Chemical Machining

Overview

- History
- Types of Chemical Milling
  - Photo-Chemical Machining
  - Immersion Machining
  - Electro-Chemical Machining
- Advantages and Disadvantages

History

- Organic acids first used for corrosive purposes in 400 B.C.
- 15th Century: salt, charcoal, and vinegar as etchants, linseed oil paint as maskant
- Used extensively in armor
- 18th and 19th century discoveries propelled chemical milling

(Ref. 2)

Maskants (Resists)

Types

- Cut & Peel
- Photographic
- Screen

Cut and Peel

These resists are applied to entire part by spray or dip method. It is then cut from the areas to be etched. Thickness of the coating applied is upto 0.2 mm, permits etching upto 1.5 mm. This type of maskant is not used in applications where critical dimensional tolerances are required.

Maskants in this category are vinyl, neoprene and butyl base materials.

Photographic

Photographic resists produce etchant resistant images by means of photographic techniques. When exposed through a high contrast negative, the materials generally produce a positive or negative image of the negative itself. These resists are generally applied in liquid form by spray, dip or roll coating techniques. Used for – thin materials up to 0.8 mm thickness, parts requiring dimensional tolerance -0.1 to +0.1 mm and upto 1x1.5 m section, automatic processing of high volume components.

Screen Resists

These are materials which can be used on the workpiece through normal silk screening techniques. The image accuracies are better than other types of resists. Screen resists are generally applied to- parts with size up to 1x1 m, flat parts or with moderate contours, etching depth up to 1.5 mm,

Selection of resists depend upon following factors

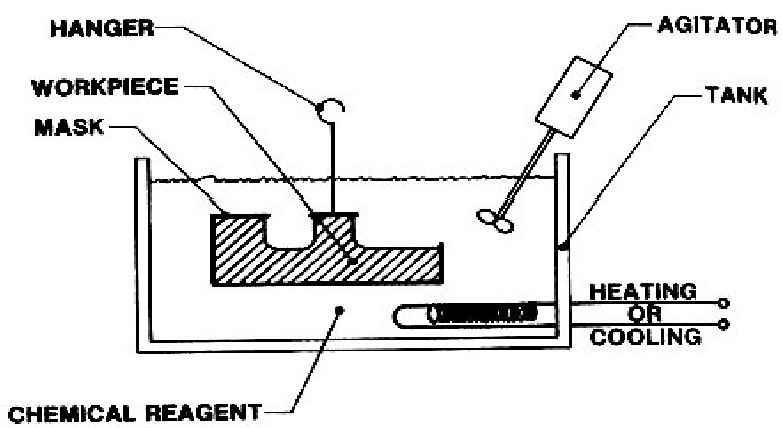
- Chemical resistance required
- Number of parts to be produced
- Detail or resolution required
- Shape and size of component
- Ease of removal
- economics

Etchant

The basic function of the etchant is to convert the material into the metallic salt that can be dissolved in the etchant, and thus removed from the work surface. Factors affecting selection of etchant are

- Material of workpiece
- Type of maskant/resist used
- Depth of etch
- Surface finish required
- Potential damage to metallurgical properties of workpiece
- Rate of material removal
- economics

Immersion Machining

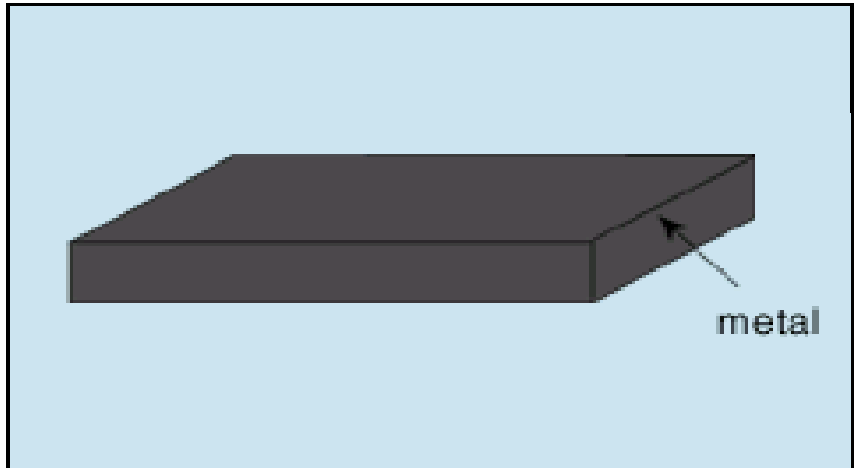


(Ref. 3)

- Similar to PCM
- Maskant attached to areas not desired to be machined
- Entire part immersed in etchant chemical
- Can be repeated until correct part created

Photo-Chemical Machining (PCM)

- Mainly used for sheets or plates
- Computer-generated picture used to produce phototool
- Part covered with photoresist and tool, exposed to UV light
- Part exposed to etchant chemical
- Photoresist removed
- See right picture (Ref. 1)



Chemically cleaned surface.

Table 3.3

Etchant Characteristics and General Applications

Etchant	*Concentration*	*Temp. (K)*	*Etch rate (cm/min) fresh solution*	*Etch factor*	*Metals that etchant will attack*
$FeCl_3$	12 to 18° Bé*	320°	.002	1.5:1 to 2.0:1	Aluminium alloys
HCl, HNO_3H_2O	10:1:9	320°	.002 to .004	2:1 (variable)	
$FeCl_3$	42°Bé	320°	.002	2:1	Cold rolled steels
HNO_3	10 to 15% (vol.)	320°	.002	1.5 to 2.0:1	
$FeCl_3$	42°Bé	320°	.004	2.5 to 3.0:1	Copper and its alloys
$(NH_4)_2S_2O_8$	0.22 g/cm³ H_2O	start at 300-320°	.002	2 to 3:1	
Chromic acid	Commercially available	325°	.0030	2 to 3:1	
$CuCl_2$	35° Bé (regenerated)	325°	.001	2.5 to 3:1	
HNO_3	12 to 15% (vol.)	300°-320°	.002 to .004	—	Magnesium
$FeCl_3$	42°Bé	320°	.001 to .002	1:1 to 3:1	Nickel
$FeCl_3$	42°Bé	325°	.002	1.5 to 2:1	Stainless steel, tin
HNO_3	10 to 15% (vol.)	320 to 325°	.002	—	Zinc

*Baumé specific gravity scale.

Materials

Virtually any material can be used as long as an etchant and maskant are available:

- Aluminum
- Titanium
- Steel
- Brass
- many more!

(Ref. 5)

Chemical Machining—PCM

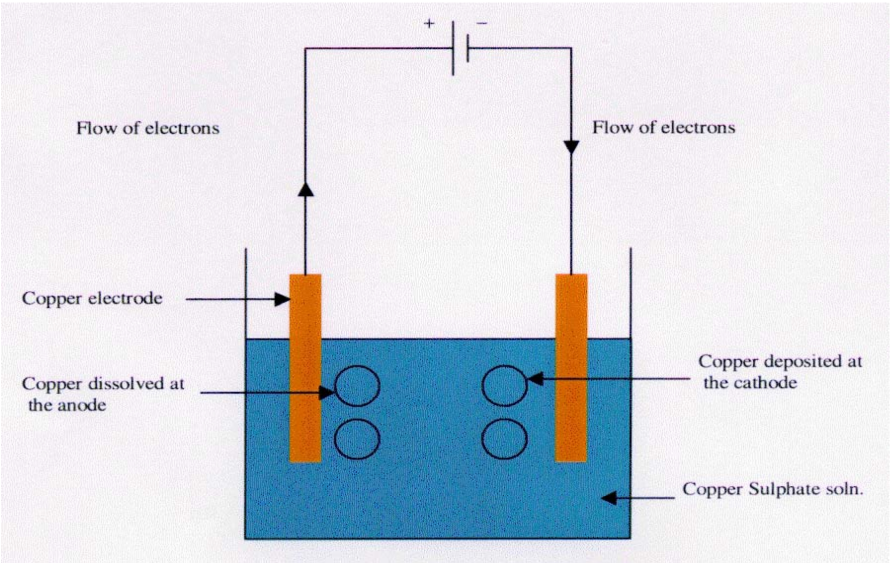
- Advantages
  - Several parts machined simultaneously
  - Low cost tooling
  - Tooling such as computer not limited to one part
  - Used on a variety of materials
  - No burrs created
  - No residual stress introduced
- Disadvantages
  - Cannot create very thin parts
  - Emphasizes surface defects
  - Uses hazardous chemicals

Conclusions

- Chemical machining began as early as 400 B.C.
- PCM, Immersion Machining, and ECM are a few examples
- Reduces tooling and cost
- Can make eccentric shapes
- Eliminates burrs and secondary finishing
- Chemicals can be hazardous to environment

