

# Advanced Manufacturing Processes (AMPs)

## Chemical Machining Processes

by

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CHM by Dr. Sunil Pathak

# Chapter Description

- Aims
  - To provide and insight on Chemical Machining processes
  - To provide details on why we need CHM and its characteristics
- Expected Outcomes
  - Learner will be able to know about CHM
  - Learner will be able to identify role of CHM in todays sceneries
- Other related Information
  - Student must have some basic idea of conventional manufacturing and machining
  - Student must have some fundamentals on materials
- References

Lecture Notes of Mr. Wahaizad (Lecturer, FTeK, UMP)



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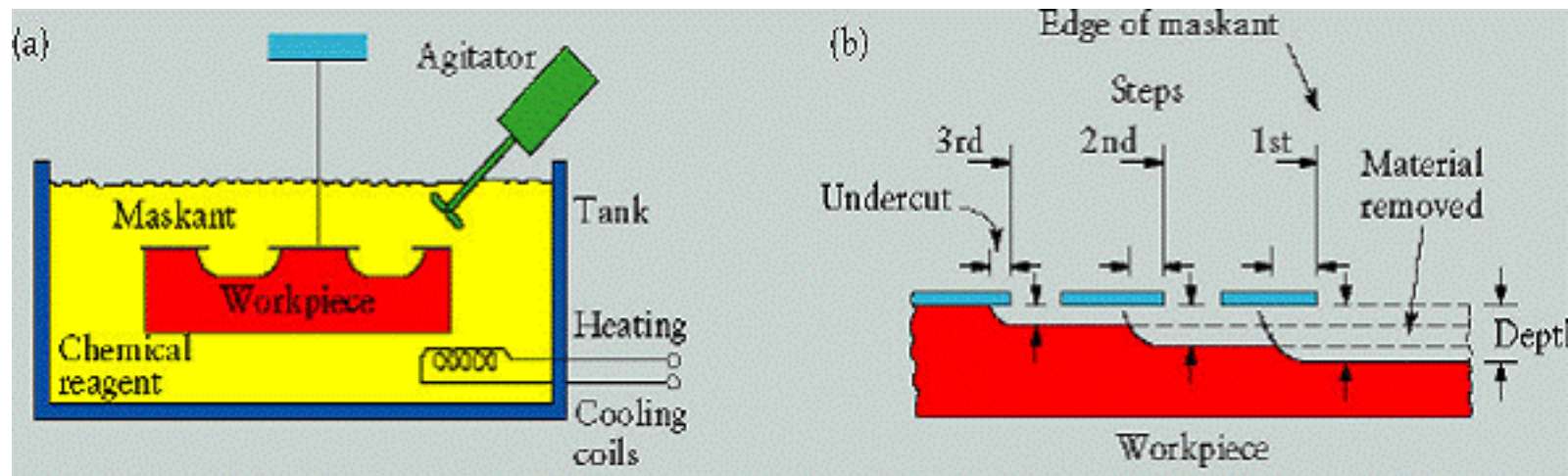
# CHEMICAL MACHINING

✓ CHEMICAL MILLING

✓ PHOTOCHEMICAL MACHINING

# ✓ CHEMICAL MACHINING

A material removal process to produce shape/ pattern on material (metal, glass, plastics, etc) by means of chemical **etching** (the etching medium is called **etchant** - acid, alkali) usually through a pattern of holes/apertures in adherent etch- resistant **stencil** (maskant/resist, photoresist).



# ✓ CHEMICAL MACHINING

Two chemical machining processes to be discussed:

- 1) Chemical Milling (CHM)
- 2) Photochemical Machining (PCM)

## 1) Chemical Milling (CHM)

- bulk machining
- when required, stencil produced by scribing technique, usually employing template
- also known by different names:
  - Chem-milling
  - Chemical or chemi-contouring
  - Chemical or chemi-machining
  - Chemical or chemi-etching



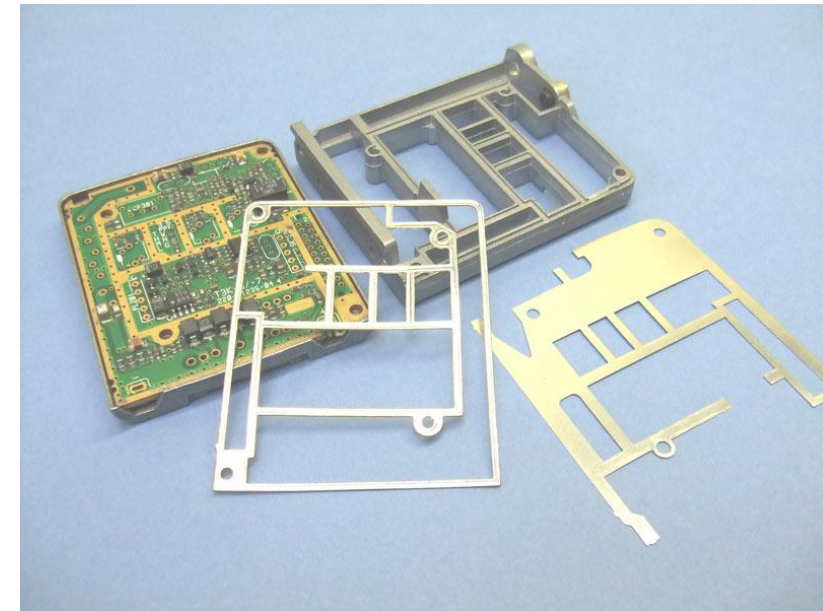
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# ✓ CHEMICAL MACHINING

## 2. Photochemical Machining (PCM)

- ❑ usually flat components from sheet material
- ❑ (less than 0.01 mm to greater than 1.5 mm)
- ❑ light-sensitive resist (photoresist),
- ❑ photographic technique for tool production.
- ❑ also known by different names:
  - Photoetching
  - Photochemical milling
  - Photomilling
  - Photofabrication
  - Chemical blanking
  - Chemical etching
  - Chemical fabrication
  - Chemi-cutting



# CHEMICAL MACHINING

In chemical machining (CHM and PCM), machining could be done:

- ✓ on all surfaces of work material, known as **overall** etching, or
- ✓ on selected area/s of the surface, known as **selective** etching.

In case of sheet or plate, it could be machined:

- ✓ on one side, called **one-sided etching**, or
- ✓ from both surfaces, called **two-sided etching**.

In case of sheet or plate, the machined feature could be

- ✓ a complete perforation across the thickness, sometimes called **through etching**, or
- ✓ a partial perforation, such as **pocket milling** or a **engraving**.

In case of sheet or plate,

- ✓ if through etching is done completely around a part (ie it separates completely from the initial strip), this is called chemical **blanking**.



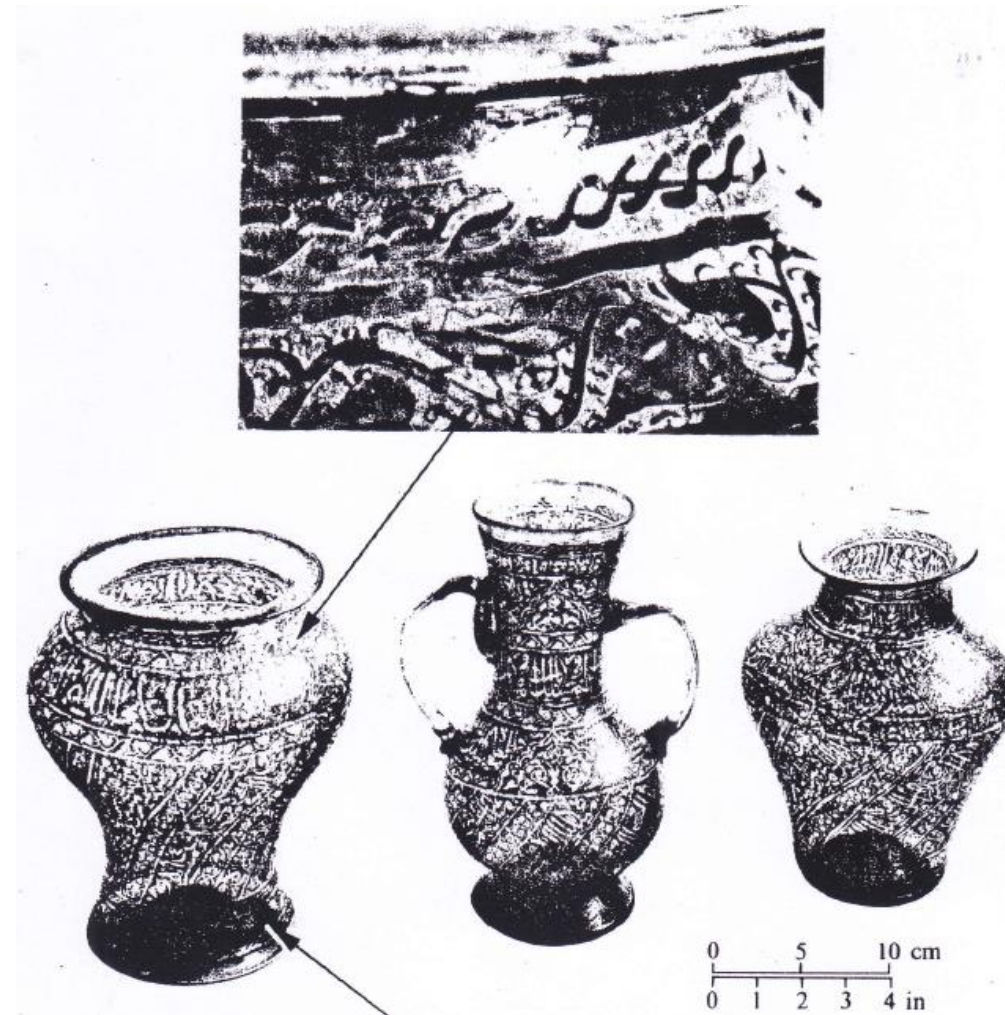
# CHEMICAL MACHINING

## HISTORICAL DEVELOPMENT

- ancient Egypt – decorative, artistic purpose
- late 40's – thin/sheet components processed entirely by chemicals
- just before WW2 – reticles for guns, bombs
- during WW2 – aircraft components
  - printed circuits (copper)
- 1953 – modern chemical milling (guided-missile casing)
- 1956 – modern chemical milling patent for structural components
- 1986 – patent for automated chemical milling operation



