Photochemical Machining (PCM) for Cost-effective, Rapid Production

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Abstract
Photochemical machining (PCM) is an excellent method for manufacturing both simple and complex parts in a wide range of engineering materials. In the harsh economic climate facing manufacturing industry today, it is important to utilise cost-effective processes to produce high-quality parts rapidly for just-in-time delivery. This paper discusses the best methodologies to utilise PCM to its full extent as an extremely versatile process within the electronics, electrical and mechanical engineering disciplines.

Introduction
PCM, also known as Photoetching, is a multi-stage manufacturing process that employs photoresist technology and chemical dissolution (etching) to produce parts, usually in metals [1], according to the schematic shown in Figure 1.

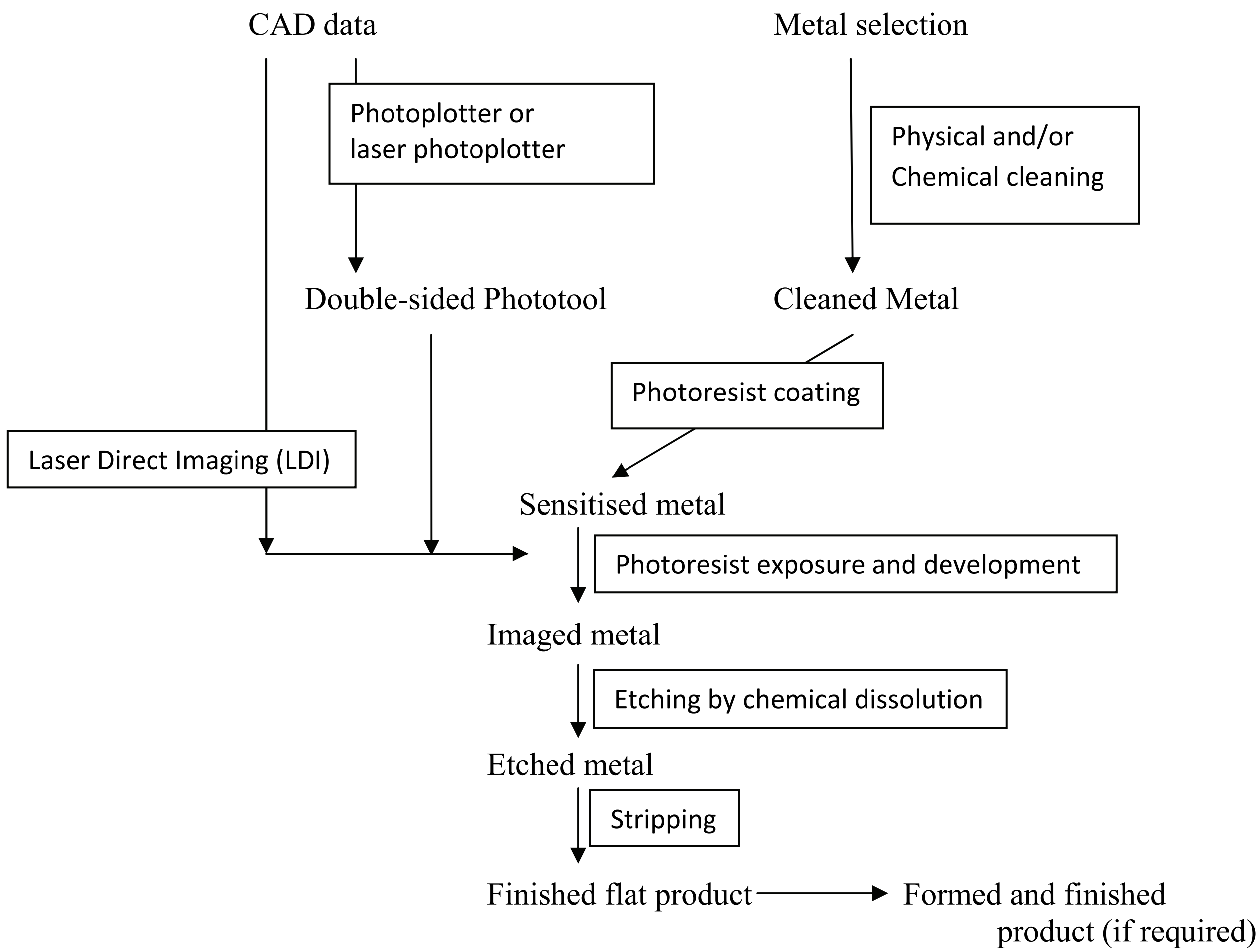

Figure 1 - The multiple-stage processes in PCM

Process Capability of PCM
Limitations
A limitation to component manufacture is a direct consequence of the phenomenon known as undercutting where the etchant diffuses in a lateral direction, as well as in the desired perpendicular direction. This results in the development of cross-sectional profiles as shown in Figure 2.

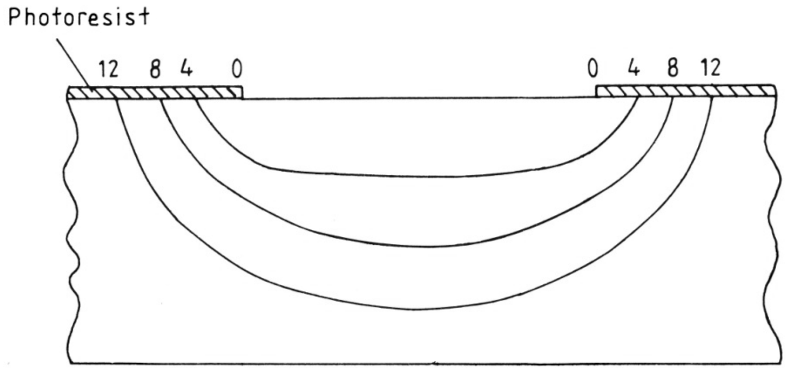

Figure 2 – Development of cross-sectional profile with increase of etching time

The undercut (U) can be calculated from the measurement of the original linewidth in the photoresist stencil (A) and the linewidth etched into the metal surface (B) as illustrated in Figure 3.

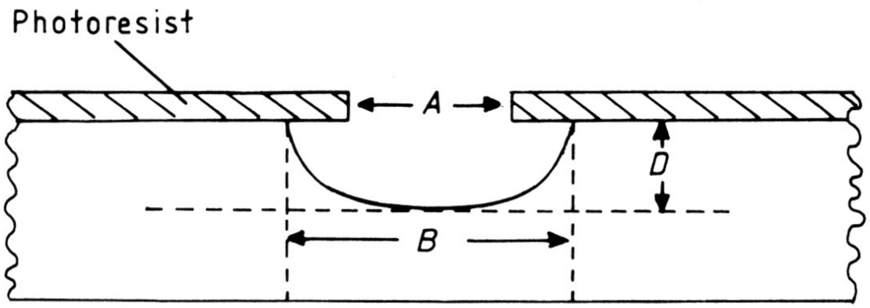

Figure 3 – Cross-section of a surface-etched part showing Undercut (U) = ½ (B-A)

The ratio of the desired depth of etch (D) to the undercut (U) is known as the etch factor (D/U) and to achieve small holes in thick materials, the etch factor therefore needs to be as high as possible.

Advantages

However, there are also benefits to the undercutting phenomenon as this means that a wide variety of profile types can be etched into or through the metal as illustrated in Figure 4.