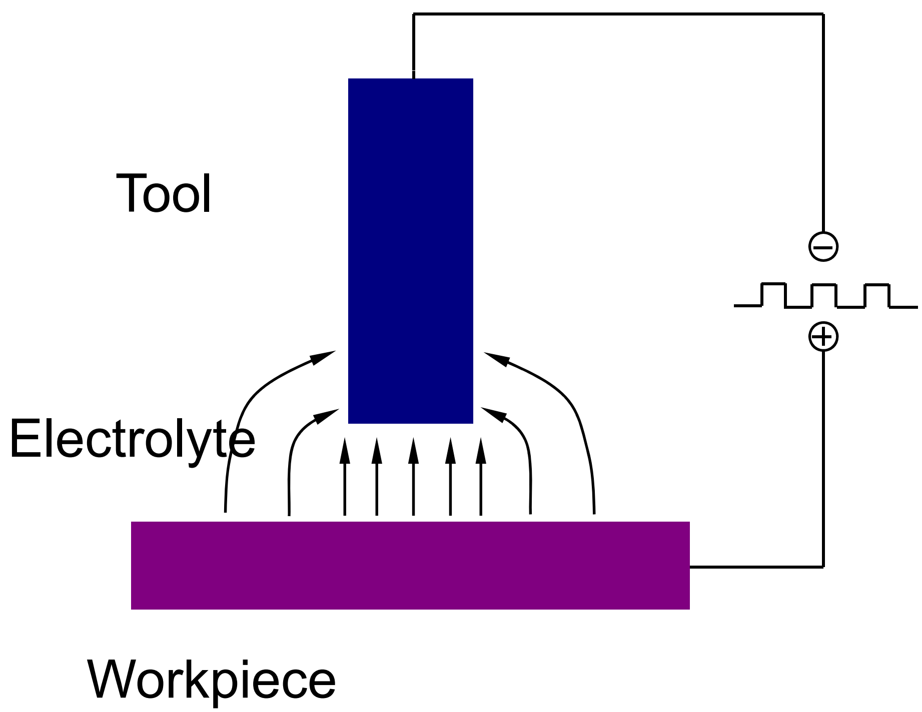
Electro-Chemical Machining (ECM)

- Uses electrolysis
- Work piece positively charged, tool (inverse of desired shape) negatively charged
- Current passed between the two
- Surface metal ionizes, removed by solution



(Ref. 4)

Principle of Electrochemical Machining/Deposition



- Machining: anodic dissolution
- Deposition: cathodic reduction
- Electric field localization at tool-end region using ultra short pulses

ECM is opposite of electrochemical or galvanic coating or deposition process. Thus ECM can be thought of a controlled anodic dissolution at atomic level of the work piece that is electrically conductive by a shaped tool due to flow of high current at relatively low potential difference through an electrolyte which is quite often water based neutral salt solution.

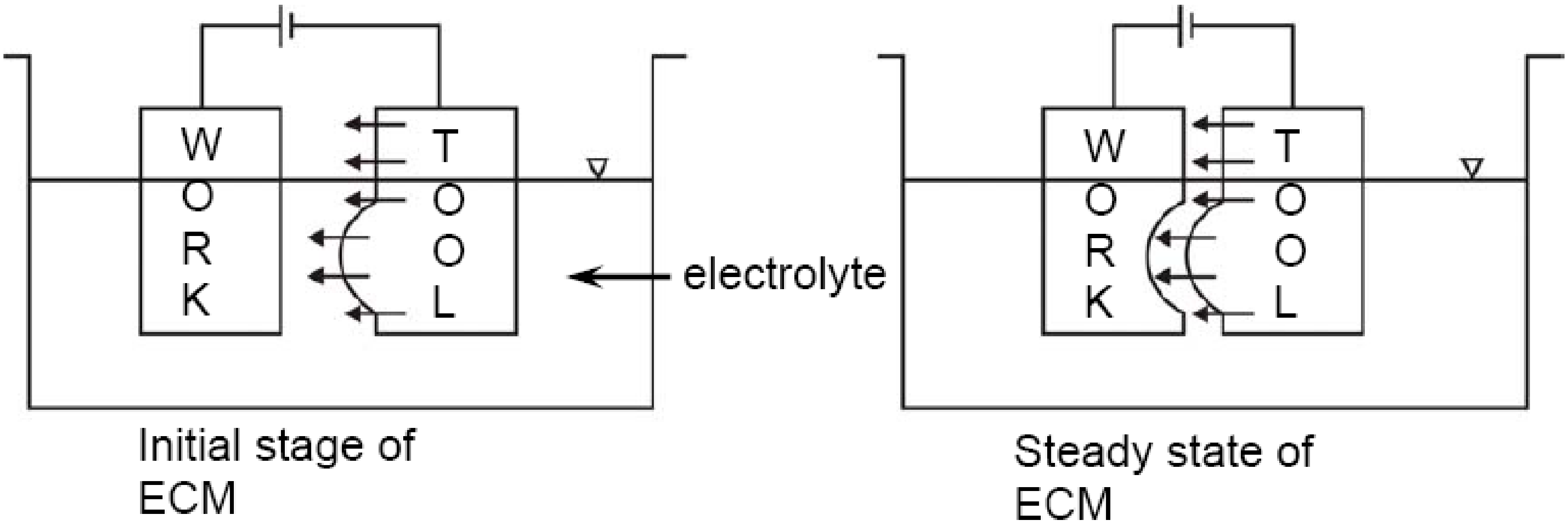


Fig. 1 *Schematic principle of Electro Chemical Machining (ECM)*

During ECM, there will be reactions occurring at the electrodes i.e. at the anode or workpiece and at the cathode or the tool along with within the electrolyte.

Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied

$$NaCl \leftrightarrow Na^{+} + Cl^{-}$$

$$H^{2}O \leftrightarrow H^{+} + (OH)^{-}$$

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece.

Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$$2H^+ + 2e^- = H^2\uparrow \text{ at cathode}$$

Similarly, the iron atoms will come out of the anode (work piece) as:

$$Fe = Fe^{++} + 2e^-$$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

$$Na^+ + OH^- = NaOH$$

In practice $FeCl^2$ and $Fe(OH)^2$ would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode. Fig. 2 depicts the electro-chemical reactions schematically. As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free.

The voltage is required to be applied for the electrochemical reaction to proceed at a steady state. That voltage or potential difference is around 2 to 30 V.