# CHEMICAL MACHINING



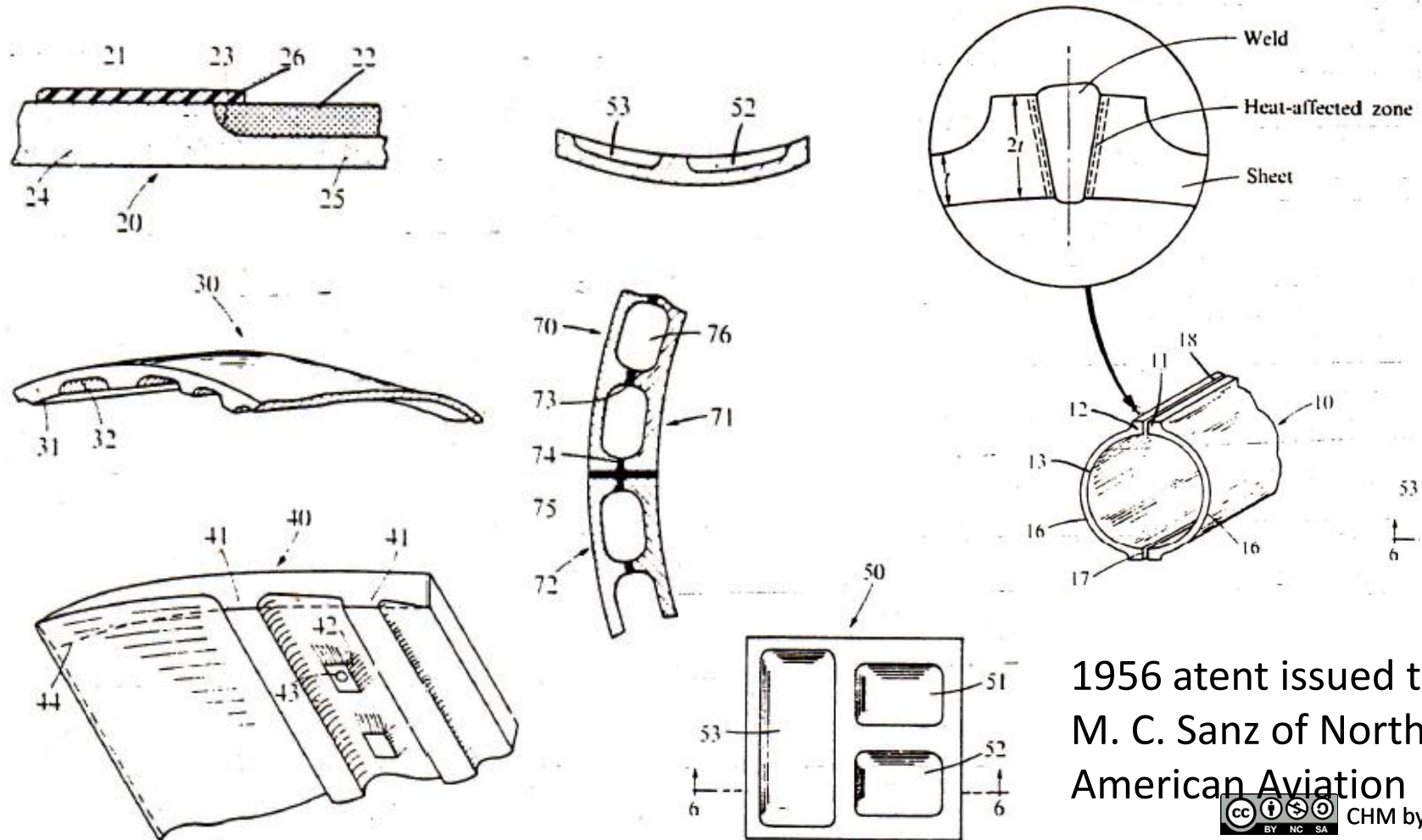
Etching on glass bottles from Middle East (1850)



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# CHEMICAL MILLING

## Patent 1: Modern chemical milling process for structural shapes (1956)



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# CHEMICAL MILLING

**Patent 2:** An automated chemical milling process for metal articles (EP 0179940 A1; 1986)  
[Grumman Aerospace Corporation]

- ✓ Metal article is first coated with an etchant **resist coating**.
- ✓ Area to be etched is **digitized** to define the x, y coordinate values for the perimeter line.
- ✓ A CPU is used to control a flatbed drafting table with a tangentially controlled **scribing tool** to cut through the resist coating along the perimeter line.
- ✓ For multi-etching steps, each perimeter line is digitized and scribed or cut in a similar manner. All but one of the perimeter lines are recoated and marked, and the resist coating peeled/removed.
- ✓ Metal part is then etched as desired.
- ✓ For 3-D workpiece, the x, y, z point coordinate values for a perimeter line are defined, and the scribing operation is done by a robotic device controlled by a CPU.
- ✓ New template or mask geometry is created on a CRT and digitized for subsequent control of the **plotting table** or other **robotic device**.

# ✓ CHEMICAL MILLING



FIG. 9

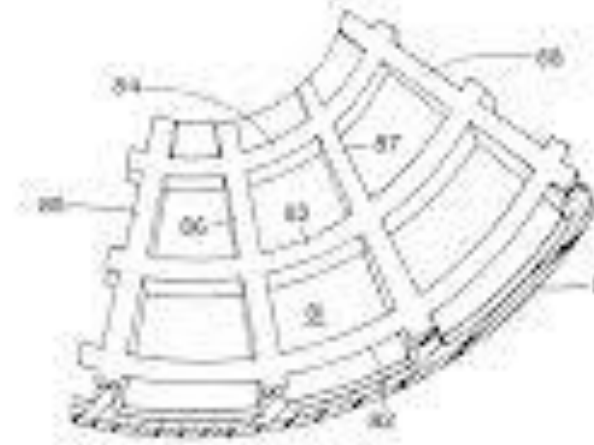


FIG. 10

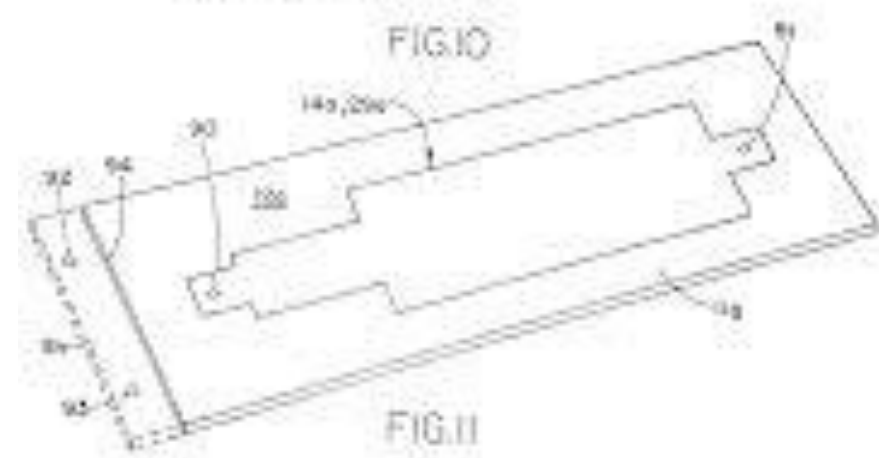


FIG. 11

# 1. CHEMICAL MILLING (CHM)



# 1. CHEMICAL MILLING (CHM)



## Example: **Manufacture of aircraft parts**

- Chemical milling consists of removing some metal on large surfaces to give a form to the pieces or to give them a thickness
- Chemicals used for milling are **acids** (sulfuric, nitric, etc.), **bases** (caustic soda), and solvents (acetone). They are used in large quantities and in high concentrations.



# 1. CHEMICAL MILLING (CHM)

## STEPS IN CHEMICAL MILLING

(Stress relieving if part has residual stress from previous process)

- 1) **Cleaning**, to ensure uniform adhesion of stencil and uniform etching
- 2) **Masking**, to cover areas that need no machining
- 3) **Scribing**, to define required pattern by exposing areas that require machining
- 4) **Etching**, to machine uncovered areas using chemicals
- 5) **Demasking**, to remove maskant

# 1. CHEMICAL MILLING (CHM)

## Step 1. **CLEANING**

- Surface must be clean of oil, grease, paint, ink, marking, oxide, etc
- All surfaces must be clean even if milling is done on one side

## **STEPS IN CLEANING**

- i. Apply solvent and/or vapour degreaser – to remove visible oil, primer, marking inks
- ii. Dip in alkaline cleaner – to remove dust, oil stain, primer, ink, small foreign surface material
- iii. Dip in deoxidiser (for aluminium alloy) or descaler (for steel and titanium) – to remove oxide and scale
- iv. Rinse (dip/spray) after every step – to ensure cleaning agents do not mix
- v. Dry workpiece after final rinsing

During and after cleaning and drying, workpiece must be handled carefully:

- Handle using suitable glove
- Handle with crane by remote control
- Handle with automatic conveyor

# 1. CHEMICAL MILLING (CHM)

## Step 2. MASKING

Maskant should have these **characteristics**:

- Can adhere sufficiently strongly (if adhesion is too strong, peeling of maskant after scribing will be hard)
- Remain adhered on work surface during dipping into or spraying by etchant up to 100 °C
- Possess enough strength to protect edges being etched

**Examples** of maskant material:

- ✓ neoprene elastomer
- ✓ isobutylene-isoprene co-polymer

NB: masking involves highly **volatile** solvents. Masking plant must have good **ventilation** to reduce fire and health risks.

# 1. CHEMICAL MILLING (CHM)

## MASKING TECHNIQUES

2.1 Dipping

2.2 Flow coating

2.3 Spraying

## DIP COATING

- Requires sufficiently large tank.
- Requires sufficiently large quantity of masking material.
- Suitable for high quantity work and processed continuously.
- Masking liquid must be kept at required viscosity by adding solvent periodically and stirring evenly.
- Stirring must be done carefully to avoid air bubbles.
- Dipping and withdrawing speed must be controlled.
- Work material is given sufficient time for excess maskant to drip before it is removed to drying section.

# 1. CHEMICAL MILLING (CHM)

## DIP COATING (contd)

- Thickness of coating is not uniform – thin at the top, thicker at the bottom.
- This can be corrected by inverting workpiece during next dip
- Each dip produces a coating between 0.05 and 0.1 mm.
- Most chemical milling work requires mask thickness from 0.25 to 0.3 mm to ensure sufficient strength.

Appropriate mask thickness depends on:

- ✓ Depth of etch (duration maskant is required to protect work from etchant)
- ✓ Type of work material
- ✓ Type of maskant material
- ✓ Method of etching



# 1. CHEMICAL MILLING (CHM)

## FLOW COATING

- Requires more complex plant than dipping.
- Requires less quantity of maskant.
- Pump feeds maskant to hoses, manipulated by hand.
- Automatic flow coating for large through-put, with multiple hose heads and overhead conveyor.
- Inversion of products after each coating to ensure uniform coating thickness.