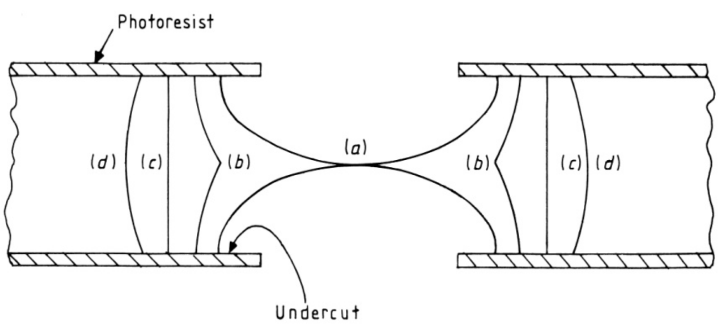

Figure 4 – Development of etched edge profiles when etching from two sides through identical resist stencils (a) Breakthrough point; (b) biconvex profile; (c) 'straight' profile; (d) biconcave profile

If a sharp 'knife-edge' profile is required, then etching can be carried out by single-sided etching as shown in Figure 5. This profile has been used to fabricate thin evaporation masks and sharp cutting blades.

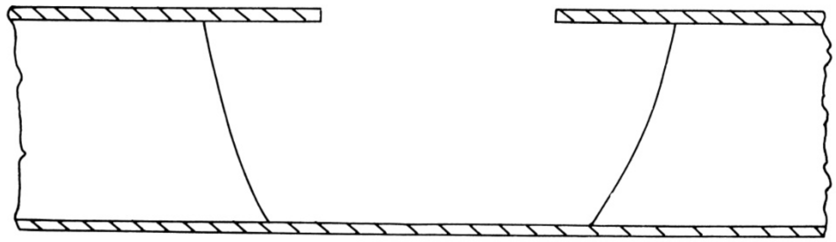

Figure 5 – Single-sided etch profile showing sharp 'knife-edge' profile

In addition, production of a tapered hole is also possible. This unconventional profile has been used extensively in the production of TV shadow masks and has also been used to fabricate burr-free hybrid circuit pack lids as illustrated in Figure 6.

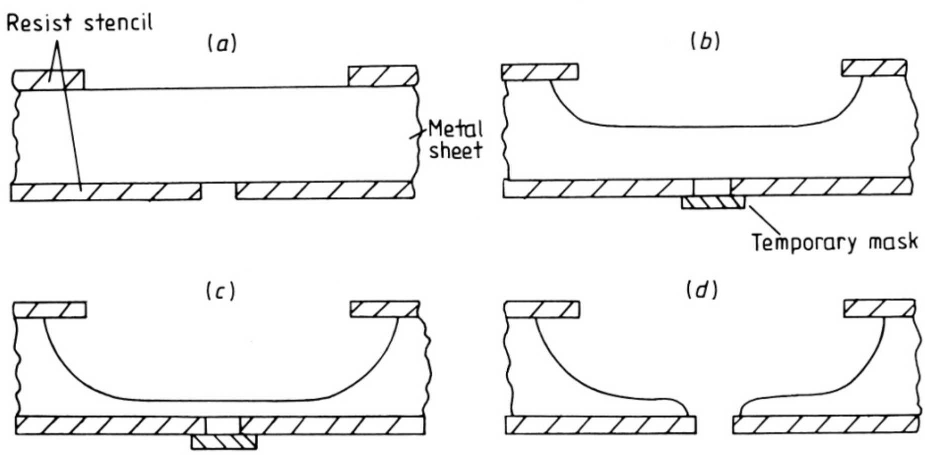

Figure 6 – Production of a tapered hole profile showing (a) dissimilar registered resist stencils; (b) etching through the larger aperture first; (c) substantial thinning of the sheet metal; (d) final profile after etching through the smaller aperture.

The relationships between minimum hole diameter and minimum metal land width to the metal thickness are shown in Tables 1 and 2. The minimum hole diameter is related to the thickness because it has been shown that the etch factor is much greater for thinner metal foils than for thicker foils [1].

Table 1 – Relationship between minimum hole diameter (Φ_{min}) and metal thickness (T)

Metal thickness, T (mm)	Φ_{min} (mm)
< 0.025	Dependent on conditions
0.025 – 0.125	≥ T
> 0.125	1.1T – 2.0T

Table 2 – Relationship between minimum land width (W_{min}) and metal thickness (T)

Metal thickness, T (mm)	W_{min} (mm)
< 0.125	≥ T
> 0.125	≥ 1.25T

However, while PCM has these limitations, it also has extremely beneficial process advantages. Unlike stamping, no burrs are present on an etched part and PCM does not affect the physical or chemical properties inherent within the sheet metal. This is very important where stress, high temperatures or loss of magnetic permeability must be avoided during manufacture. In general, etch-time dependent tolerances for PCM are ±10% of the metal thickness (T) with etch time independent tolerances (e.g. hole-centre to hole-centre tolerances) of ±0.05%T.

Rival processes such as laser cutting can produce heat-affected zones at the cut edges, while stamping affects magnetic permeability and can cause stress. PCM, on the other hand, can be regarded as a very gentle process, only affecting the material where the etchant chemically reacts with it, thus leaving the remaining metal unaffected.

Materials that can be machined by PCM

It must be remembered that chemical machining is basically accelerated but controlled corrosion. Therefore it is more difficult to etch corrosion-resistant materials than corrosion-susceptible materials. This aspect of "etchability" in PCM is reflected in Table 3. As can be seen from Table 3, all the commonly-used engineering materials can be etched but the etchant needs to be selected with care to maximise efficiency of production. For instance, molybdenum can be etched in the standard PCM etchant of aqueous ferric chloride but it will be an extremely slow process and alternative, faster etchants are usually employed instead.

Table 3 - Etchabilities of some common engineering metals and alloys

Good	Good to fair	Fair to poor	Poor
Copper	Austenitic s/s	Molybdenum	Tungsten
Copper alloys	Precipitation hardening s/s	Nichrome (Ni,Cr)	Hastelloy C
Zinc	Martensitic s/s	Vanadium	Titanium
Carbon steel	Ferritic s/s	Chromium	Niobium
Kovar / Nilo (Fe, Ni, Co)	Inconel (Ni, Cr, Fe)	Lead	Tantalum
Nickel		Manganese	
Nickel alloys		Rhenium	
Magnesium		Zirconium	
Aluminium			
Anodised aluminium			

Products

As a result of the capability of PCM to manufacture parts from a wide range of metals, it is not surprising to find that a very wide range of products can be manufactured by PCM. In addition, while perforations and peripheral boundaries are being etched, it is also feasible to etch logos, trademarks, part numbers, instructions or any other required graphics information into the surface of the part at the same time (as shown in Figure 7), making an even greater saving in processing time.

These products cover a wide field of applications (including decorative applications) but the mechanical, electronic and electrical applications *only* are listed in Table 4.

Table 4 – Products by type

Components containing arrays of perforations	Components with complex geometries	Surface-etched components
RF/EMI shields	IC lead frames	Decorative cell phone cases
Filters	Contacts	Hybrid circuit pack lids
Meshes	Springs	Fold lines for boxes and enclosures
Screens e.g. as used in SMT (surface mount technology)	Heat ladders, heat plates and heat sinks	Alphanumeric data for OCR (optical character recognition)
Light attenuators	Gaskets for cell phones	Fuel cell channels
Grids	Encoder discs	Company logos
Evaporation masks	Disk drive suspension heads	Instructions

Cost-effectiveness of PCM

As can be seen from Figure 1, the PCM process needs very strict control at all stages if the overall yield of acceptable parts is to be high and the resulting cost of production is to be low. In-process control is therefore vital if the required dimensions and tolerances are to be achieved cost-effectively.

