grind.(22)

Advantages and Disadvantages: The greatest advantages are that all work is completely free of burrs; no heat is developed, so no heat cracks or distortions are developed; and very little pressure is exerted on the work, and practically no wheel wear is found. Besides, higher metal removal rates are possible, particularly upon hard materials.

The major disadvantage is the cost of the ECG system. The metal removal rates are comparitively low being of the order of 15 (mm*3)/s, and power consumption is high.(17)

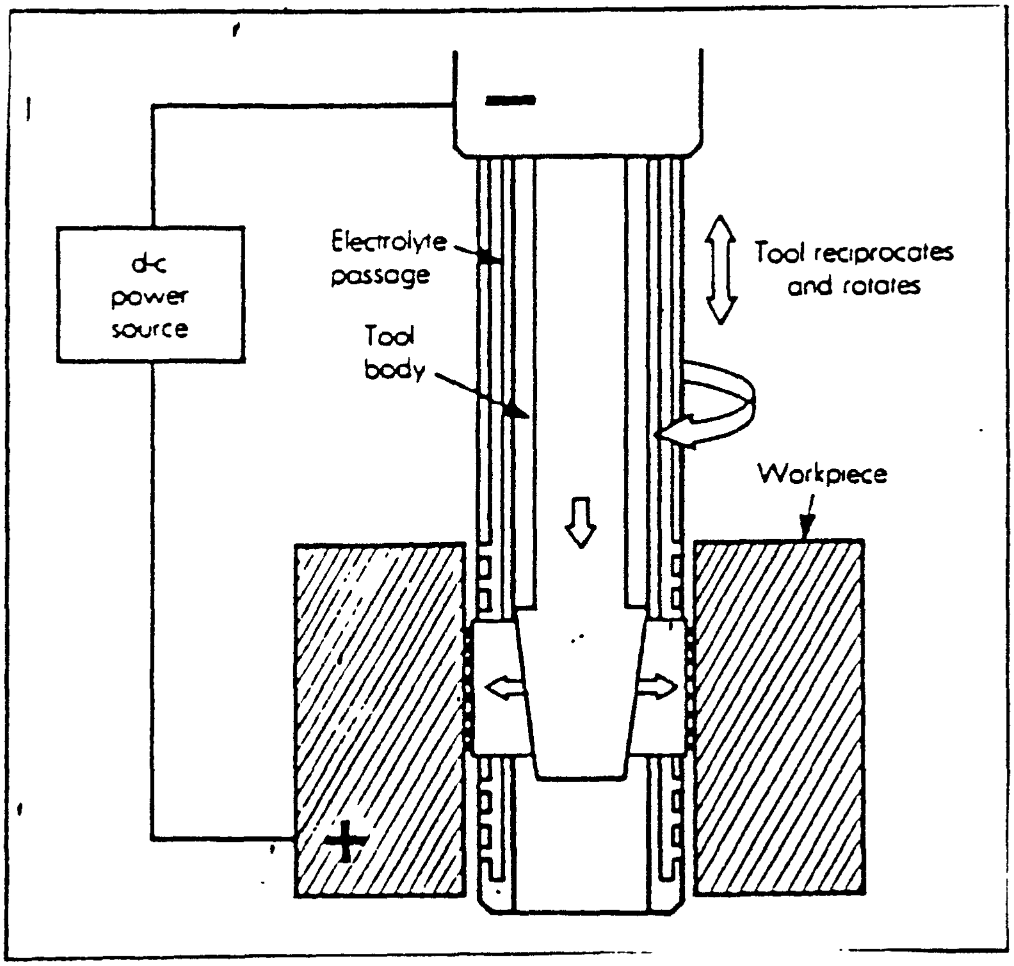

Fig:15 Setup for Electrochemical Grinding

(Tool & Manufacturing Hand Book)