## SPRAY MASKING

- For large items difficult to handle by above methods.
- Or, intermittent requirement does not justify installation and maintenance of maskant tank.
- Requires spraying equipment and spraying booth.
- Electrostatic spraying or airless spraying may be employed.



# 1. CHEMICAL MILLING (CHM)

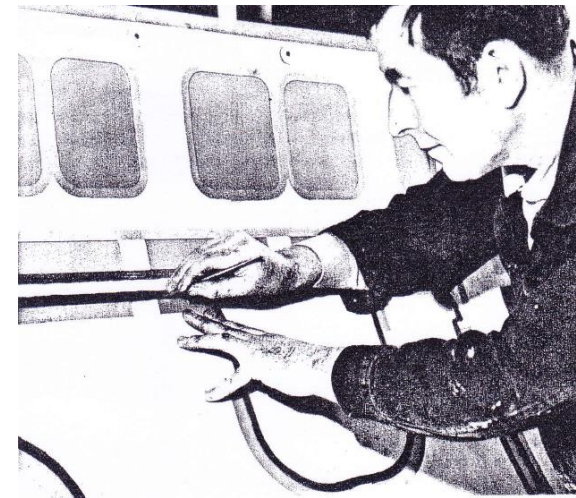
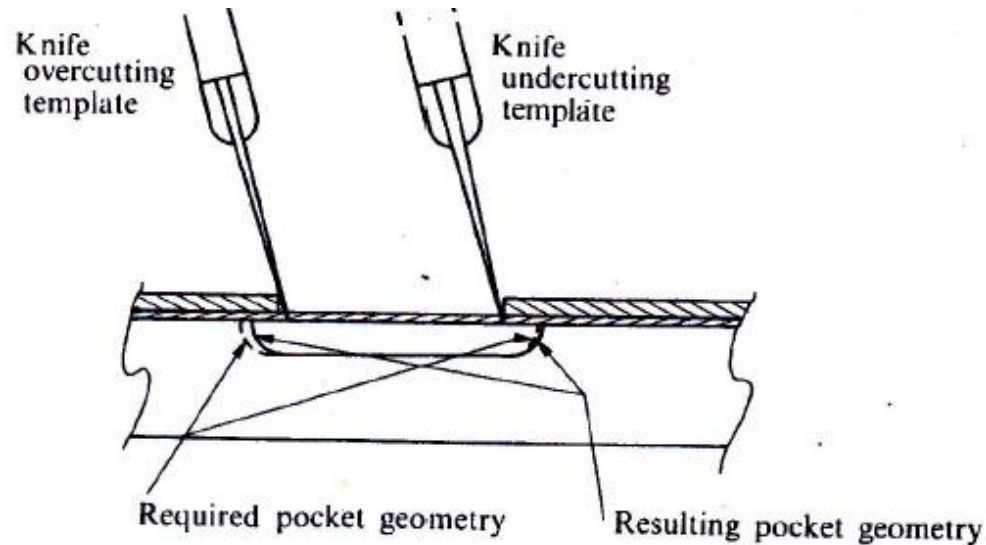
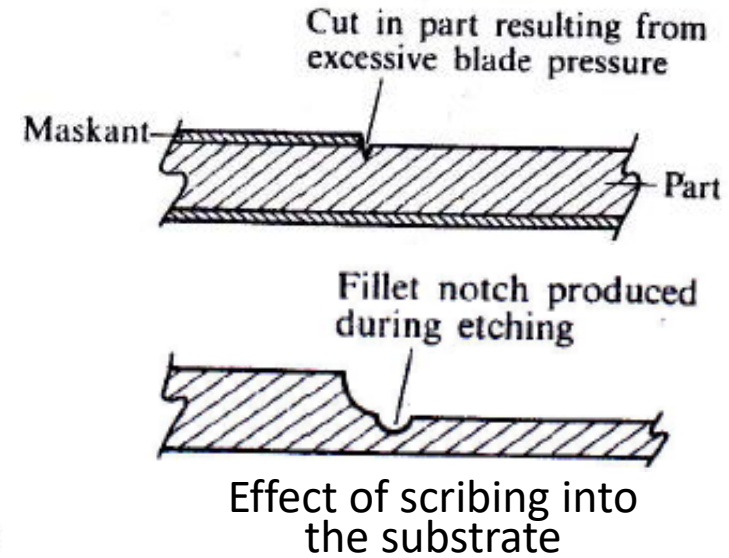
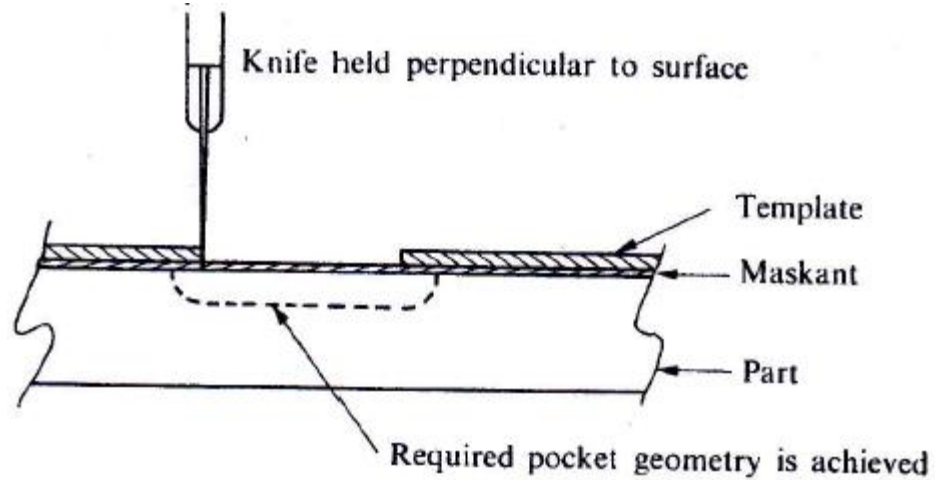
## SCRIBING

### SCRIBING KNIFE

- Scribing by means of thin-bladed knife and peeling by hand.
- Machining allowance due to side etching must be given.
- Accurate definition requires template with built-in accurate machining allowance.
- Scribing knife needs to be held perpendicular and scribing requires appropriate pressure of cut.
- If depth of cut is insufficient, maskant may lift off during peeling.
- If scribing cuts into substrate material, a notch will be cut, producing fillet notch during etching (bad for fatigue and high stress environment)
- With template, scribing operator can focus on producing good, accurate and consistent cut.

# 1. CHEMICAL MILLING (CHM)

## SCRIBING KNIFE



Effect of tilted knife when scribing

Hand scribing using template

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# 1. CHEMICAL MILLING (CHM)

## SCRIBING

### SCRIBING KNIFE



Scribing and stripping while using a template



Hand stripping of mask

# 1. CHEMICAL MILLING (CHM)

## SCRIBING (cotd)

## HOT KNIFE

- Blunt needle heated electrically, cuts maskant by local melting.
- Will not cut substrate.
- May produce irregular edge.
  
- Practical and successful for small repetitive cuts (eg. small holes on aircraft-wing leading edge).

## LASER BEAM

- Used if can be justified economically.



# 1. CHEMICAL MILLING (CHM)

SCRIBING (cotd)