Alternative processes may be considered for part production but in general, taking into account the metal thickness as a variable, it has been shown [2] that:

- Photoforming (also known as photoelectrofoming or PEF) only seems to play an important role when extremely thin metal parts are made and when the complexity and required resolution is very high
- Stamping is the most economic method of manufacturing for very large batch sizes
- Wire Electro-Discharge Machining (WEDM) is the most economic process for small batch sizes of thin components less than 1.0mm thick *but,* as the thickness and complexity of the part increases, then laser beam machining (LBM) becomes the favoured method

- For medium-sized batches, LBM and PCM rival each other for cost-effectiveness. The favoured method depends on part complexity. *For instance, for thicknesses < 0.5mm, high part complexity favours PCM.* This is understandable as all apertures of whatever shape are machined *simultaneously* by PCM, whereas a laser machines each aperture individually, leading to longer production times.

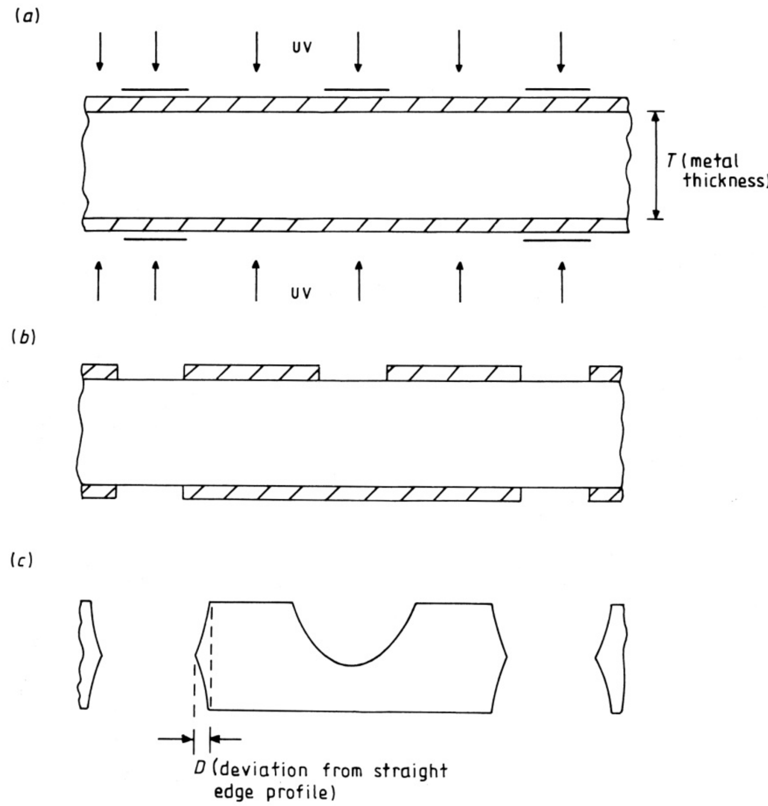

Figure 7 – Strategy for simultaneous 'chemical blanking' and surface etching

Temporal considerations

The time required to manufacture parts by PCM can be remarkably short. Examples exist of companies that have manufactured prototype parts from design sketches within 24 hours! Testing of prototypes can therefore be carried out rapidly and if a design modification is required, it can be effected quickly and the part retested at minimum time and cost. The low costs result from the use of CAD data that is easy to modify to form a revised image in the photoresist coating and hence a revised part.

In comparing PCM against stamping, it should be remembered that the cost of phototooling is very low in comparison to the cost of hard tooling required for stamping. This comparison is graphically illustrated in Figure 8.

Moving from prototype production to mass production can be an area fraught with financial complications. Many entrepreneurial companies have adopted the following production strategy:

1) Fabrication of part prototypes by PCM
2) Rapid field-testing of the prototypes
3) Redesign of prototypes and iterative fabrication by PCM until a satisfactory part design has been produced
4) Manufacture of parts by PCM until it has been decided that the part design will not be changed in the foreseeable future
5) Ordering of the hard tooling for stamping with the associated long time-delay
6) Continuation of production using PCM until the hard tooling is commissioned.

The difficulty in this strategic plan is in ascertaining if the part has a long enough lifetime to justify the expense of the hard tooling (see Figure 8). If the cost of the die set cannot be amortised over the lifetime of the part, then the purchase of hard tooling cannot be justified financially.

As integrated circuit (IC) designs change frequently, this in turn means that the lead frame design also requires frequent modifications. As modifications to hard tooling are difficult and time-consuming to carry out, this is the reason why IC lead frames are often fabricated by PCM rather than stamping, especially where the lead frame design complexity is high.

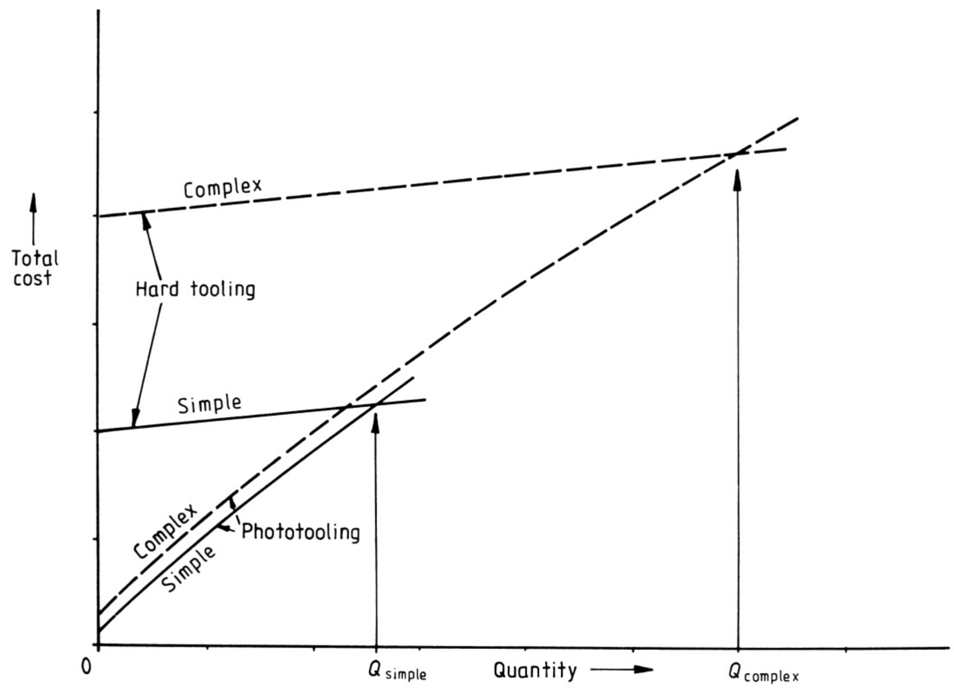

Figure 8 – Typical economics of the production of simple and complex parts by PCM and stamping showing break-even quantity (Q) increasing with part complexity

Conclusion

It is hoped that this brief outline of the PCM process, showing its attributes from the viewpoint of both technical and financial aspects, will arouse the interest of both design and manufacturing engineers. Many engineers do not realise the process capability of PCM, nor do they realise that the PCM business at the turn of the millennium was estimated to be of the order of $6 billion per annum [3]. Unless the design engineer understands the process capability of PCM, then parts will not be designed to exploit the low cost and remarkable versatility of PCM.