6.3 ELECTROCHEMICAL HONING:

Electrochemical honing is similar to electrochemical grinding (ECG) in that both processes combine electrolytic metal removal with abrasive cutting action. With ECH, metal is removed by introducing an electrolyte into a gap between a cathodic honing tool body and an anodic workpiece, as illustrated in fig 26. The honing stones are nonconductive; the difference in potential is developed across the gap between the tool body and the workpiece. Direct current is passed across the gap, and the tool is stroked through the bore with the same generating motions of conventional honing. Several rows of small holes in the tool body enable electrolyte to be introduced directly between the tool and workpiece. Conventional flooding is also used.(1)

Bonded-abrasive honing stones are inserted in slots in the tool. These stones are forced out radially by the wedging action of the cone in the tool. This expansion is controlled by an adjusting head or fluid power cylinder in the spindle of the machine. The stones, which must be nonconductive, assist in the material-removal action and generate a round, straight cylinder. They are fed out with equal pressure in all directions so that their cutting faces are in constant contact with the cylinder's stones cut most aggresively on the high or tight areas and remove the geometric errors. The removal of approximately 90% of the metal in ECH operations is accomplished via electrolyic action; the honing stones maintain size and surface finish and continuosly expose clean workpiece metal to the electrolytic process. Direct control at 6-30 V is typical. The current varies between 100-300 A, depending upon the application.

Surface finish: If the surface finish must be held to a specified roughness, the stones are allowed to cut for a few

seconds after the electricity has been turned off. The characteristics of the surface finish generated in this manner are a function of the size of the abrasive grain in the stones, the relative speeds of the rotation and reciprocation motion, and the duration of the runout period used. Surface finish of 8-32 u in. is typical in ECH process.

Applications: To be processed by ECH, workpieces must be conductive. The process is most effective when used to hone hard, tough metals and is well suited for the processing of parts that are susceptible to heat distortion. Electrochemical honing causes little heat buildup and no significant stresses, and automatically deburrs the workpiece. The process is particularly effective for parts that require fast stock removal with good surface finish control.(2)