HOT KNIFE

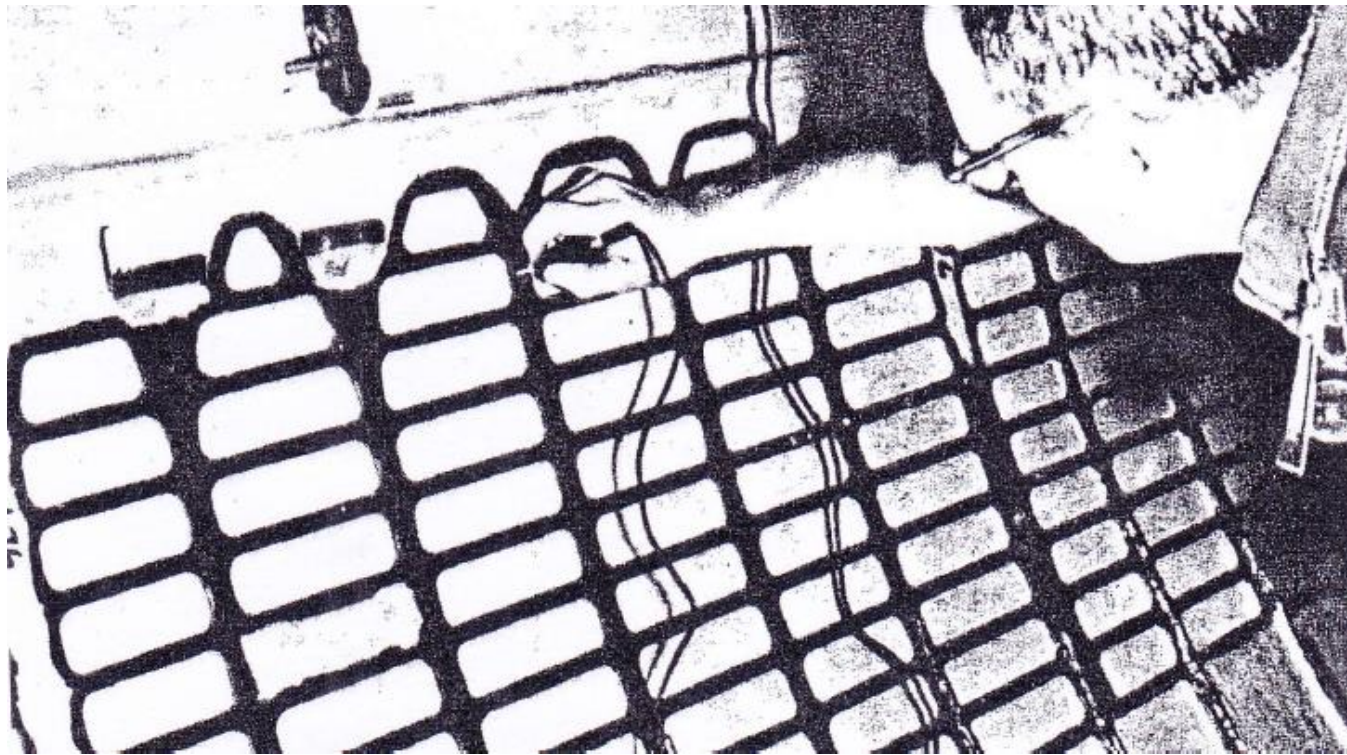


Figure: Hot knife for scribing

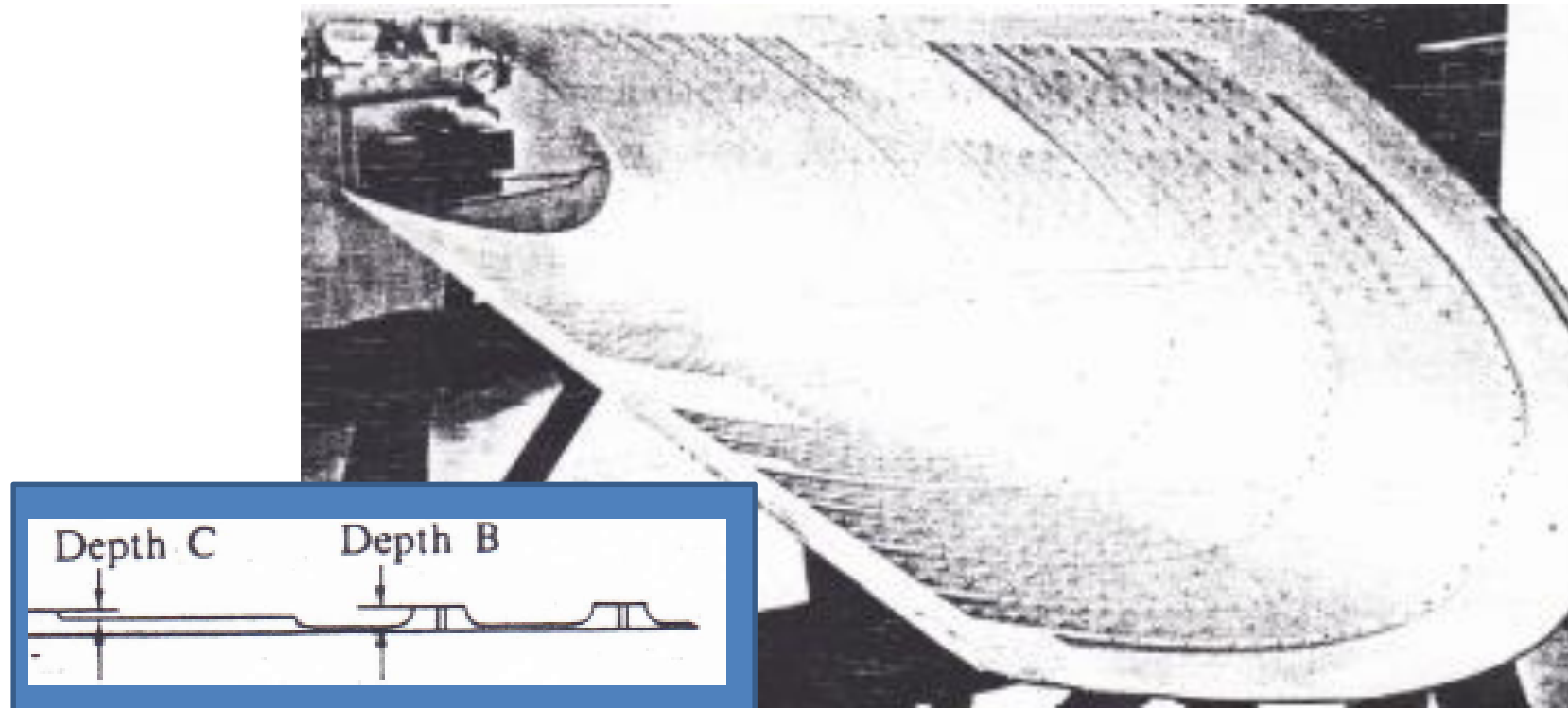


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# 1. CHEMICAL MILLING (CHM)

SCRIBING (contd)

HOT KNIFE – Case study:



**Figure:** Aircraft panel with a lot of repetitive holes (details as inset)



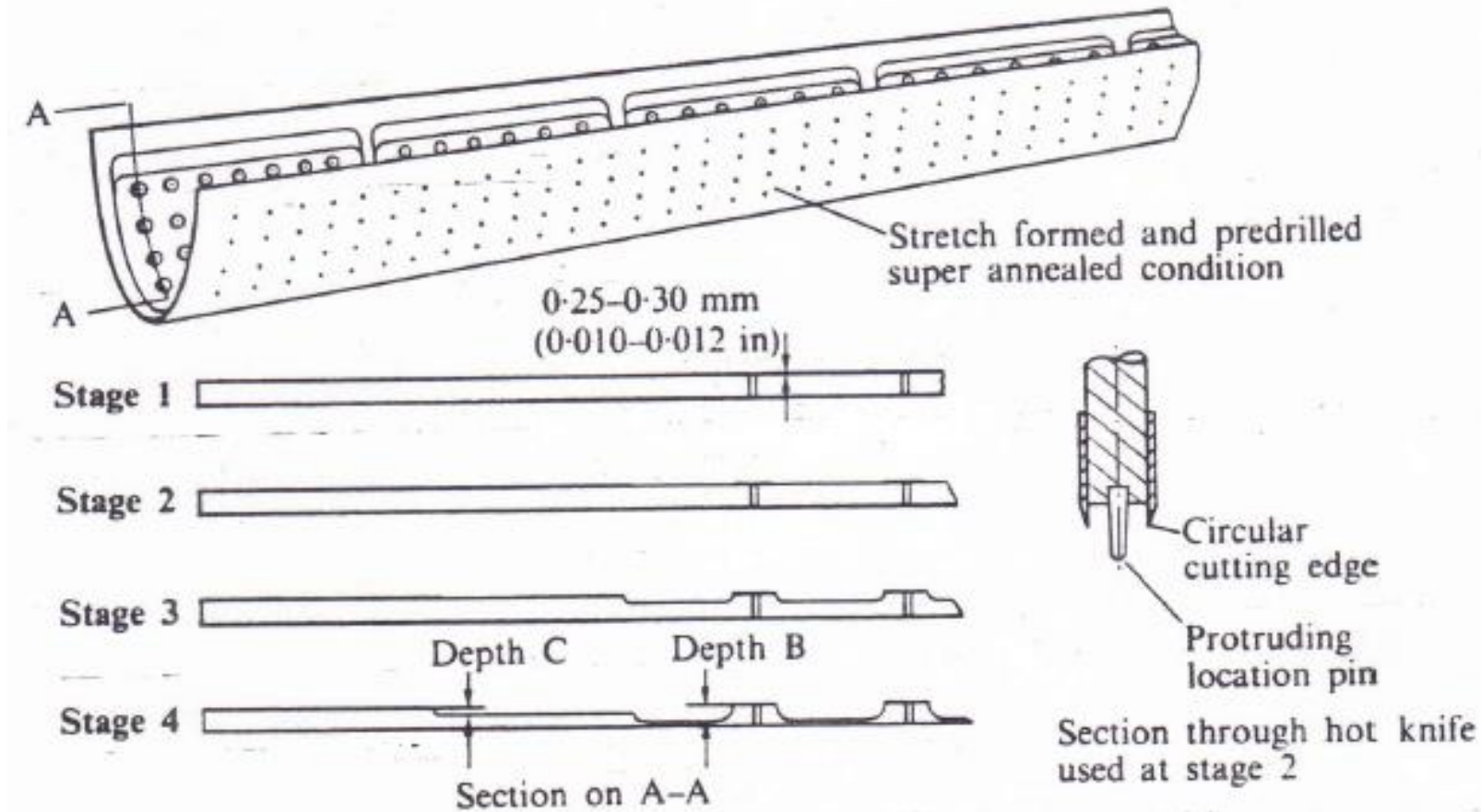
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# 1. CHEMICAL MILLING (CHM)

Step 3. **SCRIBING** (contd)

3.2 **HOT KNIFE** – Case study:



**Figure:** Aircraft panel with a lot of repetitive holes



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# 1. CHEMICAL MILLING (CHM)

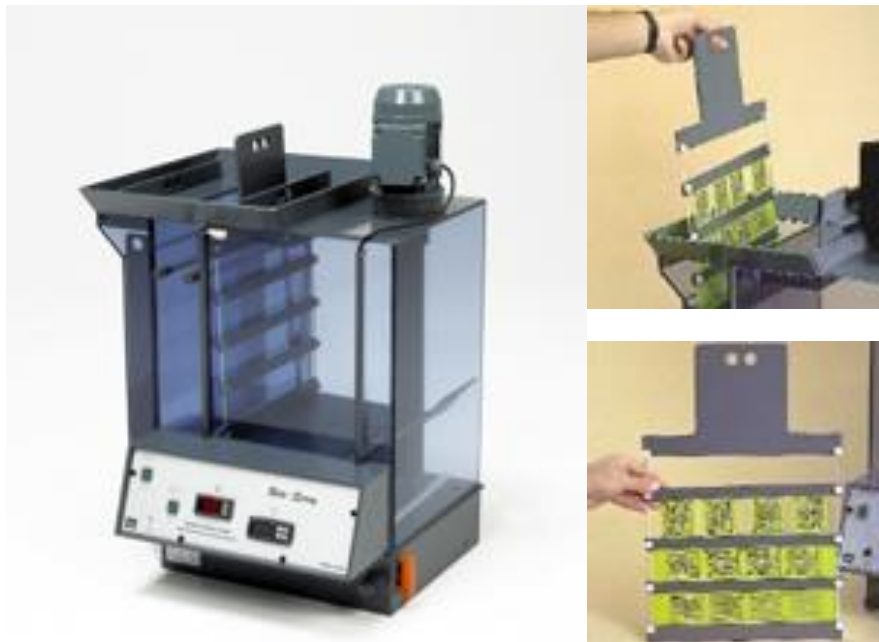
## Step 4. ETCHING

Methods of etching:

- Dip etching in etching bath
- Spray etching (aqueous/liquid)
- Spray etching (gaseous)



A 3-compartment etching bath



Spray etching machine



A 5-compartment wet etching table



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# 1. CHEMICAL MILLING (CHM)

## Step 4. **ETCHING**

Types of etching:

### 4.1 **OVER ALL** ETCHING

Workpiece cleaned but not coated with maskant.