Unfortunately, PCM has been referred to in the past as "Manufacturing's Best Kept Secret"- a title that reflects poorly on both academia and the PCM industry in the past fifty years. However, designers should find the recent PCMI publication [4] of great help in selecting the most cost-effective process for manufacturing flat metal parts.

I also hope that the presentation of this paper has helped to break down the process "secrecy" now that rival PCM companies worldwide have realised that mutual advantage can be gained by publicising the technology of PCM to attract a new generation of free-thinking engineers to use this exciting, cost-effective, rapid manufacturing technique.

Acknowledgements

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References

[1] D.M. Allen, The Principles and Practice of Photochemical Machining and Photoetching, IOP Publishing Ltd, Bristol, UK, 1986 [ISBN 0-85274-443-9]

[2] D.M. Allen, P.J. Gillbanks and A.J. Palmer, The selection of an appropriate method to manufacture thin sheet metal parts based on technical and financial considerations, Proceedings of International Symposium for Electro-Machining (ISEM-9), Nagoya, Japan, 1989, 246-249.

[3] D.M. Allen, Photochemical machining: from 'manufacturing's best kept secret' to a $6 billion per annum, rapid manufacturing process, Annals of the CIRP, 2004, 53/2, 559-572.

[4] Photo Chemical Machining Institute, Choosing the right tool for the job: Selecting the correct manufacturing process for creating flat metal parts, 2007.