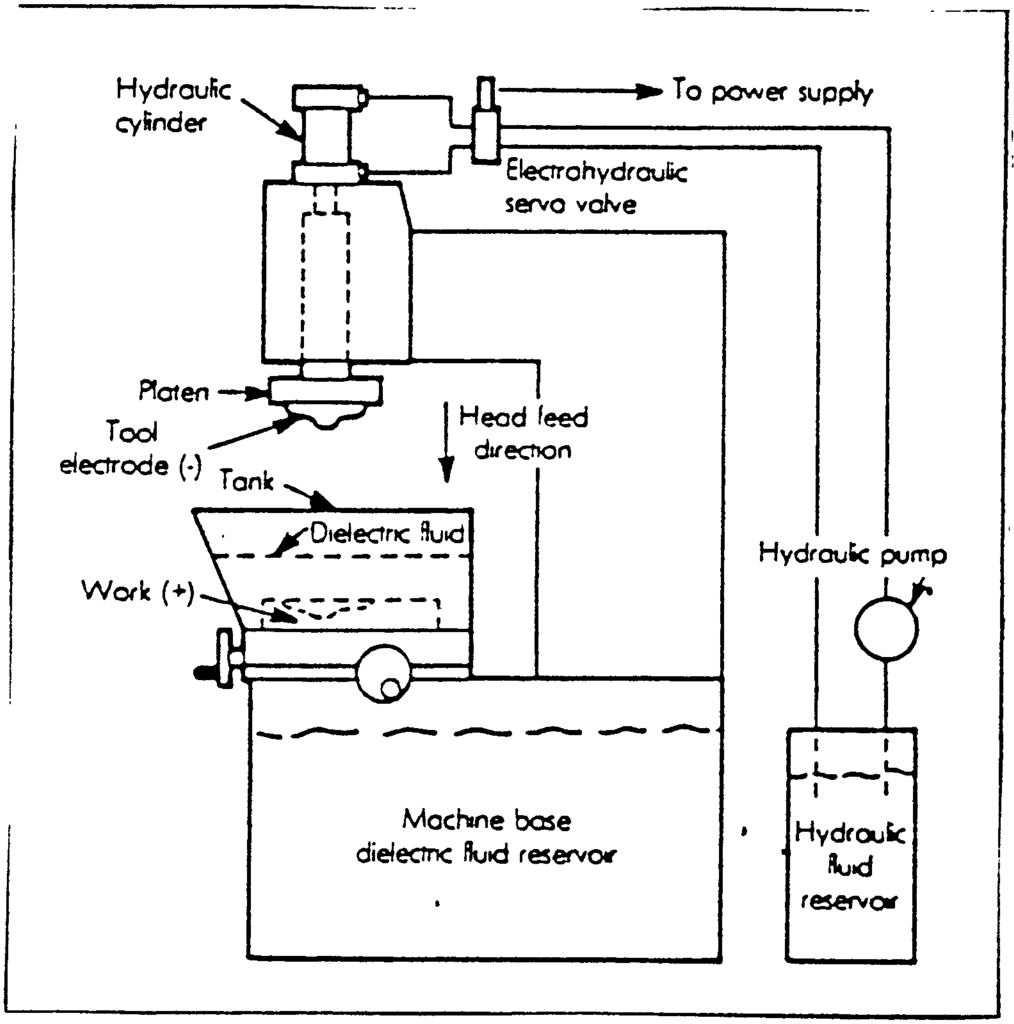

Fig: 26 Schematic of Electrochemical Honing

(Tool & Manufacturing Hand Book)

CHAPTER 7

Conclusions

The results of preliminary Surface milling experiments indicate that abrasive waterjets have great potential in this application .

1) Optimum stand-off distances exist for maximum volume removal rates.

2) An increased stand-off distance, which results in the exposure of a larger portion of the surface to the jet, is associated with a decrease in volume removal.

3) Increasing the abrasive flow rate does not significantly change the trend of the effect of stand-off distance on volume removal.

4) Hard abrasive is found suitable for fast material removal rates and soft, frangible abrasives for finishing.

5) Since regular surface is required for milling, this is controlled well by traverse speed. Increasing the traverse speed continually improves the depth uniformity of the produced slot.

6) Depth uniformity should be considered at the beginning of the milling process. Irregularities produced by one pass or traverse are not corrected in subsequent passes but rather exaggerated. A different pattern of traverse is considered in the experiments and it is found to complicate the milling process.

7) It has been observed that the textures of waterjet cut glass surfaces are a kind of complex combinations of random and deterministic patterns and the surface finish varies with the cutting thickness change, unlike in conventional machining methods which is generally uniform. Striation marks are found to develop which transpire below on area of relatively smooth surface finish.

Future work can be in the area of producing an excellent surface quality which may be achieved throughout the entire depth of cut by properly controlling the machining process parameters, which is possible when a large data base is available on optimized parameters for several materials. A method of in-place inspection of machined surfaces needs to be developed. A method, wherein, the jet is constant and work-sample is manipulated can be explored.

A study of different nontraditional machining processes reveals that , these are characterized by higher power consumption as a function of material removal rate as compared with traditional machining techniques and are typically employed when workpieces are complex or possess special material properties.

APPENDIX

PROGRAM on Allen Bradley 8400 Series Robot Controller

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***************************************************************************

(Program - Block)

G91# ----- Incremental Mode
P100# ----- Water on, Abrasive on
F8.0# ---- Traverse Speed
G01 X + 3.0#
G01 Y + 2.0#
G01 X - 3.0#
G01 Y - 2.0#
P101# ----- Water off, Abrasive off
M2#

***************************************************************************

(Program 32 - Sample)

G91#
G25 X 0.0 Y .036 I 0 J 40 P26# (Step & Repeat)
M2#

(Program 26 - Sample)