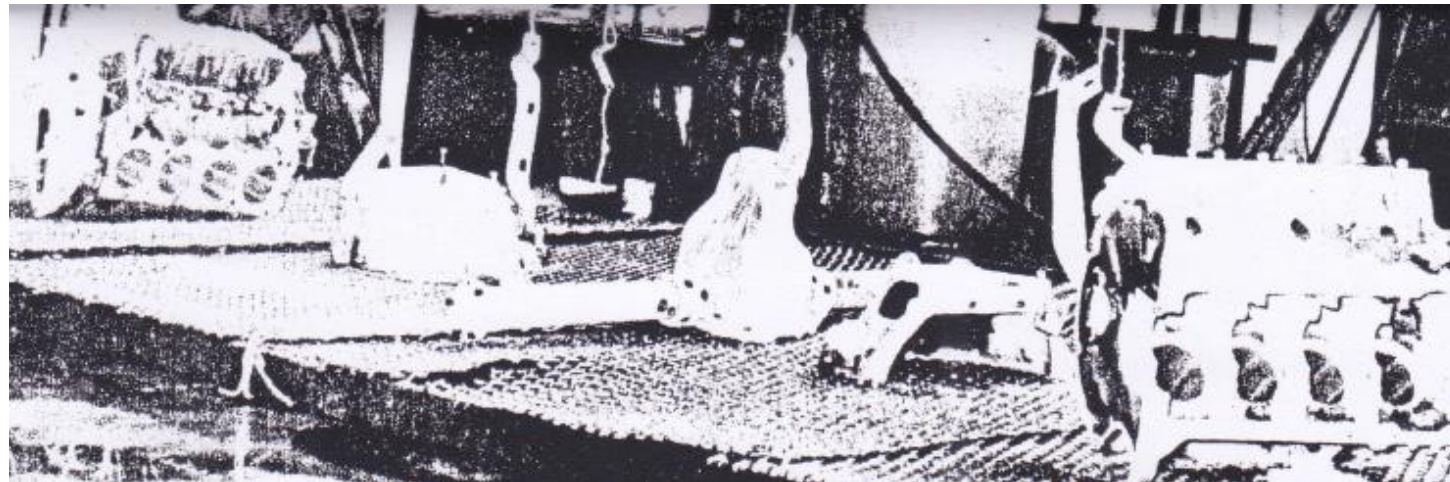
Applications:


- To reduce weight of forging, casting, assembled part.
- To produce non-standard gauge thickness of sheet.
- To remove oxide layer from components.
- To modify surface characteristics. Examples: car wheel before plating; silicon wafer before circuit making

# 1. CHEMICAL MILLING (CHM)

## 4.1 OVER ALL ETCHING

Car wheel chemically etched to assist adhesion of chemical plating processes



High performance car engine and transmission parts chemically milled up to 1.02  CHM by Dr. Sunil Pathak



# 1. CHEMICAL MILLING (CHM)

## Step 4. ETCHING

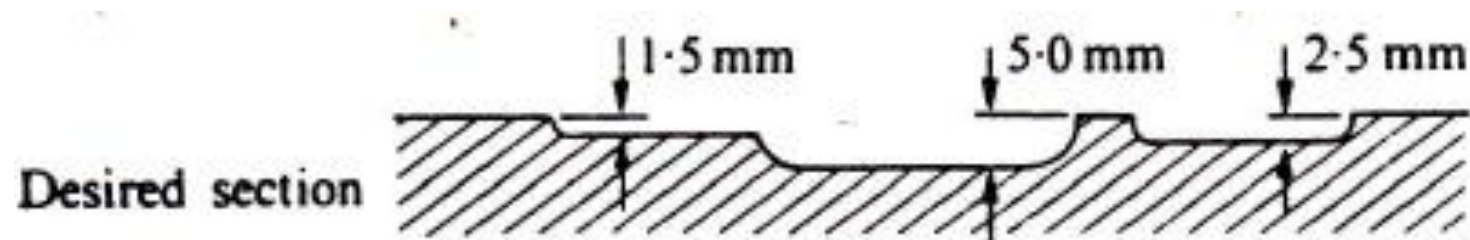
Types of etching:

### 4.2 SELECTIVE ETCHING

- Maskant is scribed to the required pattern.

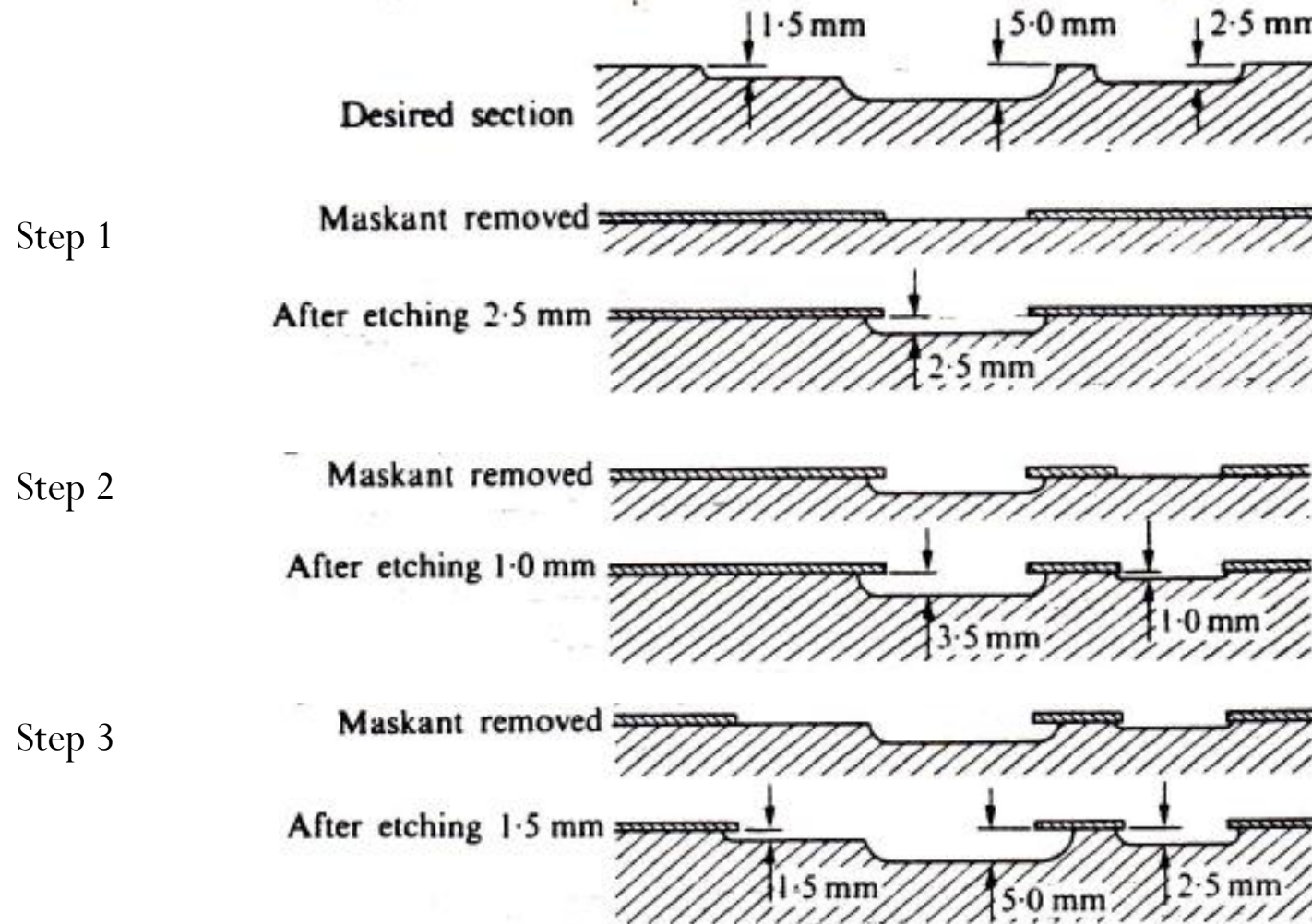
### 4.3 MULTI-STEP ETCHING

- To produce several different depths of cut.
- Tolerance at each depth of cut is additive.
- Template is colour-coded to assist scribing.



# 1. CHEMICAL MILLING (CHM)

## 4,3 MULTI-STEP ETCHING



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Figure: Example of multi-step etching involving 3 steps



# 1. CHEMICAL MILLING (CHM)

## Step 4. **ETCHING**

Types of etching (cotd)

### 4.4 CHEMICAL **BLANKING**

- Etching is done simultaneously from both sides until penetration is achieved.
- Extensively used in PCM (eg shim, PCB, recording-head lamination).

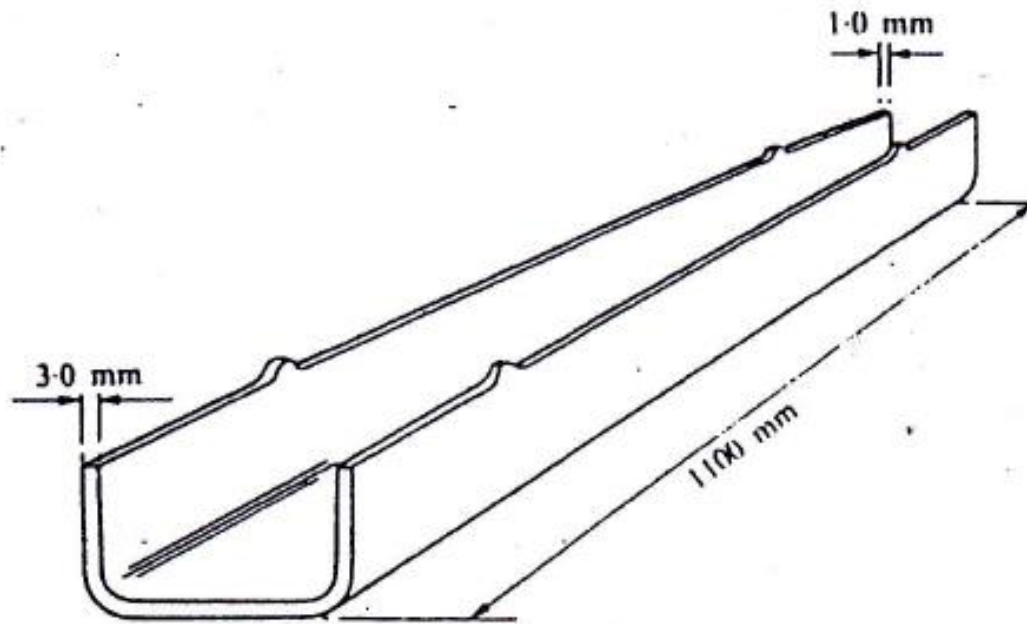
### 4.5 **TAPER** ETCHING

- ✓ To produce long, gradual taper.
- Product is immersed or withdrawn at controlled speed.
- Etching tank must be sufficiently deep.
- More than 2 passes required for good finish.
- Finish is better in dipping pass compared with withdrawing.
- Final pass is normally an immersion followed by withdrawing at maximum speed.