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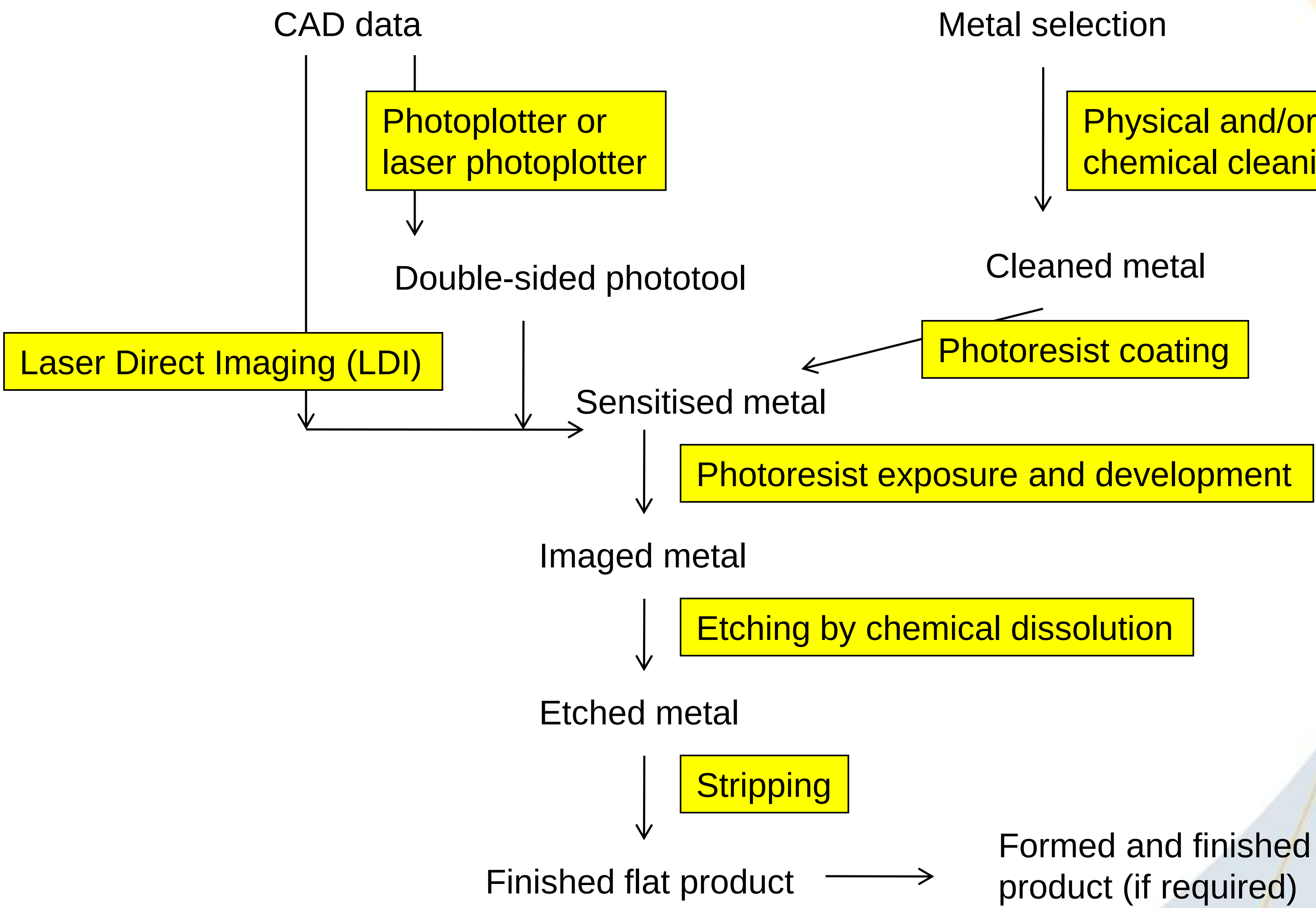
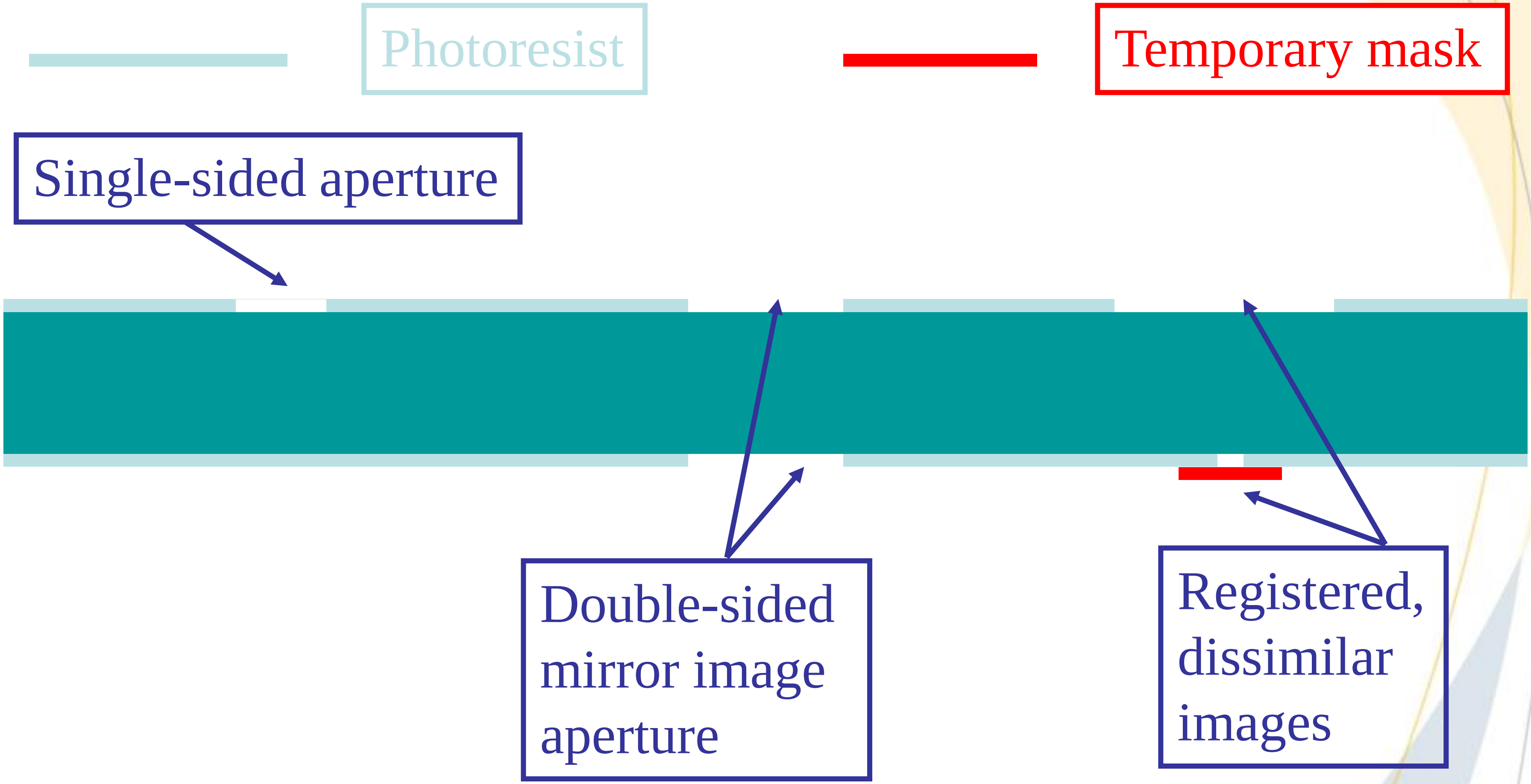