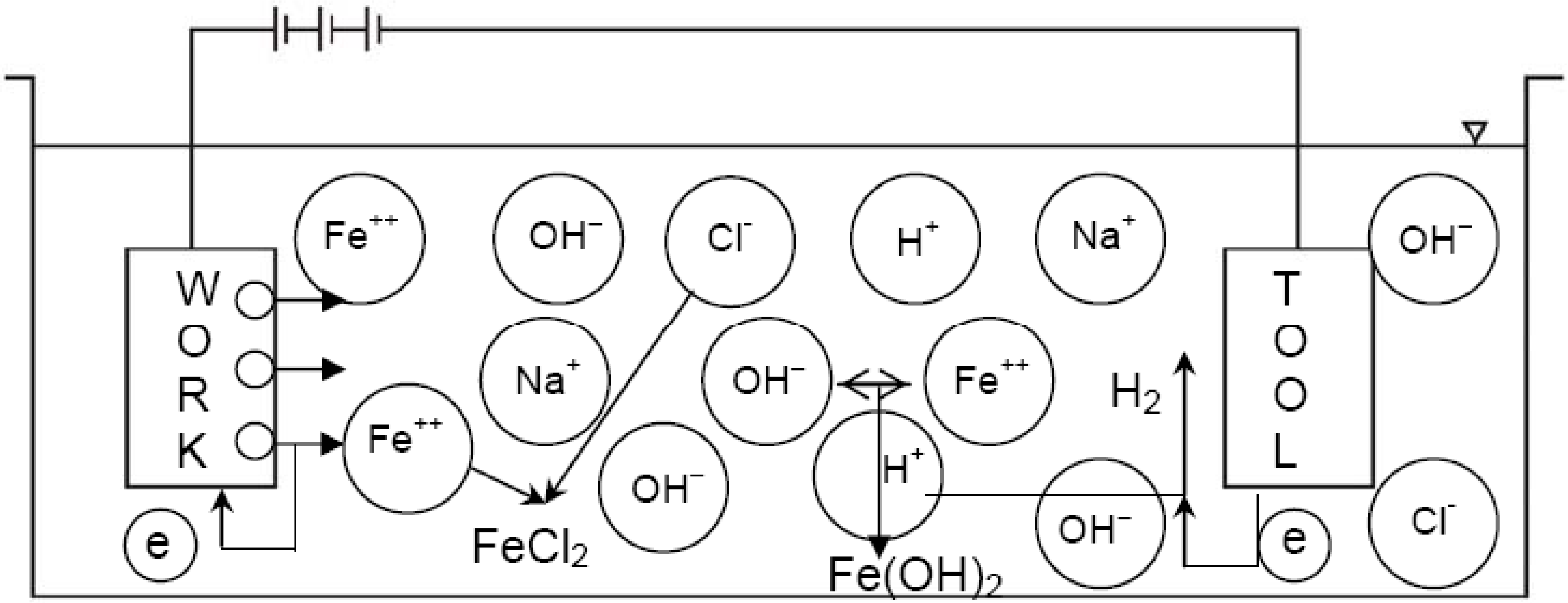


Fig. 2 Schematic representation of electro-chemical reactions

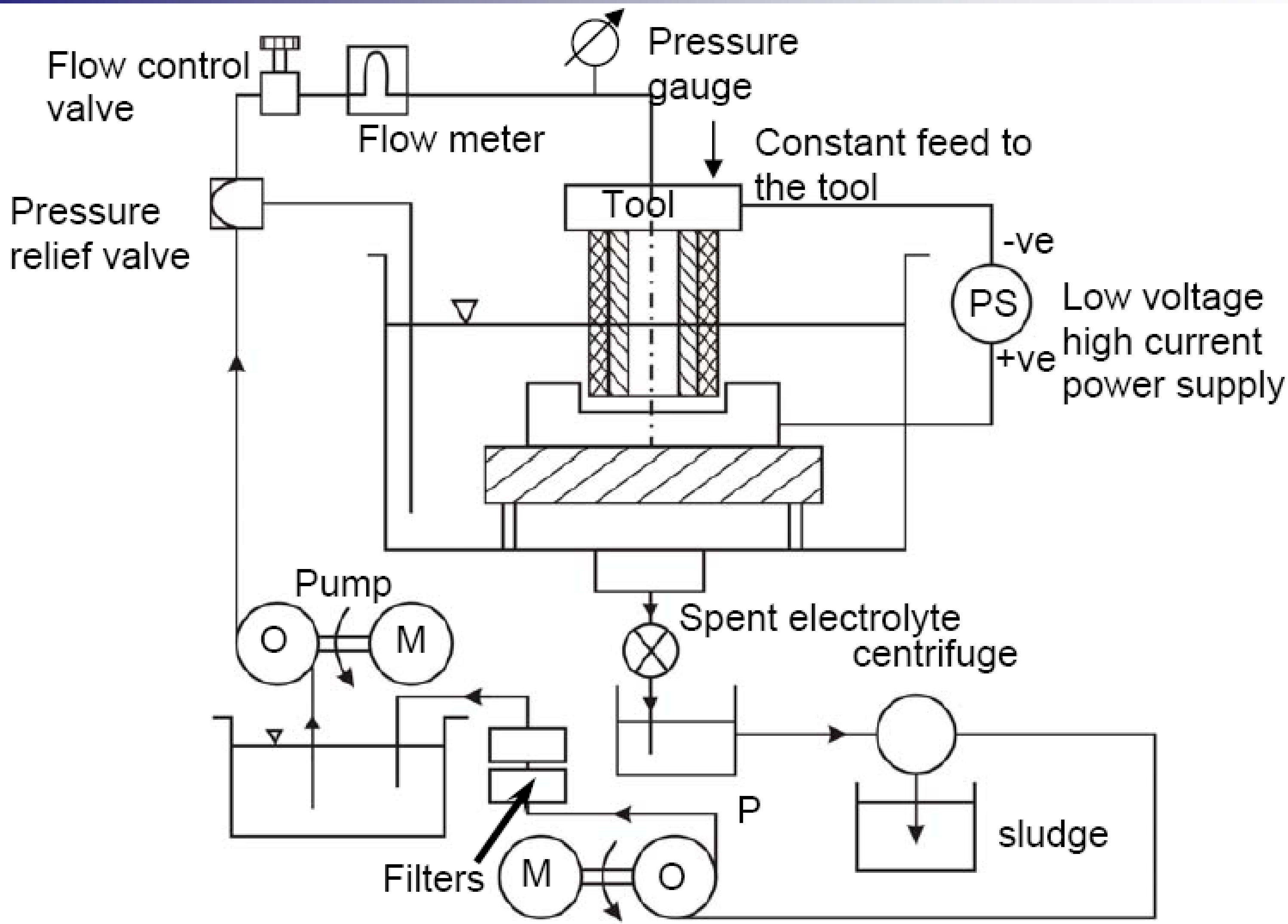
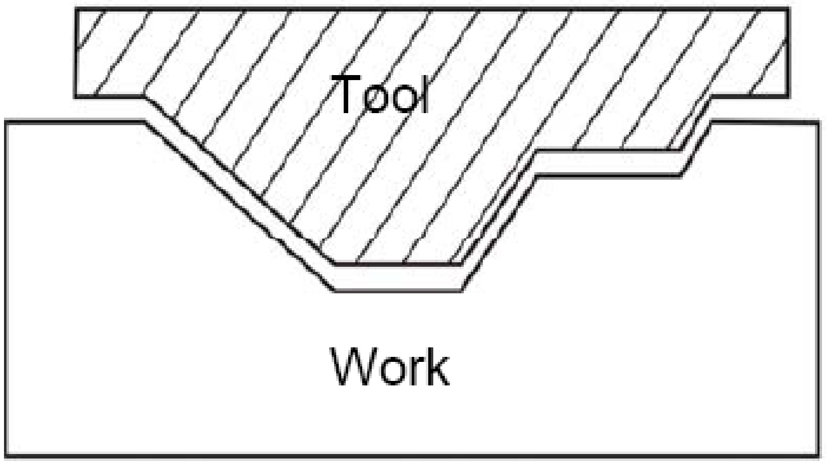
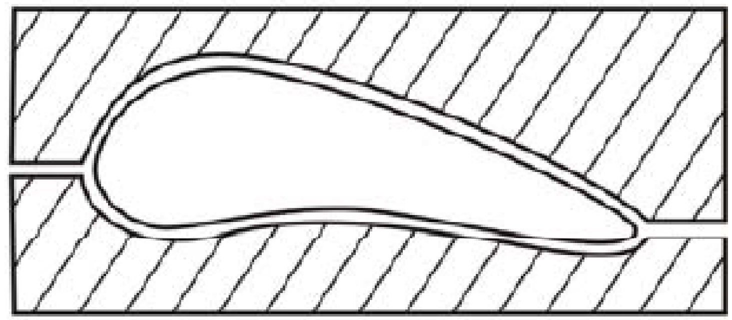