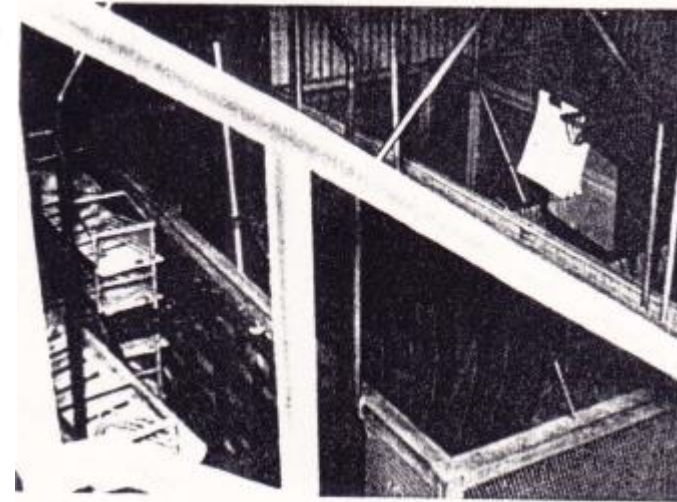
# 1. CHEMICAL MILLING (CHM)

## Step 5. DEMASKING

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Aircraft wing spar tapered over whole length



Parts in rack ready for immersion  
into etchant tank



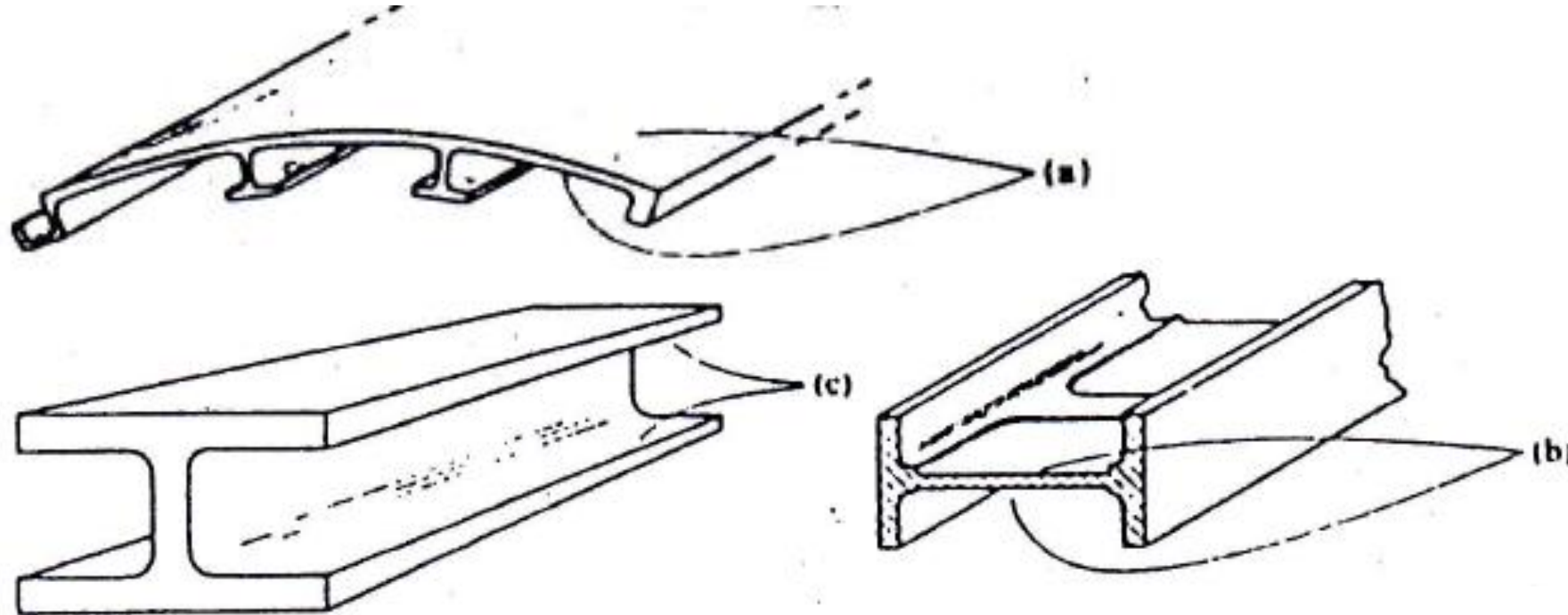
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# 1. CHEMICAL MILLING (CHM)

## Step 5. DEMASKING

Solvent is used to dissolve maskant

\*\*\*\*\*



**Figure:** Examples of extruded sections that are chemically milled: (a) over all etching to thickness not possible with extrusion, (b) pockets cut to reduce weight in web, (c) tapered inner flange

# 1. CHEMICAL MILLING (CHM)

## Taper etching

Speed of immersing/withdrawal,  $v = \frac{NLE}{D}$  (mm/min)

where, N = no. of etching passes

L = length of taper (mm)

E = etch rate per side (mm/min)

D = difference in depth of cut per side (mm)

*Example: Calculate  $v$  if section is 5.0 mm thick and 500 mm long. The taper required is such that thickness at one end is 5.0 mm and 2.6 mm on the other. Assume  $N = 5$  and  $E = 0.025$  mm/min.*

$$v = \frac{5 \times 500 \times 0.025}{2.5 - 1.3} \approx 52 \text{ mm/min.}$$

# 1. CHEMICAL MILLING (CHM)

## Etching Rate

Workpiece is etched for a duration necessary to produce the required depth of etching.

If depth of etch =  $s$  ( $\mu\text{m}$ ) or (mm)

etching time =  $t$  (min)

rate of etching =  $E$ [per side]

$E = s/t$  ( $\mu\text{m}/\text{min}$ ) or (mm/min)

*Example: If thickness of material is 3.0 mm, etching time is 10 min and thickness of material after simultaneous etching from both sides is 2.5 mm,*

$$E = \frac{3.0 - 2.5}{2 \times 10} = \frac{0.5}{20} = 0.025 \text{ mm/min or } = 25 \mu\text{m/min}$$

# 1. CHEMICAL MILLING (CHM)

## Etching Rate (contd)

*If milling to 1 mm depth is required,*

*etching time,  $t = 1.0/0.025 = 40$  min  
(assuming uniform etch rate)*

Etch rate for a particular work material depends on:

- ✓ Etchant concentration
- ✓ Etching temperature
- ✓ Workpiece material type
- ✓ Heat treatment experienced by work material



# 1. CHEMICAL MILLING (CHM)

## Etchant Concentration

Expressed in degree Baume' ( $^{\circ}\text{Be}'$ ).

$$^{\circ}\text{Be}' = \frac{145 \times (\text{s.g.} - 1)}{\text{s.g.}}$$

Where s.g. is specific gravity, measured using a **hydrometer** of a suitable reading range or a **digital density meter**.

To obtain a particular concentration in  $^{\circ}\text{Be}'$ , the etchant is diluted to a corresponding value of specific gravity:

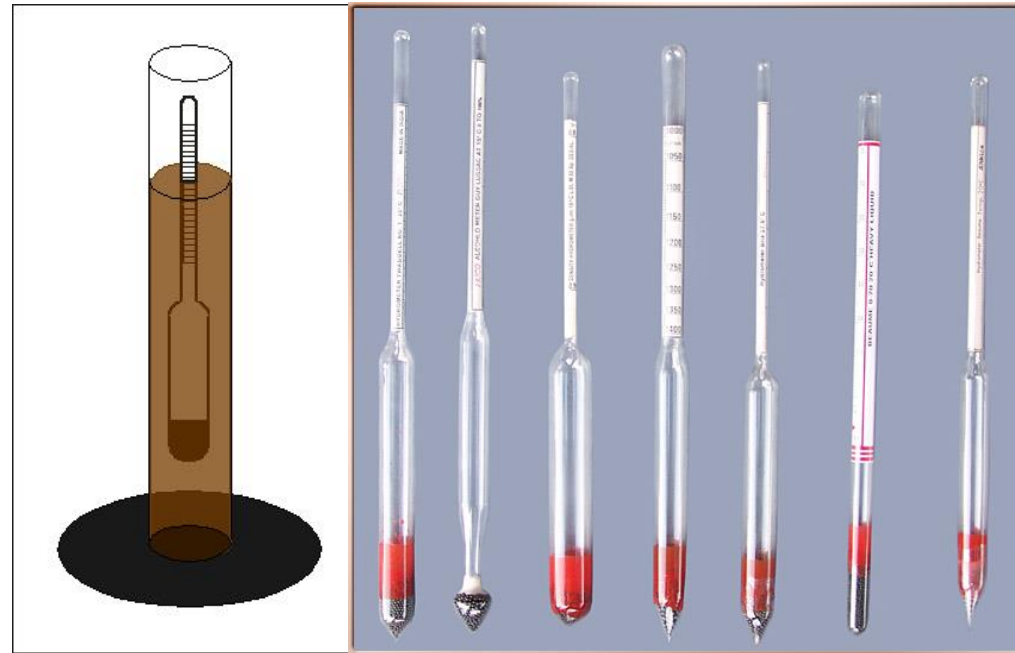
$$\text{s.g.} = \frac{145}{(145 - ^{\circ}\text{Be}')} ,$$

# 1. CHEMICAL MILLING (CHM)

Measurement of etchant concentration



digital density meter



Hydrometer



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# 1. CHEMICAL MILLING (CHM)