G91#
P100#
G4 F0.5# (Dwell for .5 Sec)
F120.0# (Variable)
G01 X + 3.0#
Y.018
G1 X - 3.0#
M2#
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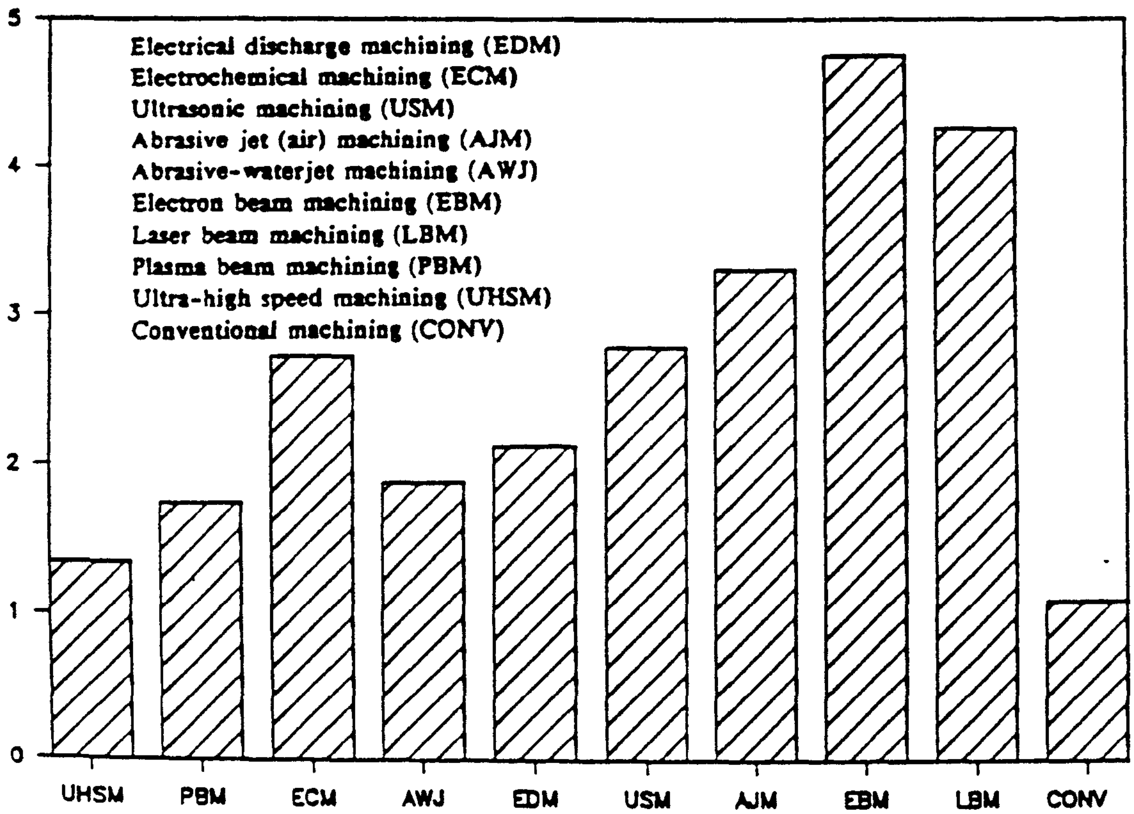