Fig. 4 *Schematic diagram of an electrochemical drilling unit*

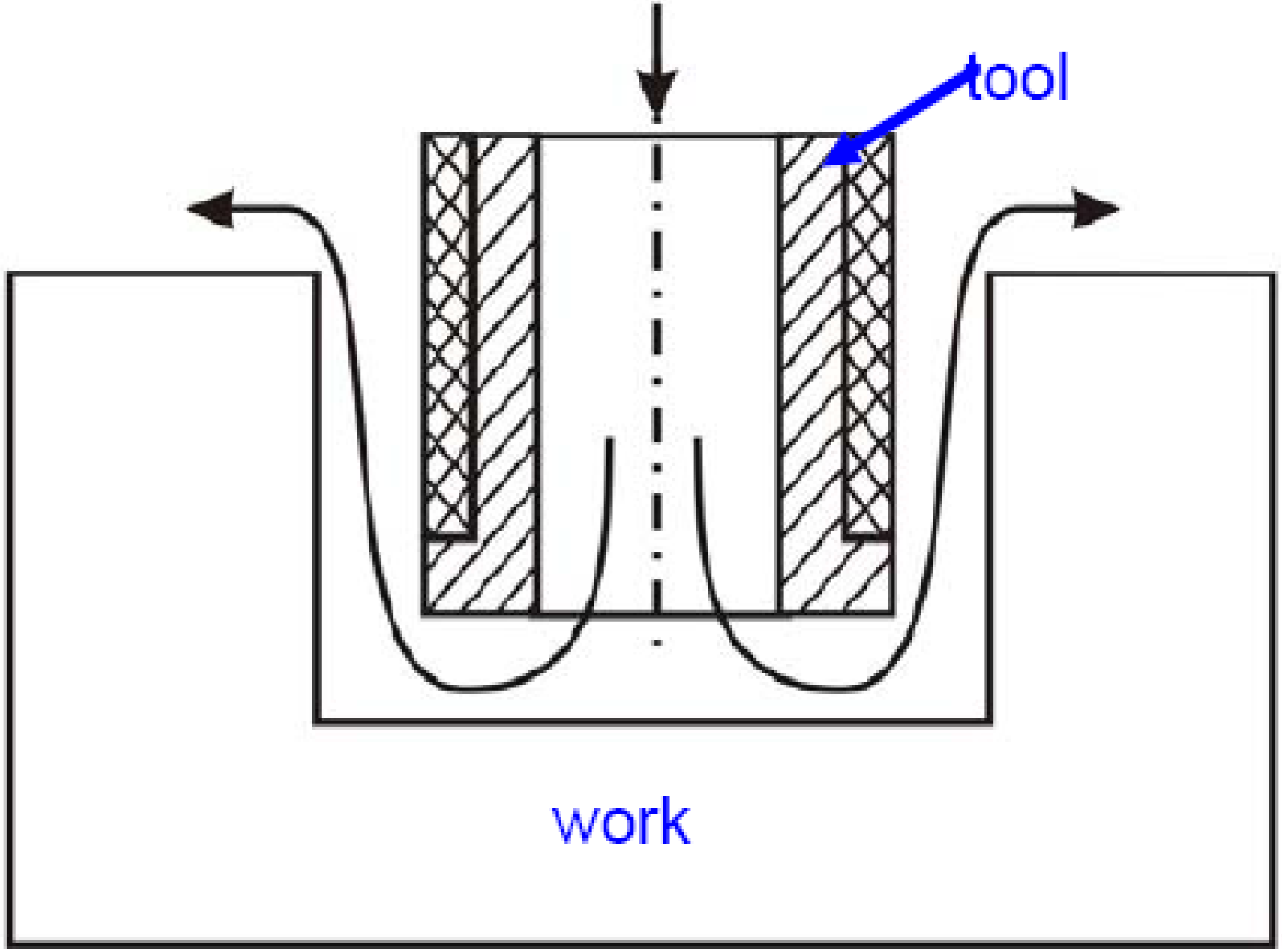


Die sinking



3D profiling

Fig. 8 *Different applications of Electro Chemical Machining*



(drilling)

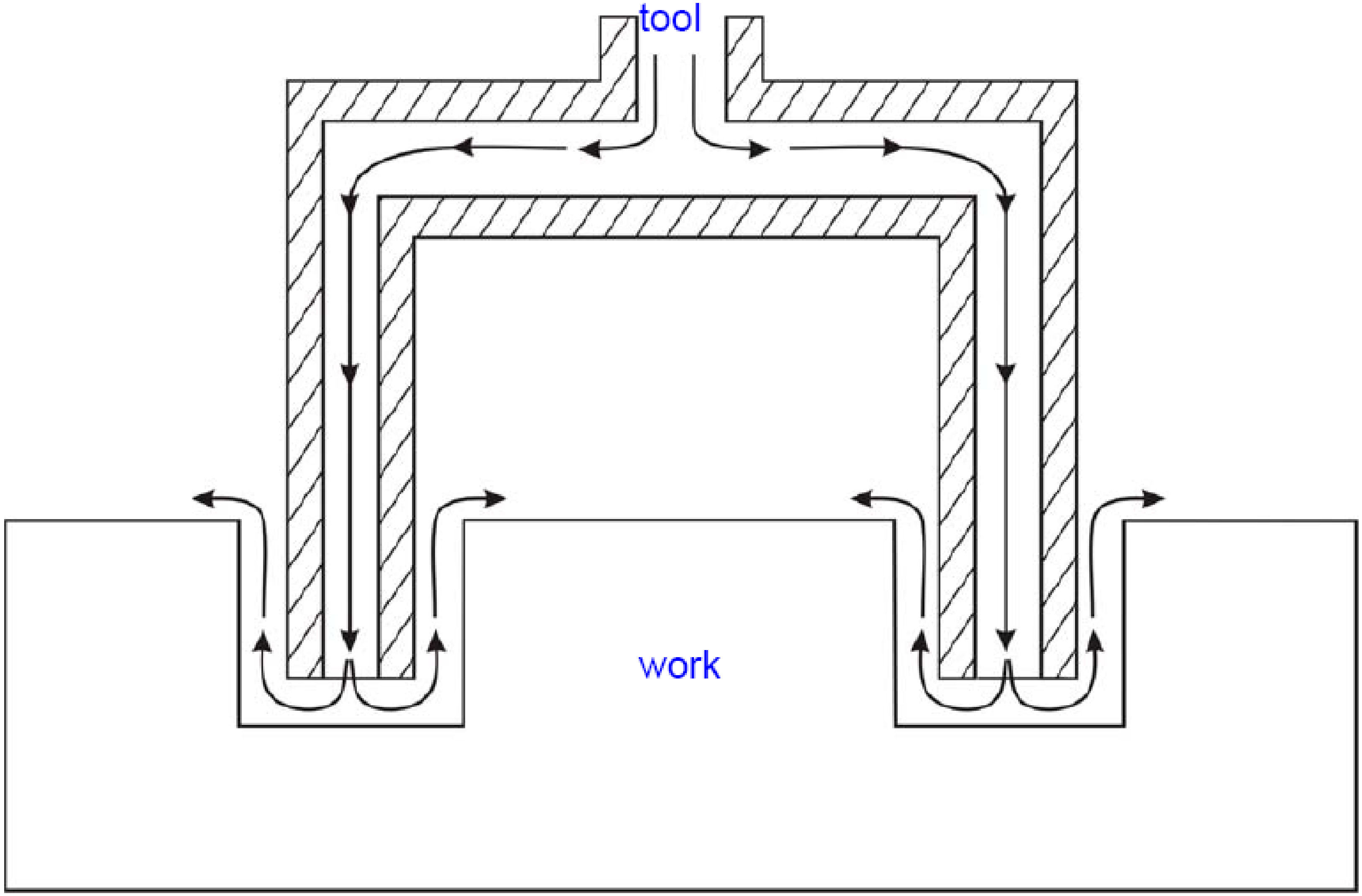
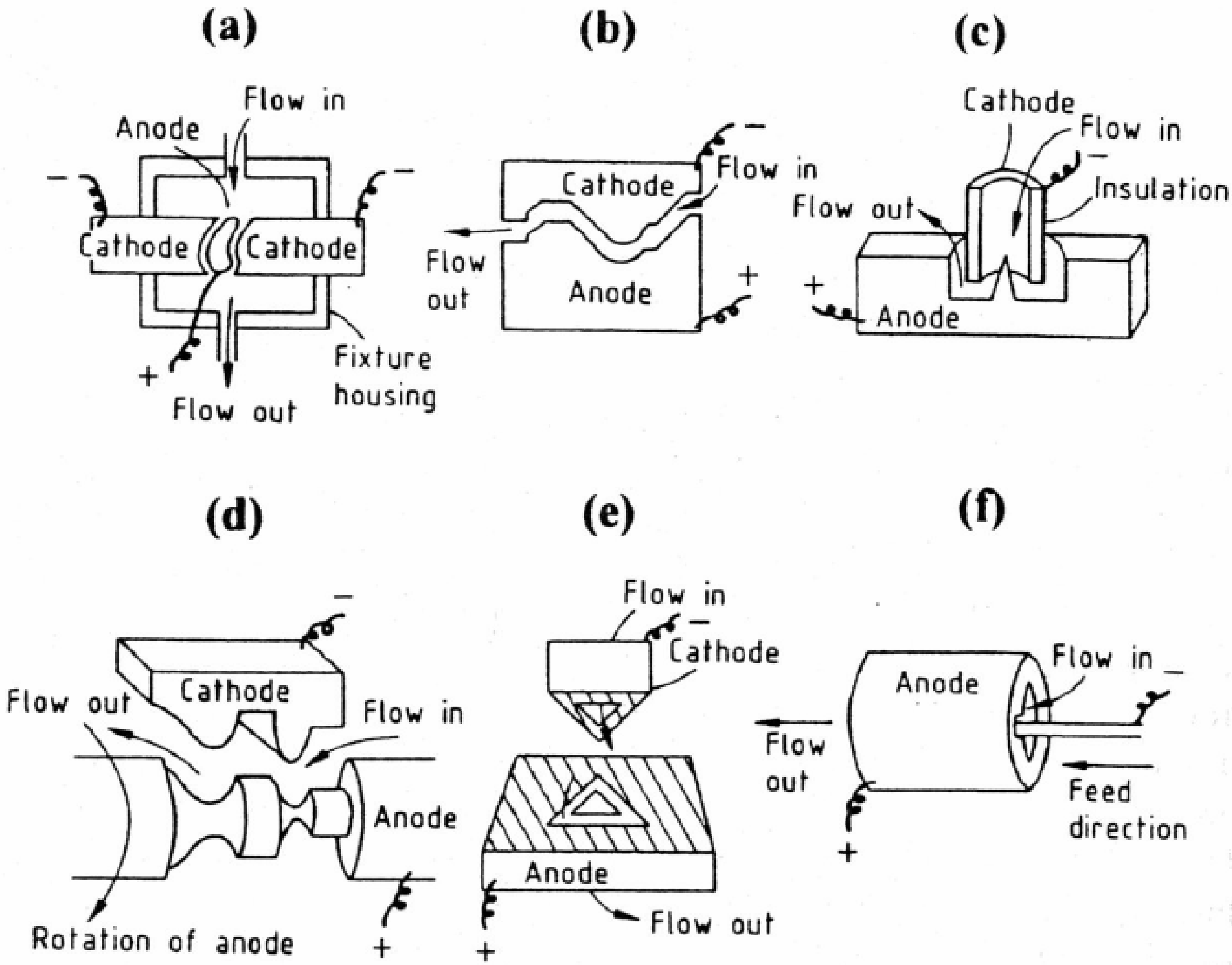