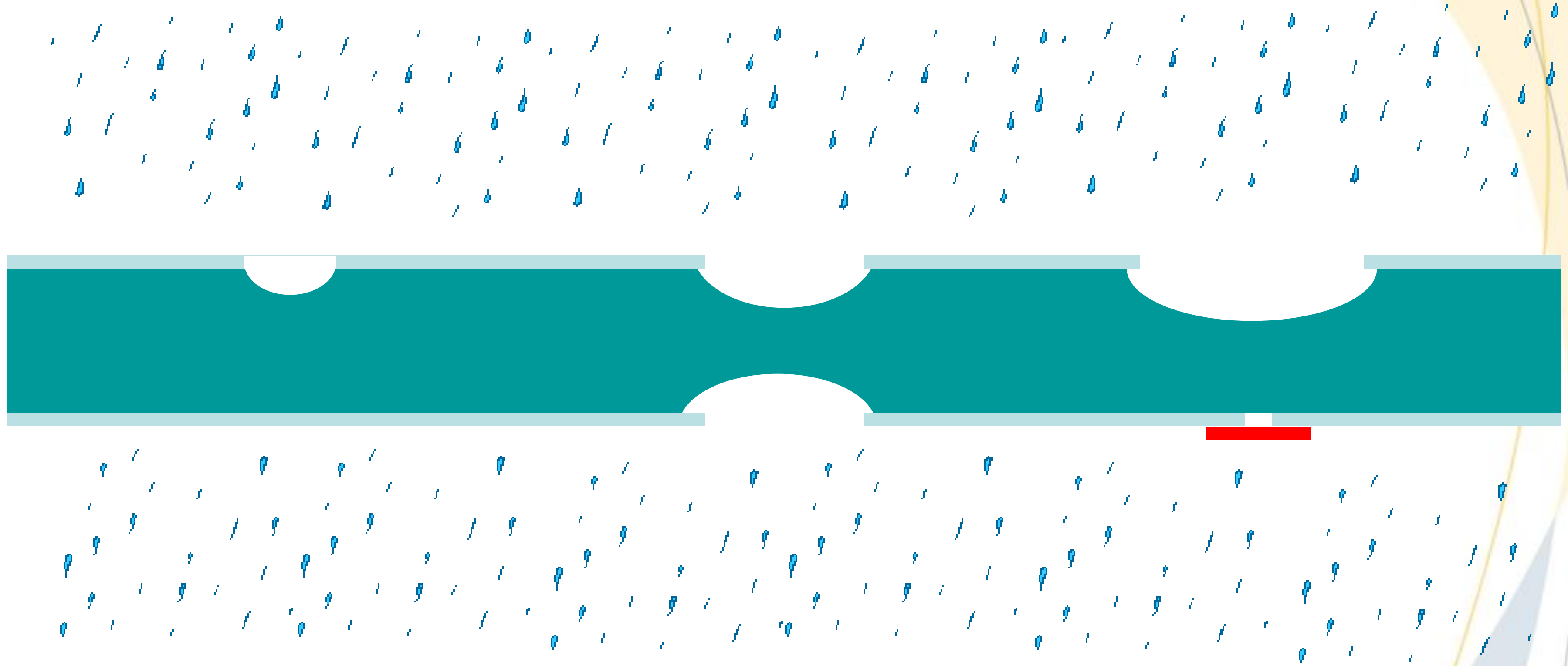
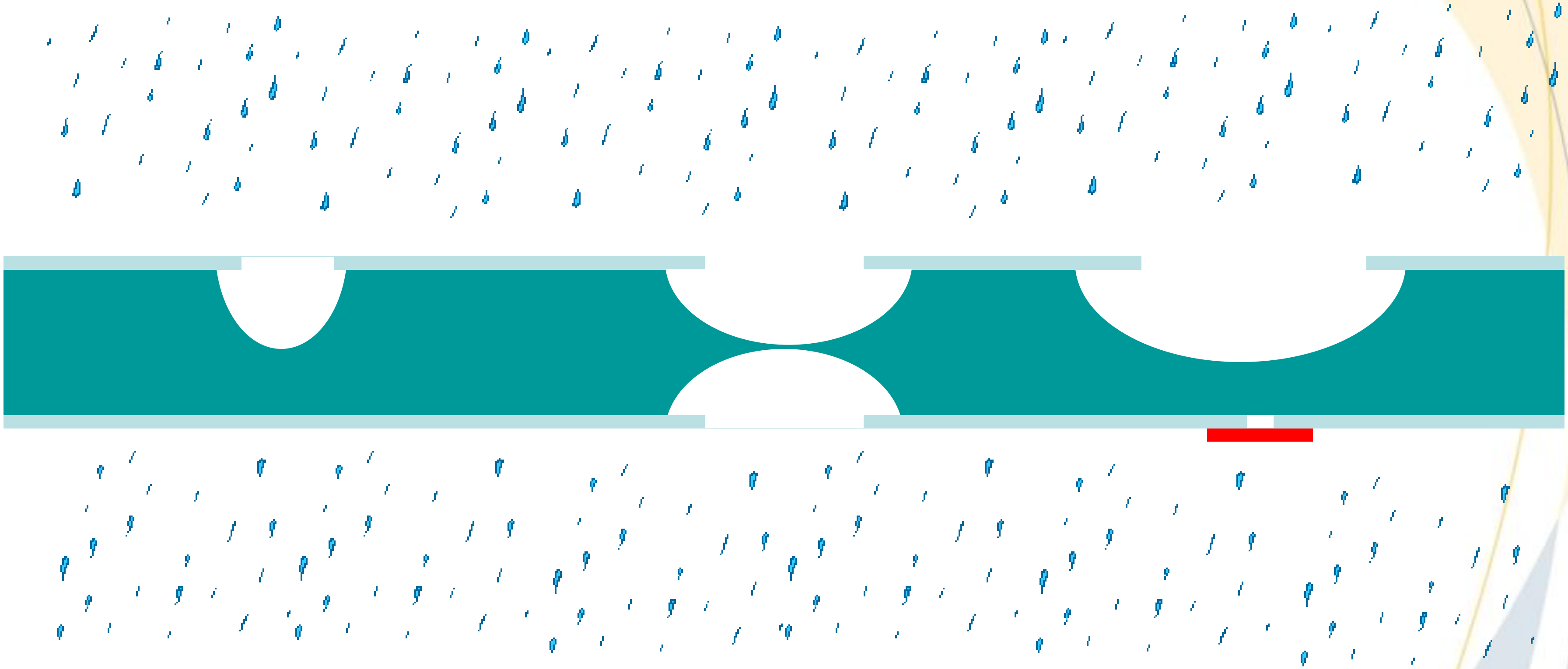
The Multiple-Stage Processes in PCM