Fig:27 Typical Specific Energy for Steel Machining with different methods

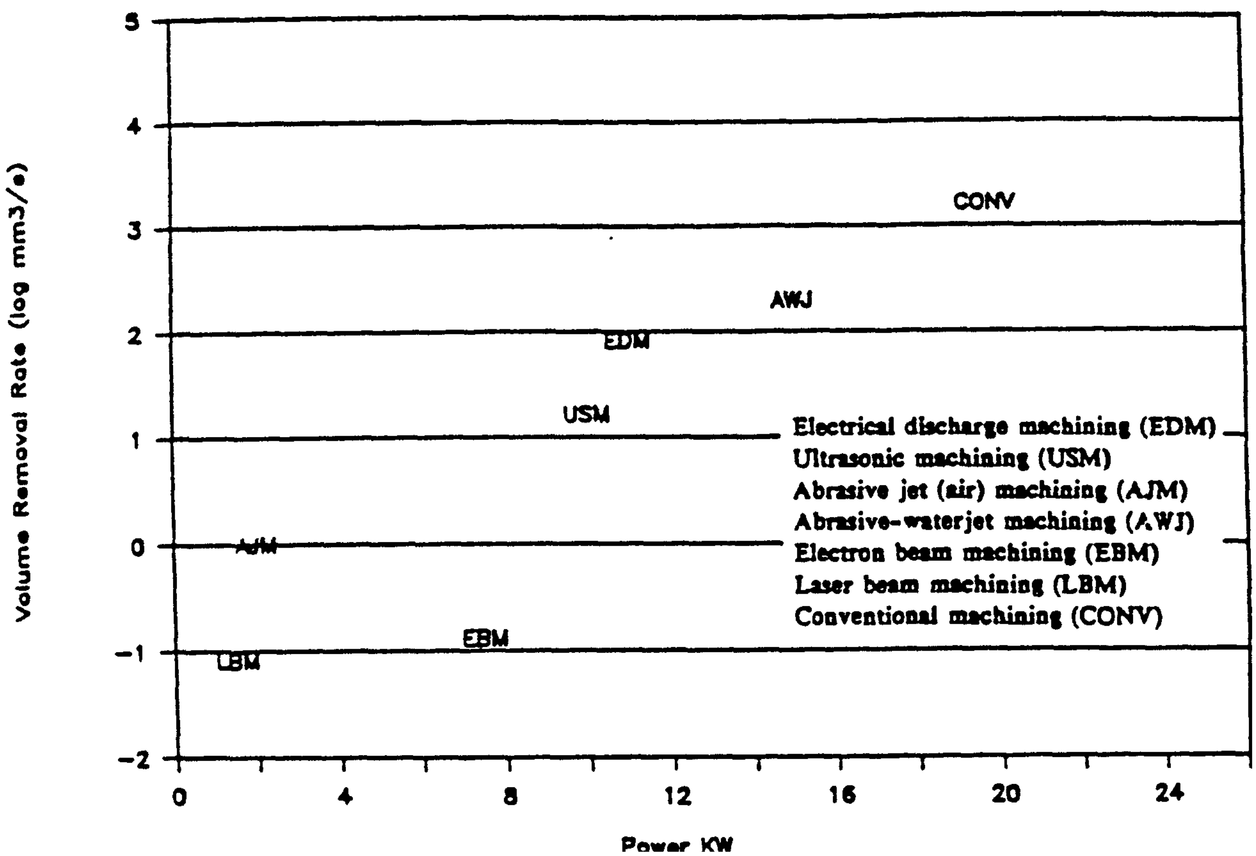

Fig:28 Power levels & typical volume removal rates of different Machining methods

Method	Volume Removal Rate	Typical Power Requirements	Surface Roughness
EDM Electrical Discharge Machining	Material removal rate 7 mm^3/s	Current of up to 20 amps and voltage of up to 400 volts are needed	3-12
ECM Electrochemical Machining	35 mm^3/s per 1000 amps (typical for steel)	DC volts up to 30 is used; a 10,000-amp machine is typical	0.4-6.3
CHM Chemical Machining	0.3 mm^3/s in steel; volume depends on area of blanking	Cost of blanking is 3 to 6 times that of mechanical blanking	
USM Ultrasonic Machining	4 to 60 mm^3/s in tool steel glass		0.3-0.8
AJM Abrasive Jet Machining (air)	up to 1 mm^3/s	Typical microblaster power requirement is 2-5 kW	
EBM Electron Beam Machining	up to 5 mm^3/s	130 volts and 5000 microamps are needed	0.8-6.3
LBM Laser Beam Machining	Very inefficient in consumption; no date available	4000 volts and 3000-joule pulse for one millisecond are typical for operations	0.8-6.3
PAM Plasma Arc Machining	1000 mm^3/s	200 kW is needed	
AWJ Abrasive-Waterjets	Volume removal rate of 50 to 200 mm^3/s	Typical power of 10 to 50 kW	1-10

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