Fig. 9 *Drilling and Trepanning by ECM*


(a)
Flow in
Anode
Cathode
Cathode
Fixture housing
Flow out
(b)
Cathode
Flow in
Flow out
Anode
(c)
Cathode
Flow in
Insulation
Flow out
Anode
(d)
Cathode
Flow out
Flow in
Anode
Rotation of anode
(e)
Flow in
Cathode
Anode
Flow out
(f)
Anode
Flow in
Flow out
Feed direction

Micro-tool fabrication

- Electrochemical etching
- Wire electrical discharge machining

Electrochemical machining

- Micro-hole
- Micro-groove
- Micro-mold

Electrochemical deposition

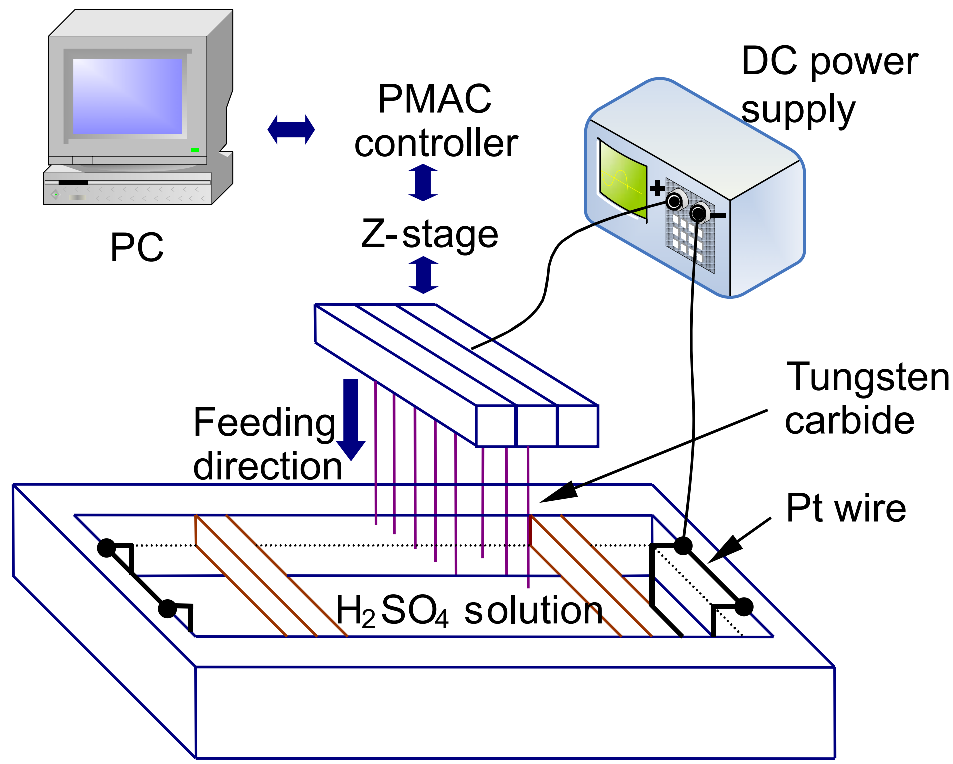
- Micro-column
- Micro-spring
- Micro patterning

Electrochemical Etching

❖ Electrochemical etching of WC rod (high rigidity & high hardness)

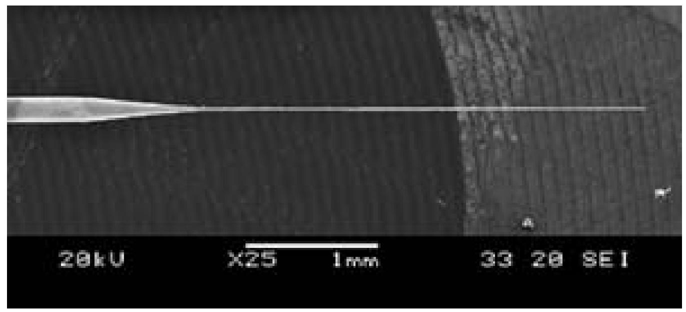
❖ Electrolyte: 1.5 M H_2SO_4 solution

❖ Shaft size, shape, and surface quality according to electrolyte concentration, applied voltage, etching time, etc.

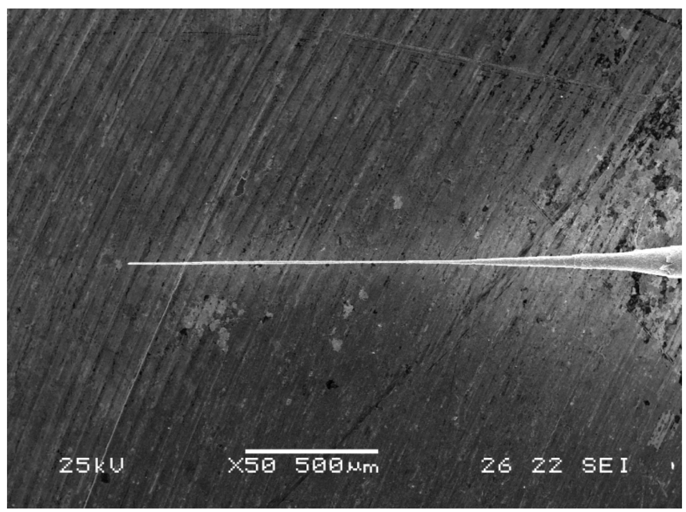


Schematic diagram of the ECE system

Micro-tool Fabricated by Electrochemical Etching



ϕ 30 μm



ϕ 4 μm

Chemical Machining—ECM

- Advantages
  - Current and metal removal rate can be controlled
  - Can create elaborate shapes and contours
  - Tool lasts indefinitely once created
  - No burrs created
  - No residual stress introduced
- Disadvantages
  - Expensive equipment and tools
  - Electrolytic solution is hazardous to environment as well as equipment

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4. “Electrolysis.” 20 October 2002. <http://www.unl.edu/nmrc/ecevolution.html>
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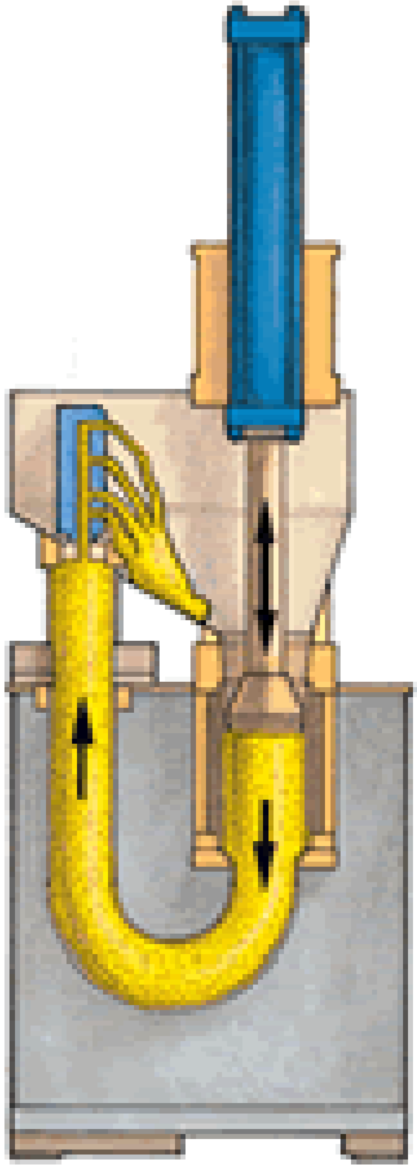
Abrasive Flow Machining