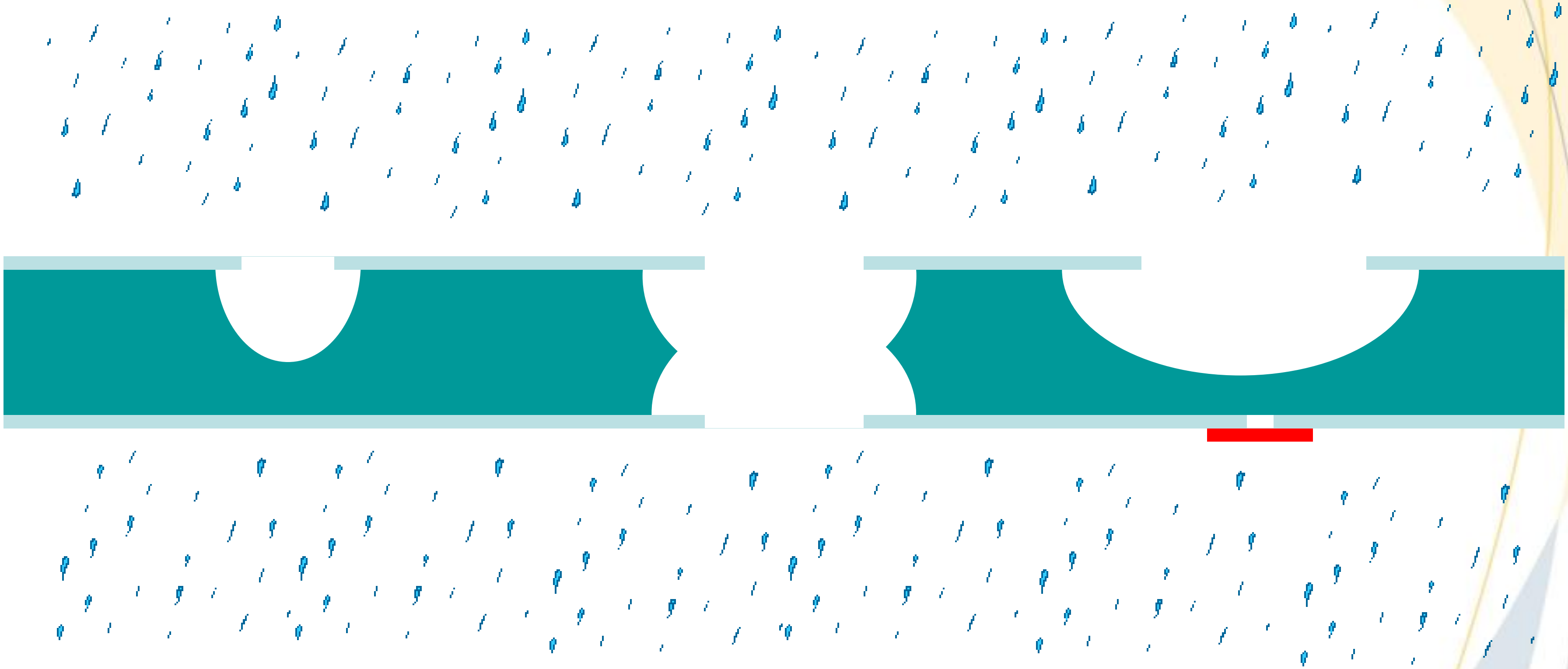


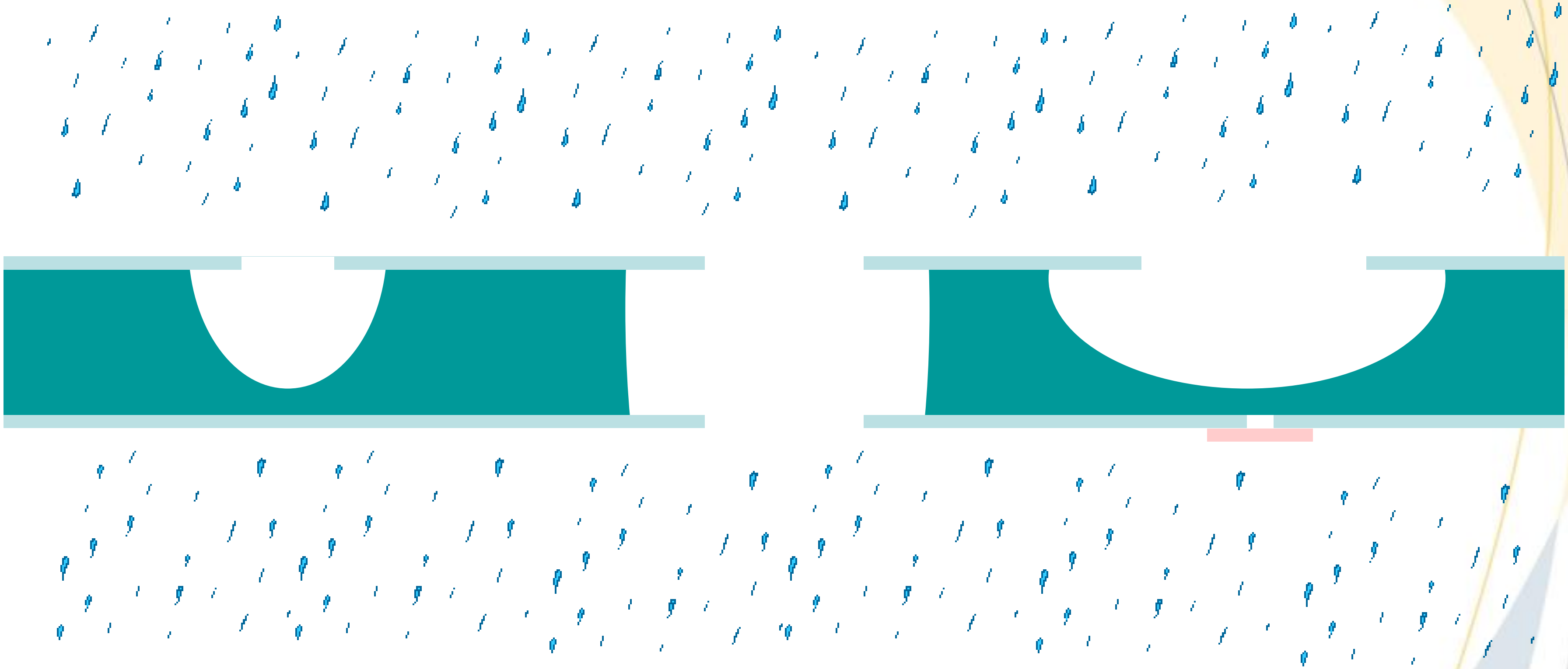
Multiple profile production

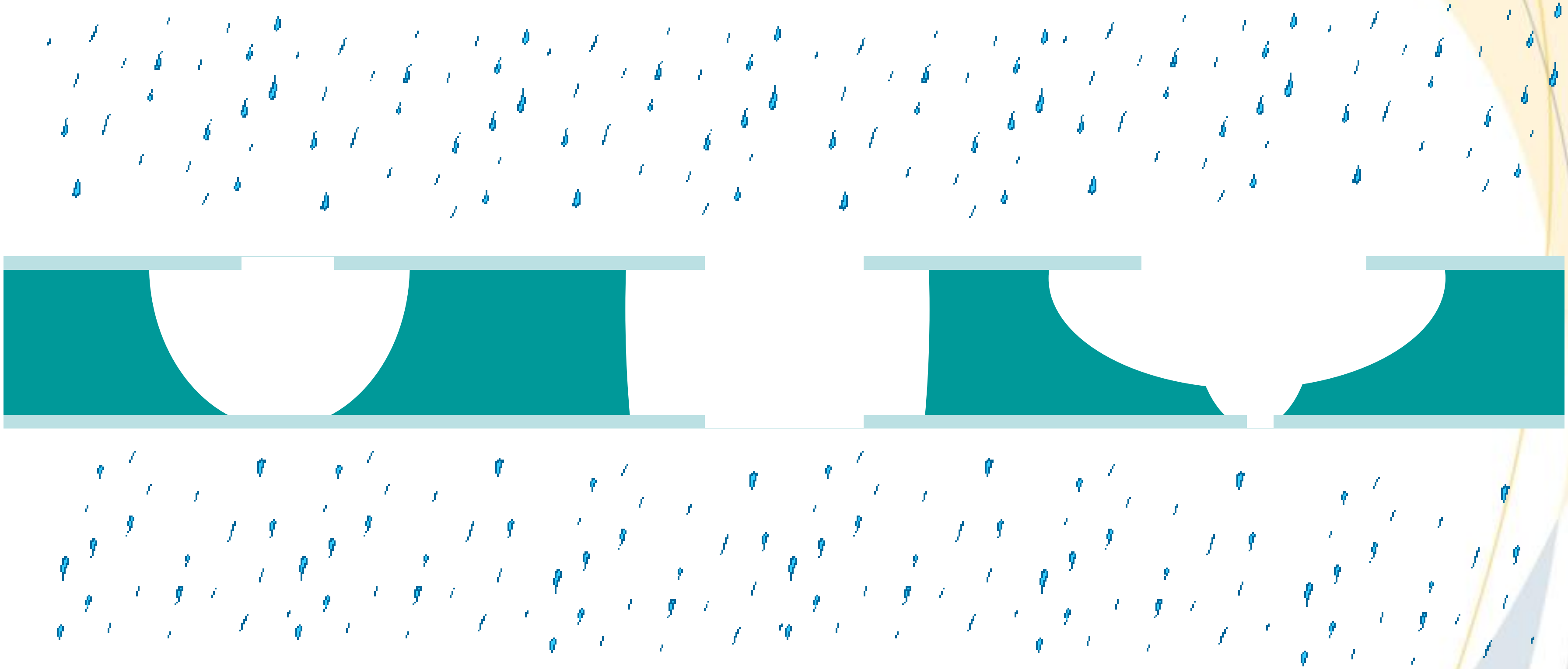


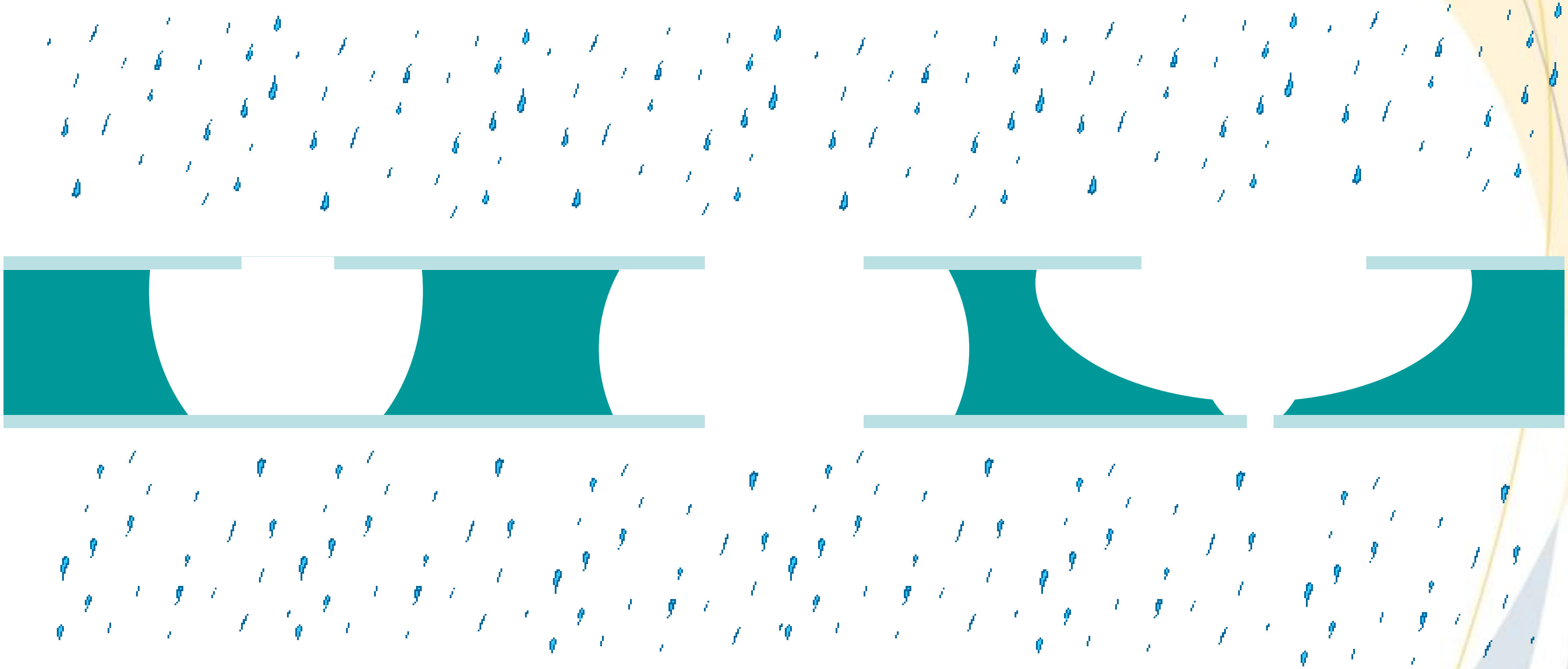






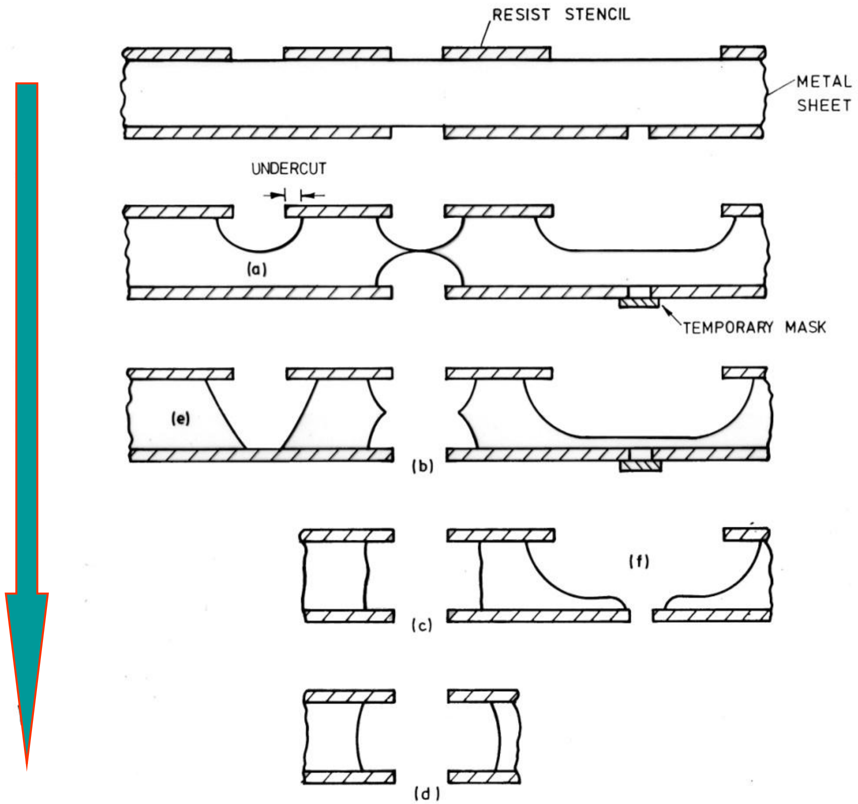






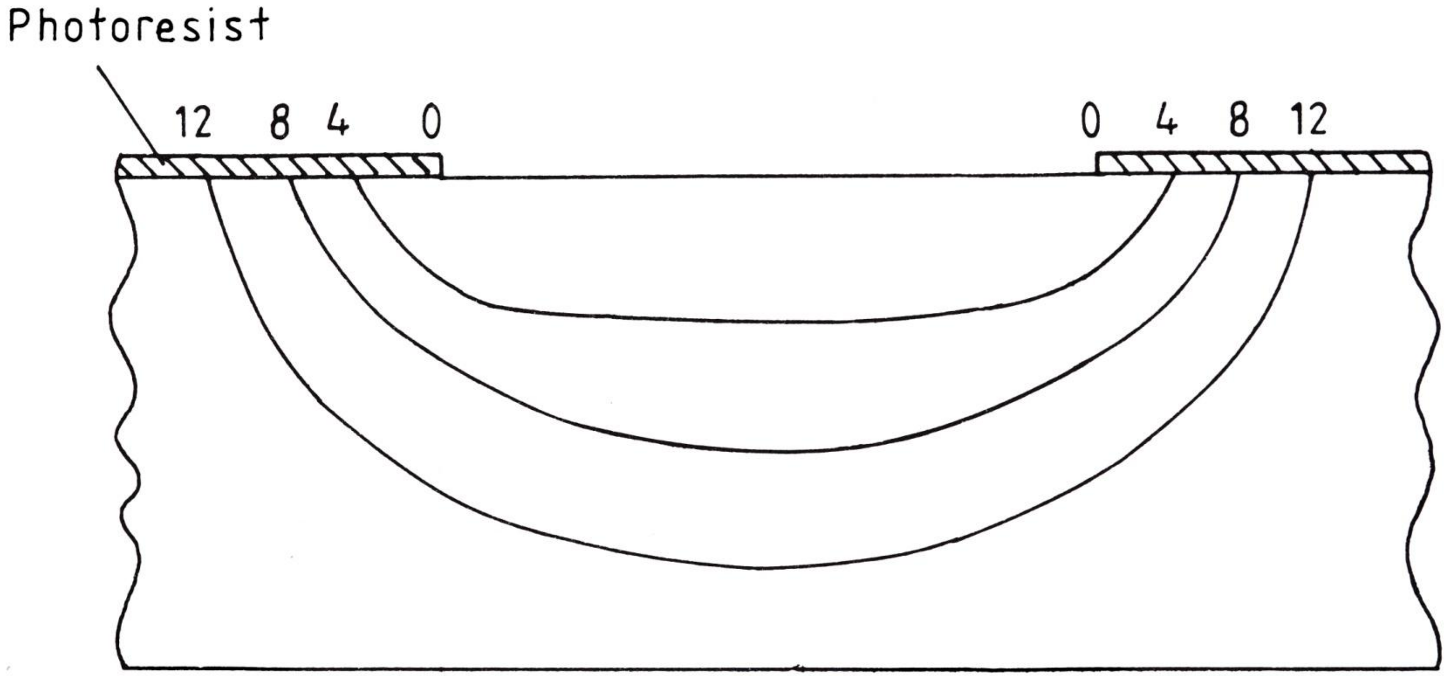