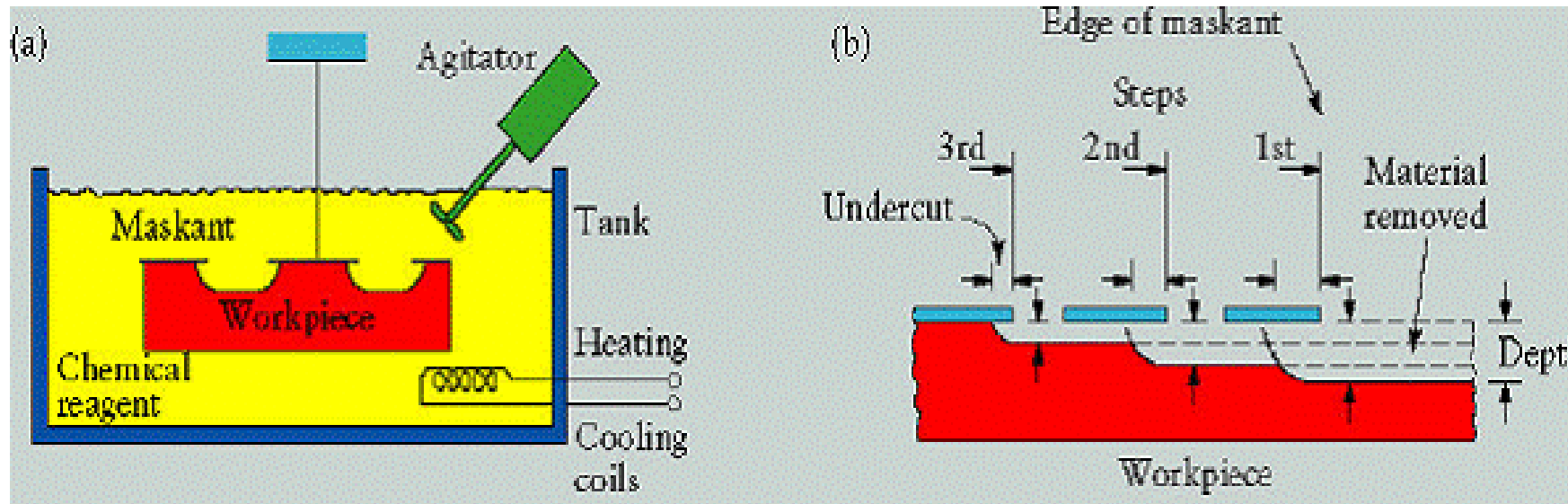
## Etchant Concentration (contd).

*Example: The s.g. of a ferric chloride solution is 1.45. What is its concentration in °Be'? It needs to be diluted to 25 °Be'. What should the hydrometer reading be?*

$$^{\circ}\text{Be}' = 145 \times \frac{(1.45 - 1)}{1.45} = 45^{\circ}\text{Be}'$$

$$\text{s.g.} = \frac{145}{(145 - 25)} = 1.208$$

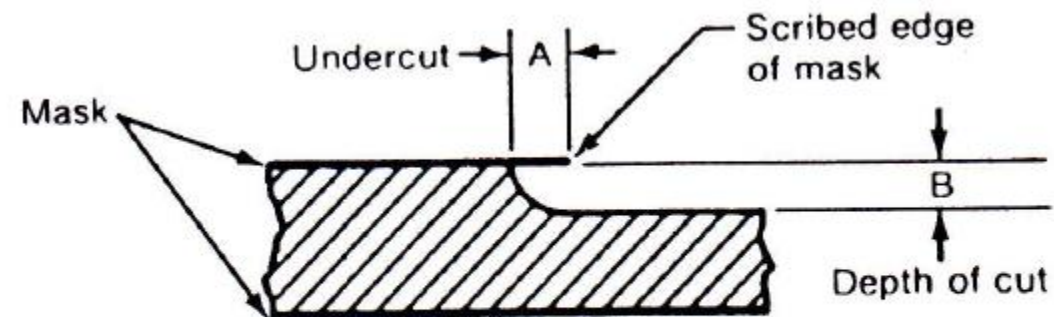
# CHEMICAL MILLING



## Control of Dimensions

In chemical machining (CHM, PCM), two types of dimension need to be controlled:

- 1) **Depth** of etch (or thickness) of part after etching
- 2) Dimensions in **lateral** (ie horizontal) direction  
(eg hole diameter, width of pocket and land)

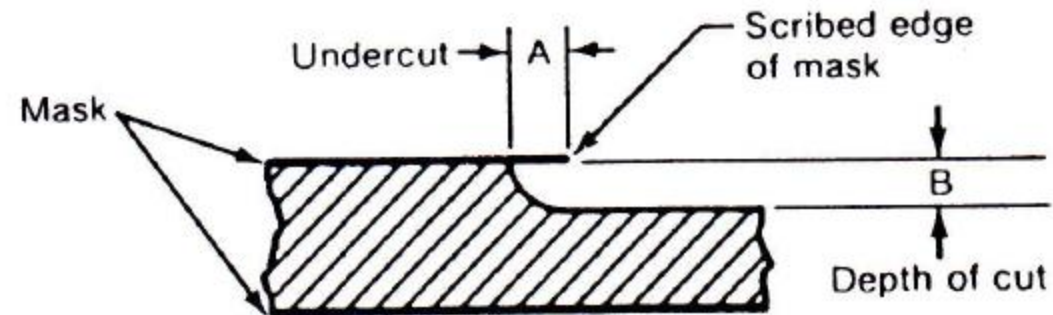


$$\text{Etch factor} = \frac{\text{Depth of cut}}{\text{Undercut}} = \frac{B}{A}$$

## Control of Dimensions

Tolerance on thickness after etching is influenced by:

- ✓ Variations in **etching** operation
- ✓ Tolerance on workpiece thickness **before etching**  
(ie material is removed with original workpiece surface as reference)



$$\text{Etch factor} = \frac{\text{Depth of cut}}{\text{Undercut}} = \frac{B}{A}$$





## Control of Dimensions (cotd)

Dimensions in lateral/horizontal direction is influenced by:

- ✓ Variations in etching operation
- ✓ Side/lateral etching which needs to be compensated
- ✓ Accuracy of template (template tolerance  $\approx \pm 0.25$  mm, can be improved to 0.125 mm)
- ✓ Accuracy of scribing

Normal tolerance of lateral dimensions in Chemical Milling is  $\pm 0.25$  mm or  $\pm 0.5$  mm.

# CHEMICAL MACHINING

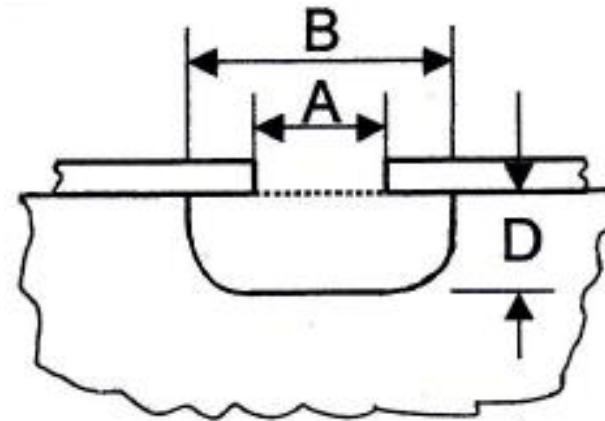
## Control of Dimensions (contd)

### ETCH FACTOR

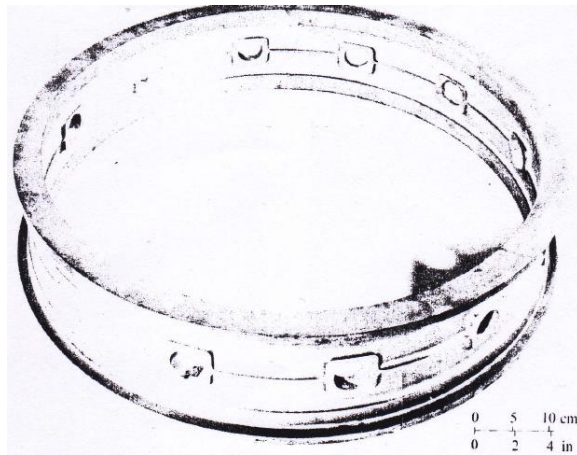
Etch factor is the ratio of inward etching to lateral etching. It is sometimes used as a measure of etching efficiency.

side/lateral etching,  $u = \frac{B - A}{2}$   
(or undercut)

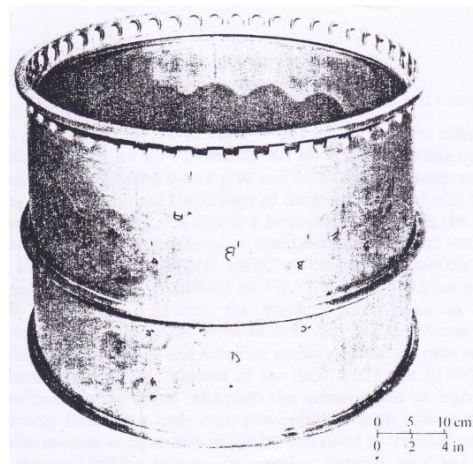
Etch factor,  $EF = \frac{D}{u} = \frac{2D}{B - A}$ ,



# CHEMICAL MILLING



Turbine case (aluminium –  
deepest depth : 7.25 mm)



Aero-engine outer combustion  
case (stainless steel)

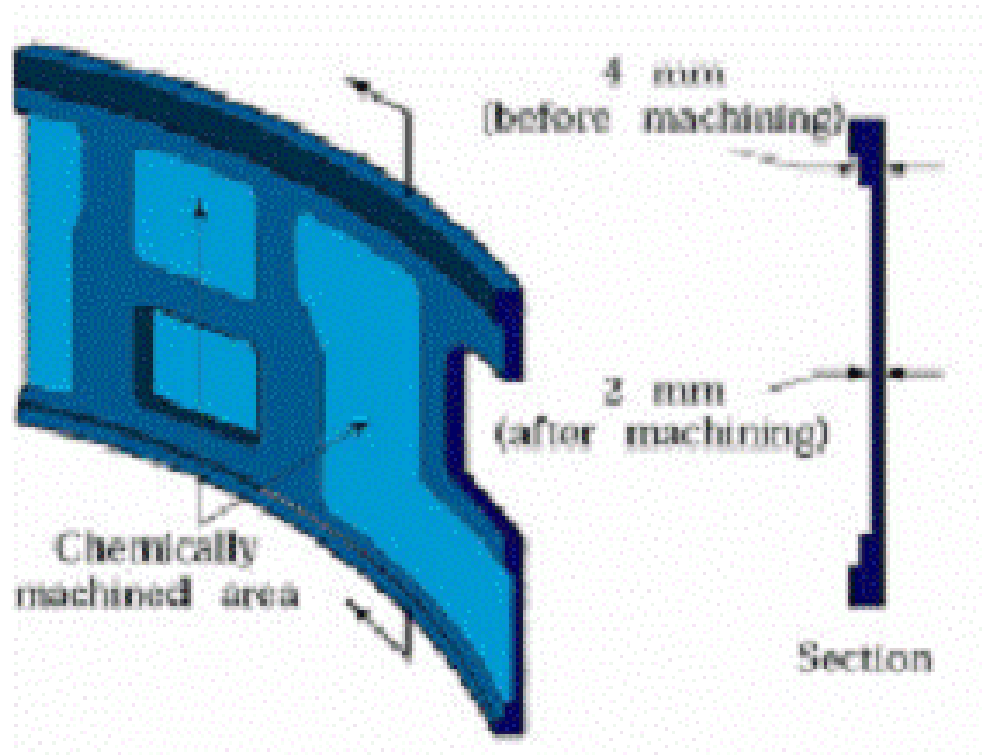


Apollo heat-shield skin (stainless steel)  
Tolerance of pockets:  $\pm 0.025$  mm



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# CHEMICAL MILLING



**Figure:** Missile skin panel contoured by chemical milling to improve stiffness-to-weight ratio [Kalpakjian]

**Figure:** Aircraft part

# CHEMICAL MILLING



**Figure:** Chemically milled fuselage skin panel



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## SURFACE FINISH

- Surface finish depends on surface quality of original workpiece. On most materials, scratches and local damage will be reproduced and magnified. Chemical milling removes small defects or scratches in magnesium, and to some extent in steel and titanium sheets.
- At deeper etching, the influence of original work surface diminishes, the surface finish produced being nearer to typical finish for a particular work material, which has undergone a particular history of heat treatment, and for a particular etchant formulation and etching parameters.