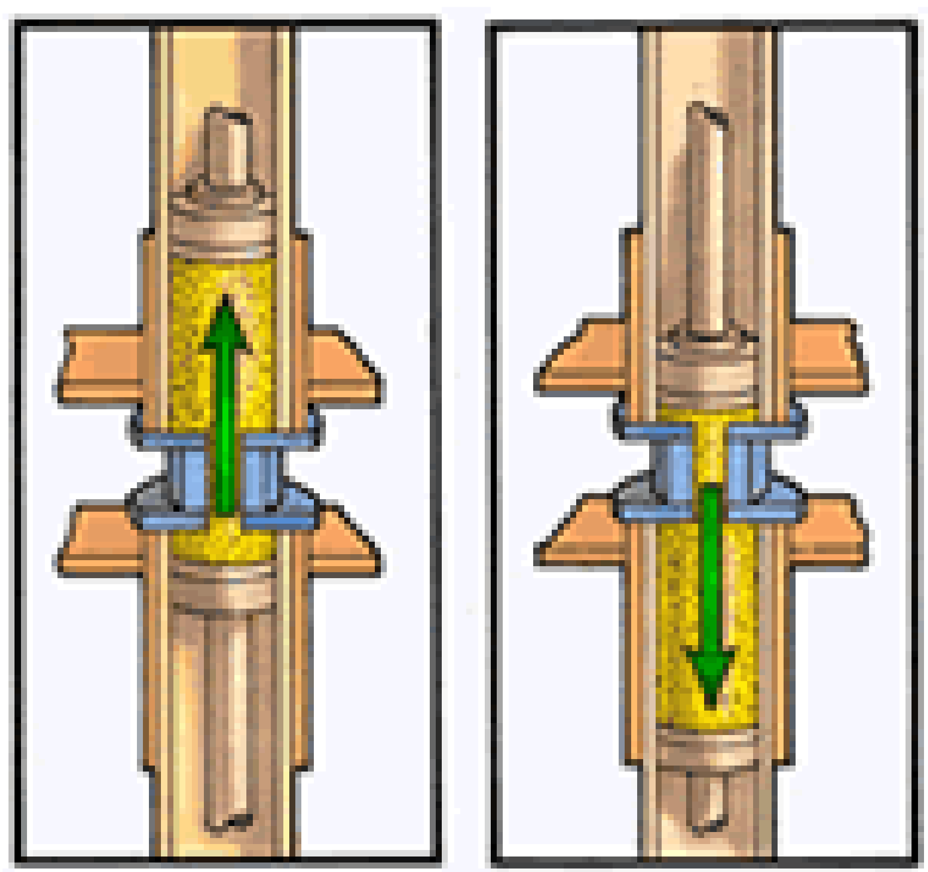
AFM involves the use of flow of viscous elastic media, which flows at a lesser speed but under high pressure through the passage, and faithfully approaches every fine detail of the component and is able to finish virtually any minute details in the component. This flexible nature of the viscoelstic media provides unique capabilities to this process.

- In AFM, a semisolid media consisting of a polymer based carrier and abrasives in a specific proportion is extruded under pressure through or across the surface to be machined (Benedict 1987). The media acts as a flexible tool whenever it is subjected to any restriction. The special deformable ability of media is responsible for its movement through any shape of the passage. Restricted media flow passages are necessary at the surfaces to be processed by AFM wherein the media behaves somewhat like flexible grinding stone, abrades the material, and provides a good surface finish over the surface.

- The workpiece is hydraulically clamped between two vertically opposed media cylinders. Lower media cylinder is filled with required volume of abrasive laden media . The media is then extruded through the workpiece into the upper media cylinder . The procedure is reversed and the media is fed back through the workpiece into the lower cylinder. The combination of these up and down strokes constitutes a process cycle.



One Way AFM



Two Way AFM

AFM Technology

- To describe the process technology, three elements namely the machine, the media, and the tooling are considered important. The machine decides the *extent* of abrasion, the media determines what *kind* of abrasion will occur and the fixture determines the exact *location* of abrasion. All machines regardless of size are positive displacement hydraulic systems, which force the abrasive laden media through the fixtured workpiece at a selected pressure and flow rate. Standard units operate within 10 bar to 200 bars pressure range with flow rates up to 400 litres /min.

- AFM systems are essentially provided with controls on hydraulic system pressure, clamping and unclamping of fixtures, volume flow rate of media, and advance and retract of media pistons. Several accessories such as automatic flow timers, cycle counters, volumetric displacement systems, pressure and temperature compensated flow control valves, media heat exchangers, media refeed units may be integrated to the conventional AFM systems for production applications.

- The most essential component of the process is the media, which is considered a proprietary item by machine manufacturers. It consists of base material or carrier, abrasive grains, and proprietary additives. Most widely used carrier is a high viscosity rheopetic fluid (at any constant rate of shear its apparent viscosity increases with time to some maximum value). The base material has enough degree of cohesion and tenacity to drag the abrasive grains along with it through various passages/regions. Aluminium oxide and silicon carbide are most suitable abrasives for many applications but boron carbide and diamond are specifically used for special applications.

- Abrasive grains to base material ratio can vary from 2 to 12 (McCarty 1970). The additives are mainly used to modify the base material properties to get desired flowability and rheological characteristics of the media. Hydrocarbon gels are the commonly used lubricants in the media. All additives are carefully blended in predetermined quantities to obtain consistent formulations.

- The primary function a fixture is to hold the workpiece in proper position between two opposed cylinders and direct the media by restricting it to the areas to be worked during the process cycle. When necessary, the fixture can protect edges or surfaces from abrasion by acting as mechanical mask. Steel, urethane, and nylon are the main materials used for manufacturing fixtures. The fixture design may be straightforward or very complex depending upon the workpiece configuration. For instance, a part with straight through passage needs tooling to only hold the part in place between two media cylinders allowing the workpiece passage itself to offer maximum restriction in the flow path.

AFM APPLICATIONS

- Initially, this process was developed for effective deburring of hydraulic control blocks but the field of applications rapidly diversified into defence, medical, and production. The inaccessible areas in components, which are impossible to finish with traditional methods, can be easily finish machined by AFM up to 90% improvement in original roughness with in the range of acceptable accuracy (Rhoades 1985, Jain & Jain, 1999a).

- Typical applications include improving airfoil surfaces of compressor and turbine components, edge finishing of holes and attachment features, improvement of fatigue strength of blades, disks, hubs and shafts with consistent and polished true radius edges, adjustment of air flow resistance of blades, vanes, combustion liners, nozzles and diffusers, finishing of fuel spray nozzles, fuel control bodies, bearing components, reworking the components to remove coke and carbon deposits, improving surface integrity and enhance eddy current readings.

- In die polishing industry, AFM has numerous applications such as polishing of carbide compacting dies, stamping, cold heading and extrusion dies, and punches. Die life is significantly improved if processed by AFM .
- Finishing of transfer tubing for special gases and liquids used in manufacture of semiconductors and food-processing equipment is accomplished on production basis. Providing improved surface finishes and imparting radii in passages through which gas or fluids flow, reduces boundary layer turbulence and improves the flow rates .

- Recently, AFM has been successfully employed for removing nickel aluminide coatings from turbine engine blades and vanes to replace the traditional procedure, which was lengthy and involving hazardous nitric acid solutions causing environmental pollution.

Flexible Manufacturing Systems

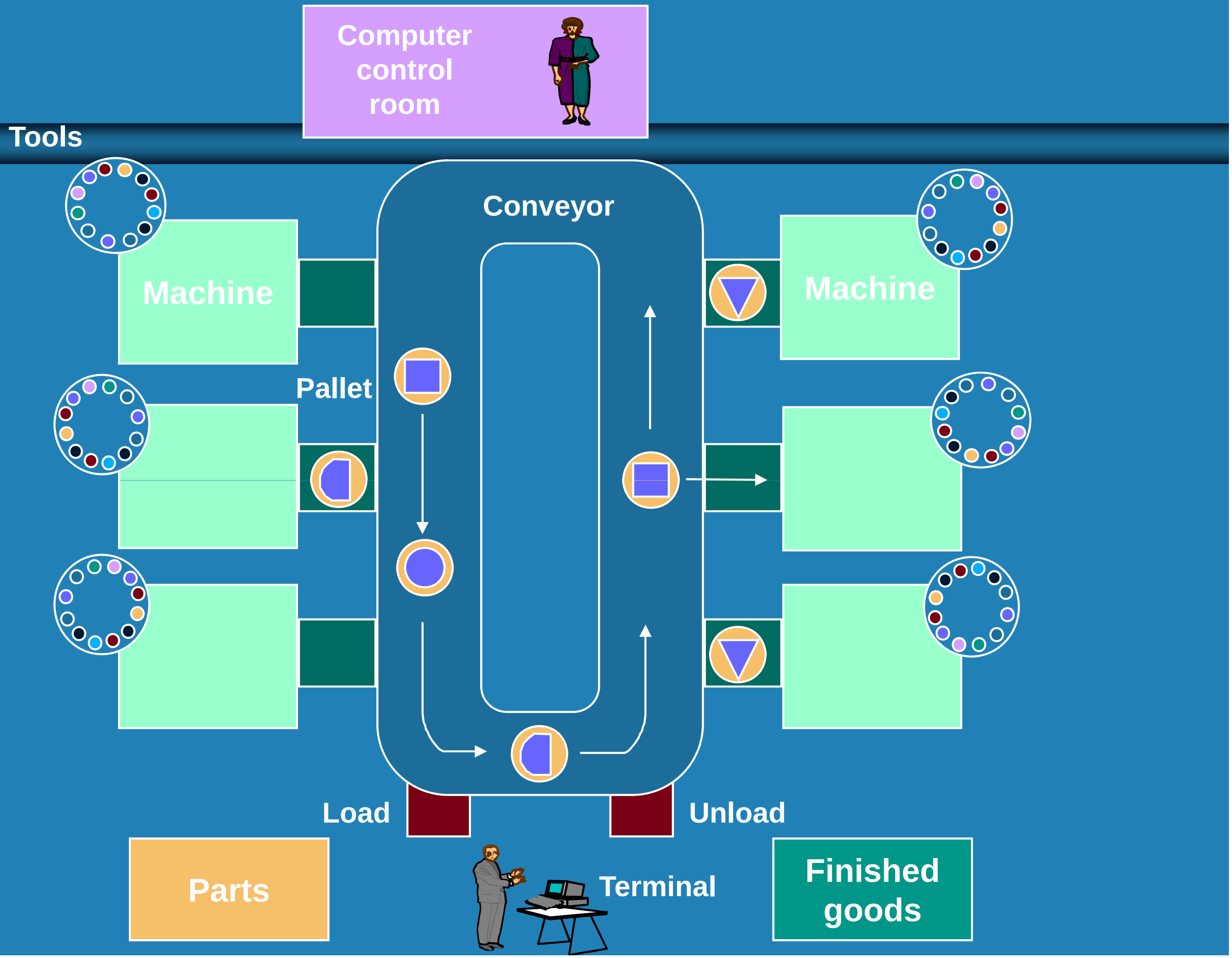
Flexible Manufacturing Systems (FMS)

- An FMS is a “reprogrammable” manufacturing system capable of producing a variety of products automatically. Conventional manufacturing systems have been marked by one of two distinct features:
  - The capability of producing a variety of different product types, but at a high cost (e.g., job shops).
  - The capability of producing large volumes of a product at a lower cost, but very inflexible in terms of the product types which can be produced (e.g., transfer lines).
- An FMS is designed to provide both of these features.

FMS Components

- Numerical Control (NC) machine tools
- Automated material handling system (AMHS)
  - Automated guided vehicles (AGV)
  - Conveyors
  - Automated storage and retrieval systems (AS/RS)
- Industrial Robots
- Control Software

Flexible Manufacturing System



Classification of FMS-related Problems

- Strategic analysis and economic justification, which provides long-range, strategic business plans.
- Facility design, in which strategic business plans are integrated into a specific facility design to accomplish long-term managerial objectives.
- Intermediate-range planning, which encompasses decisions related to master production scheduling and deals with a planning horizon from several days to several months in duration.
- Dynamic operations planning, which is concerned with the dynamic, minute-to-minute operations of FMS.

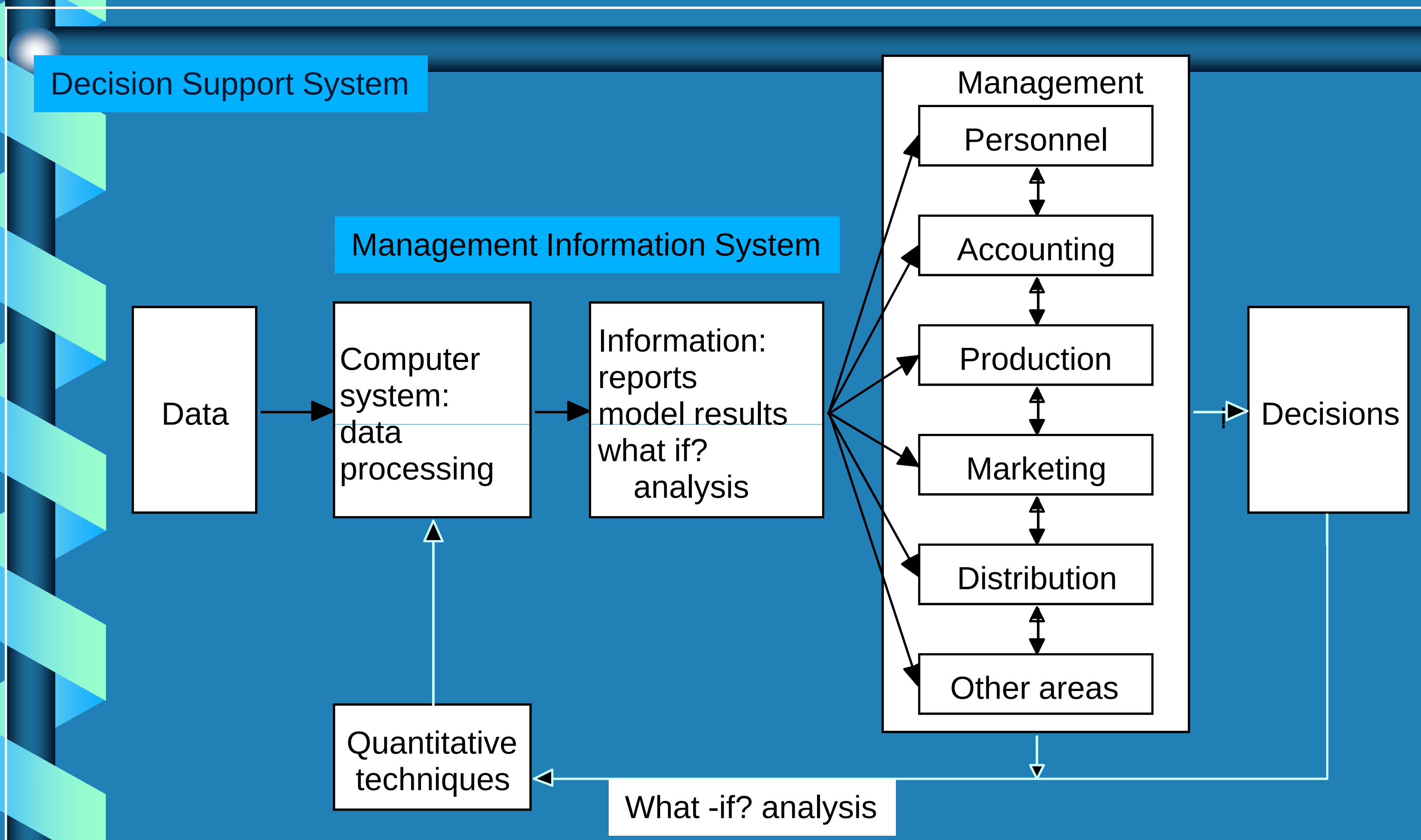
FMS Problems

- **Part type selection** (Askin) - selecting parts that will be produced in the FMS over some relatively long planning horizon.
- **Part selection** (Stecke) - from the set of parts that have current production requirements and have been selected for processing in the FMS, select a subset for immediate and simultaneous processing.
- **Machine grouping** (Stecke) - partition machines into groups where each machine in a group can perform the same set of operations.
- **Loading** (Stecke) - allocate the operations and required tools of the selected part types among the machine groups.
- **Control** - provide instructions for, and monitor the equipment in the FMS so that the production goals identified by the above problems are met.