## SURFACE FINISH (cotd)

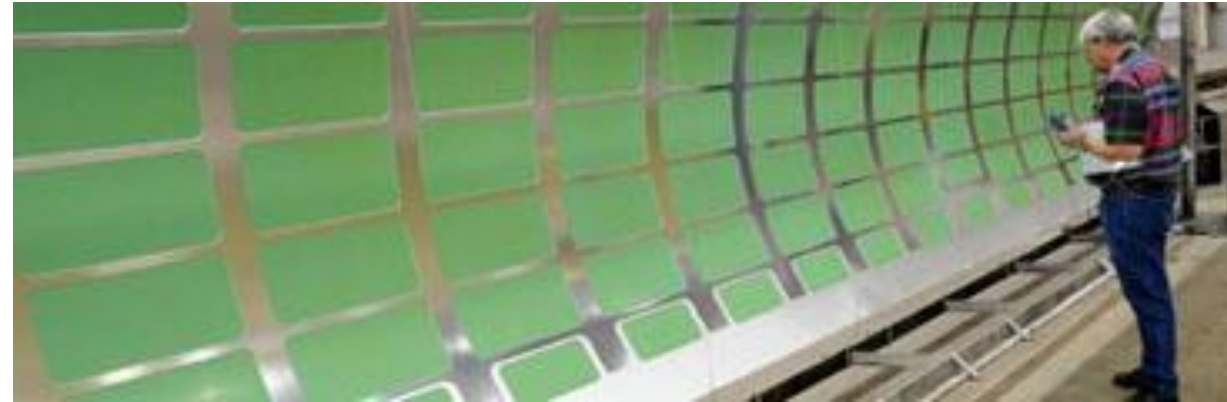
- For a very wide range of material, such as aluminium alloys, copper alloys and steels, surface finish is extremely good, between 0.85 to 2.5  $\mu\text{m}$  rms.
- Titanium alloy gives very fine finish, 0.25  $\mu\text{m}$  being usual.
- Surface finish of many castings (particularly magnesium), extrusions and forgings may be improved by chemical milling.
- Surface finish is influenced by factors like etchant type and degree of alloying. Example: aluminium alloys typically produce a finish of 2.7  $\mu\text{m}$  in alkaline etchant and 0.8  $\mu\text{m}$  in acid etchant, aluminium alloy with higher copper content produces poorer finish than that nearer the commercially pure aluminium.

# SURFACE FINISH ACHIEVED BY CHEMICAL MILLING

<b>MATERIAL</b>	<b>FORM</b>	<b>SURFACE FINISH AFTER 0.25 – 0.40 mm REMOVED (<math>\mu\text{m CLA}</math>)</b>
Aluminium alloys	sheet	2.0 – 3.8
	casting	3.8 – 7.6
	forging	2.5 – 6.4
Magnesium alloys	casting	0.75 – 1.4
Steel alloys	forging	
	sheet	0.75 – 1.5
	forging	
Nickel alloys	sheet	0.75 – 1.0
Titanium alloys	sheet	0.2 – 0.8
	casting	0.75 – 1.5
	forging	0.38 – 1.0
Tungsten	bar	0.5 – 1.0
Beryllium	bar	3.8 – 6.4
Tantalum	sheet	0.25 – 0.5
Columbium	bar	1.0 – 1.5
Niobium	sheet	1.0 – 1.5
Molybdenum	sheet	1.5 – 3.3



# ✓ CHEMICAL MILLING



## Spirit AeroSystems, Wichita, USA [1 of 2]

- Largest chemical tanks in the world, which can accommodate skin sections measuring up to 48 feet long and weighing up to 1,000 pounds
- The operation is capable of running 15,000 parts a day
- Tank lines are elevated for easy detection of leaks
- Employs automated robotic processing, and automated storage and retrieval system that electronically stores and retrieves small parts

# ✓ CHEMICAL MILLING



## **Spirit AeroSystems**, Wichita, USA [2 of 2]

For manufacturer of large-aircraft skin panels, massive stretch presses are used to exert as much as 1,500 tons of pressure and are capable of stretching material ranging in width from 0.3 to 2.8 m and in gauge thickness from .13 to 7.2 mm. Maximum length between jaws is 15 m. Using the latest laser trace technology, protective masking is etched onto the panels in production. The panels are then placed in chemical mill tanks to remove excess material.

## BENEFITS OF CHEMICAL MILLING

### 1. BENEFITS TO DESIGN ENGINEER (cotd)

- ❑ Tapered shapes for progressively changing stress level requirement.

Chemical milling can produce thickness tapers over long, thin component. Examples: titanium fail safe strap (Lockheed), aircraft wing spar, wing and fuselage stringers.

- ❑ Weight control and reduction on forgings, castings and extrusions.

Examples: forged SAE 4130 steel aircraft landing gear leg, forged nickel alloy aircraft engine combustion chamber, cast cylinder block, cylinder head and boost supercharge of sports cars.

### ***BENEFITS TO DESIGN ENGINEER***

#### ***Special design benefits.***

A designer can benefit from special material properties by choosing from a wider range of materials if he does not preclude chemical milling as a possible process. Examples: PCM of recording head frets from highly magnetic mumetal, chemical milling of beryllium and uranium without formation of dangerous swarf or dust.



## ***BENEFITS TO PRODUCTION ENGINEER***

### **Versatile cutting tool.**

- With liquid cutting tool, there is:
- Less constraint on cutter accessibility problems
- Less constraint on final shape being produced
- Both sides of components can be worked simultaneously
- Many components can be processed simultaneously.

### **Minimal cutting forces.**

- No cutter marks, chatter and mismatches
- Strong alignment and clamping not required
- Can work with thin components and produce thin sections easily

## ***BENEFITS TO PRODUCTION ENGINEER***

### **Reduced number of parts.**

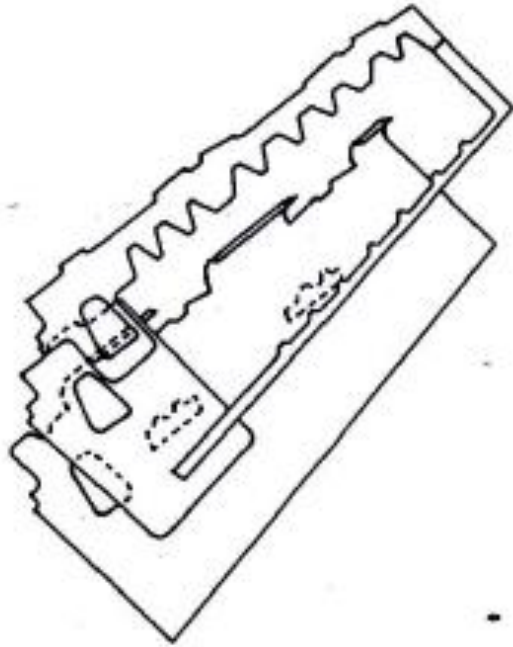
The design benefit in using integral parts such as integral panels has several production benefits. Since number of parts for a product is reduced:

- Planning and scheduling functions for an assembly are reduced
- Tooling requirement is reduced (including cost, planning, storage and maintenance)
- Reduction in assembly time and assembly errors
- Reduction in detail inspection time and Improved weight and dimensional control.

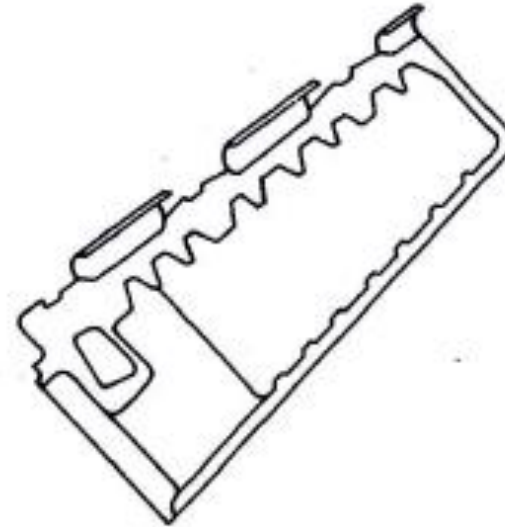




# CHEMICAL MILLING



Original design  
33 Tools  
7 Details  
14 h assembly time  
4.0 kg



Chemical milling design  
3 Tools  
1 Detail  
No assembly time  
3.4 kg

**Figure:** Aircraft skin panel – comparison between original design and design utilising CHM

# CHEMICAL MILLING

## EXAMPLES OF ETCHANTS:

Stainless steel	Etchants based on nitric acid or hydrochloric acid or ferric chloride
Tool steel	Solution of ferric chloride and nitric acid
High tensile steel	Nitric and sulphuric acids
Aluminium	Sodium or potassium hydroxide solutions (10 to 20 %)
Copper	Ferric chloride
Nickel Alloy	Etchants based on nitric acid or hydrochloric acid (eg 50 % hydrochloric acid, 17 % nitric acid, 10 % sulphuric acid)
Magnesium	Etchants based on sulphuric or nitric acid
Titanium	Etchants based on hydrochloric acid, usually mixed with chromic or nitric acid.
Glass, ceramics	Etchants based on hydrofluoric acid
Plastics	Chromic-sulphuric-phosphoric acid etchant (ABS, PP), sodium-aryl solution (PTFE)
Zinc	Etchants based on nitric acid or hydrochloric acid



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