Information Technology

- Management information system (MIS)
  - –move large amounts of data
- Decision support system (DSS)
  - –add decision making support
- Expert system
  - –recommend decision based on expert knowledge

Decision Support System

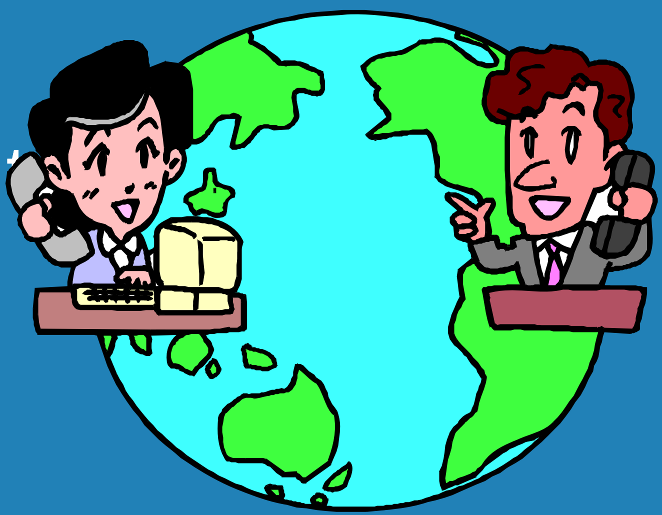


Artificial Intelligence

- Neural networks
  - –emulate interconnections in brain
- Genetic algorithms
  - –based on adaptive capabilities in nature
- Fuzzy logic
  - –simulate human ability to deal with ambiguity

Advanced Communications

- Electronic data interchange (EDI)
- Internet
- Wireless communications
- Teleconferencing
  & telecommu
- Bar coding
- Virtual reality

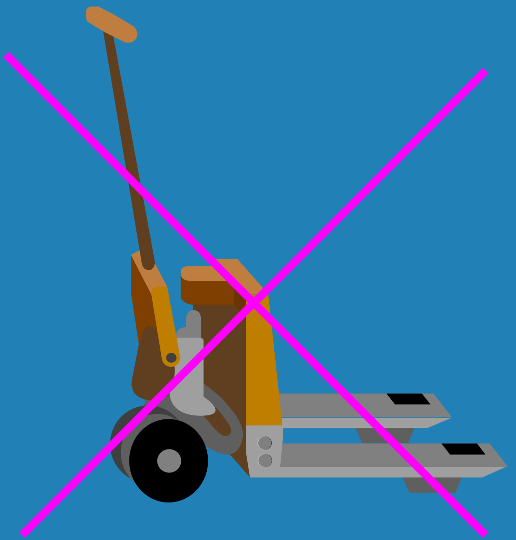


Manufacturing Technology

- Numerically controlled (NC) machines
  - –controlled by punched tape
- Computer numerical controlled (CNC)
  - –controlled by attached computer
- Direct numerical control (DNC)
  - – several NC machines controlled by single computer

Automated Material Handling

- Conveyors
- Automated guided vehicle (AGV)
- Automated storage & retrieval system (ASRS)



Flexible Manufacturing Systems (FMS)

- Programmable machine tools
- Controlled by common computer network
- Combines flexibility with efficiency
- Reduces setup & queue times

NON-CONVENTIONAL MACHINING

Non-Conventional Machining (NCM) represents one of the technologies, which emerged after Second World War to cope with the demand of sophisticated, more durable and cost competitive products. There has been a rapid growth in the development of harder and difficult to machine metals and alloys such as metal-matrix composites, super alloys, ceramics, aluminides, carbides, stainless steel, heat resisting steels and many other High-Strength-Temperature-Resistant (HSTR) alloys (Sarwar1999) etc. These materials find wide applications in aerospace nuclear engineering and other industries due to their high-strength-to-weight ratio, hardness and heat resisting qualities.

- Due to many attractive properties, ceramics is widely used in medical, electronic and defense applications. The cemented carbides because of their high hardness and excellent impact resistance are most commonly used for cutting tools in lathes and other industrial machines.
- In spite of recent technological development, conventional edged tool machining is uneconomical for such materials and degree of accuracy and surface finish attainable is poor. Moreover, machining of these materials into complex shapes is difficult, time consuming and sometimes impossible. For example, Poly-crystalline diamond (PCD), which is almost as hard as natural diamond, cannot be effectively machined by traditional machining processes. Further, the high costs associated with these difficult-to-machine materials and damage generated during their machining is major impediments to the use of these materials. For example, the costs of machining of the structural ceramics (such as silicon nitride) often exceed 50% of the total production cost.

- The stringent requirements to machine complex shaped geometrical shapes with high precision and accuracy and the advancing strength level has a catastrophic effect on the total machining bill if there was no corresponding improvement in the machining technology. In view of the seriousness of this problem, Merchant (1960) emphasized the need for the development of newer concepts in metal machining. By adopting a unified programme and utilizing the results of basic research, it has now become possible to process some of the materials which are formerly considered to be unmachinable under normal conditions. The newer machining processes, so developed, are often called modern machining processes or non-conventional machining processes. These are non-conventional in the sense that the conventional tools are not employed for metal cutting. But energy in some other form is utilized for machining.

- The processes in this category differ from conventional processes in either utilization of energy in an innovative way or in using forms of energy that were unused for the purpose of manufacturing. The conventional machining processes normally involve the use of energy from electric motors, hydraulics, gravity, etc. and rely on the physical contact between tools and work components. On the contrary, NCM processes utilise energy such as that from electrochemical reactions (chemical/Electro chemical energy), high temperature plasma (Heat/thermal energy), high velocity jets and loose abrasives mixed in various carriers (mechanical energy) etc.

- Although these processes were originally developed to handle unique problems in aerospace industry (machining of very hard and tough alloys), today a wide range of industry has adopted this technology in numerous manufacturing operations. On the basis of type and nature of energies [such as chemical, electrochemical, thermal and mechanical (Shan 2002, Weller 1984)] used in the machining, NCM processes are classified in to following categories:
- **Chemical Processes**
- **Electro-Chemical Processes**
- **Thermal Processes**
- **Mechanical Processes**

- **Chemical Processes**: The processes based on chemical energy, use chemical reactions for the purpose of material removal. The basic principle is that most of the metals are vulnerable to be attacked by one or more chemicals; consequently the metal is eroded in to the desired form. These processes involve the application of resistant material (acidic or alkaline in nature) to certain portion of the work surface. The desired amount of material is removed from the remaining area of the work-piece by the subsequent application of an etchant that converts the work-piece material into a dissolvable metallic salt; consequently the metal is eroded in to the desired form. No forces are involved in theses processes. Chemical Machining (CHM), Photochemical Machining (PCM) are some of the important processes in this category.

- **Electro-Chemical Processes**: Electro-Chemical processes involve removal of metal by the mechanism of ion displacement (reverse of the electroplating principle). High current is required as the source of energy and electrolyte acts as transfer media. The material removal occurs due to a high-speed liquid electrolyte that flows between a cathode tool and anodic work component. Electro-Chemical Machining (ECM), Electro-Chemical Grinding (ECG), Electro-Chemical Honing (ECH) and Electro-Chemical Shaping (ECS) are the major processes, which employ this principle.

- **Thermal Processes**: Thermal processes involve the application of very intense local heat. Here, melting or vaporizing the small areas at the surface of the work-piece removes material. The source of energy used is amplified light, ionized material and high voltage. Necessary heat is generated by high frequency electric sparks, high-speed electrons, or ionized plasmas. Due to provision of a variety of energy sources, a wide range of materials can be machined with these processes. The processes in this group include Plasma Arc Machining (PAM), Laser Beam Machining (LBM), Ion Beam Machining (IBM), Electrical Discharge Machining (EDM) and Wire-Cut Electrical Discharge Machining (WEDM).

- **Mechanical Processes**: In mechanical processes, the metal removal takes place either by the mechanism of simple shear (conventional machining) or by erosion where high velocity particles are used as transfer media. Generally, the abrasive particles are added into high-speed jet of gas or water. The kinetic energy of the jet imparts acceleration to the fine abrasive particles, which bombard the workpiece material and cause erosion. In these processes, there is a direct mechanical action between the abrasive particles and the work surface. Apart from a vast range of materials, ceramics, composites and organic materials are good candidates for these processes [Benedict 1987]. Abrasive Jet Machining (AJM), Ultrasonic Machining (USM), Water Jet Machining (WJM), and Abrasive Flow Machining (AFM) are the major processes in this group.

- Based upon the four types of energy mentioned above, a large number of NCM processes have been developed in the past. Each process has its own advantages and limitations. As far as the range of materials to be machined by theses processes is concerned, the mechanical type NCM processes have an edge over the other NCM processes. The material of any hardness and toughness notwithstanding its nature (conductive/ non-conductive, metallic/ non metallic, organic) can be successfully machined with these processes. Thermal energy based processes can also machine a wide range of materials but distortion of workpiece, the generation of heat-affected zones and thermal recast layers generally limit their applications. One typical problem that cannot be solved by all the processes mentioned above is the machining of complex, irregular, zigzag and fine details inside a component.

- Among various mechanical NCM processes, MAM process possesses special /unique capabilities in machining inaccessible regions and complex shapes on the workpiece when compared to other processes in this category. Barring high costs of Magnetic Abrasives, MAM possesses remarkable process capabilities. It has been noticed that AJM, WJM, LBM and USM give almost comparable accuracy and possess nearly similar capabilities but have no solution when the task is to finish machine irregular and complex shapes in the interior of the components. Although AJM has been exploited to be used in machining of cross-drilled holes (Balasubramaniam 1999) but one serious limitation is due to high velocity of the jet; several sharp edges in the region to be machined may remain unmachined (McCarty 1970). This is due to the probable generation of dead/ stagnation zone over the sharp corners, which causes the jet to often pass without touching the sharp edges.