A wide range of etch profiles is possible

Development of etch profile with increasing time of etch



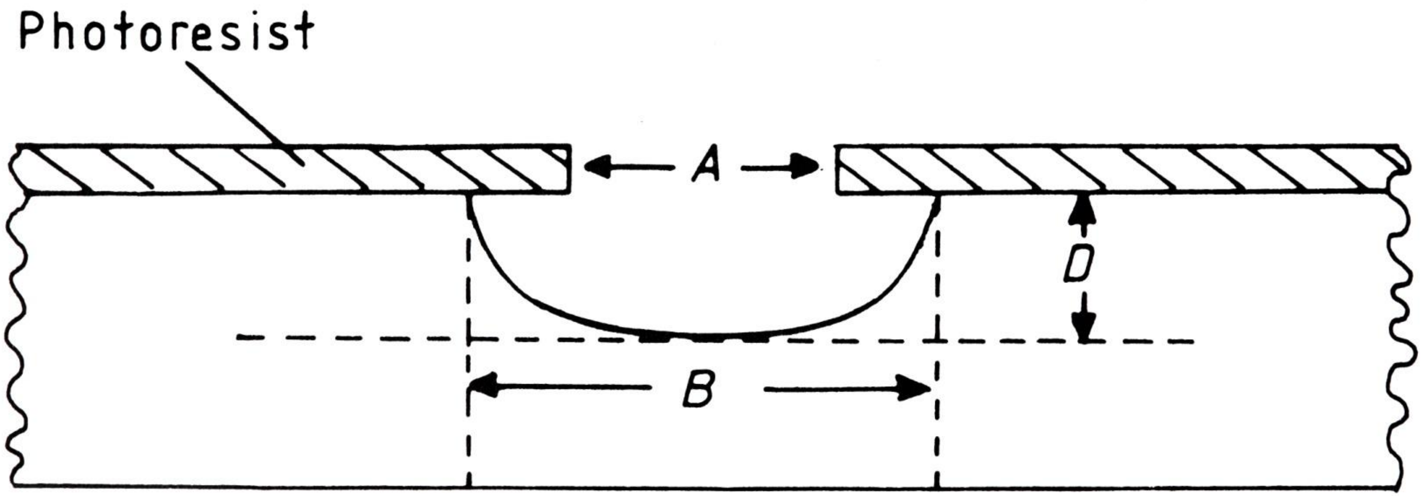
Note the ability to produce tapered holes and the superiority of double-sided etching over single-sided etching.

Development of cross-sectional profile with increase of etching time



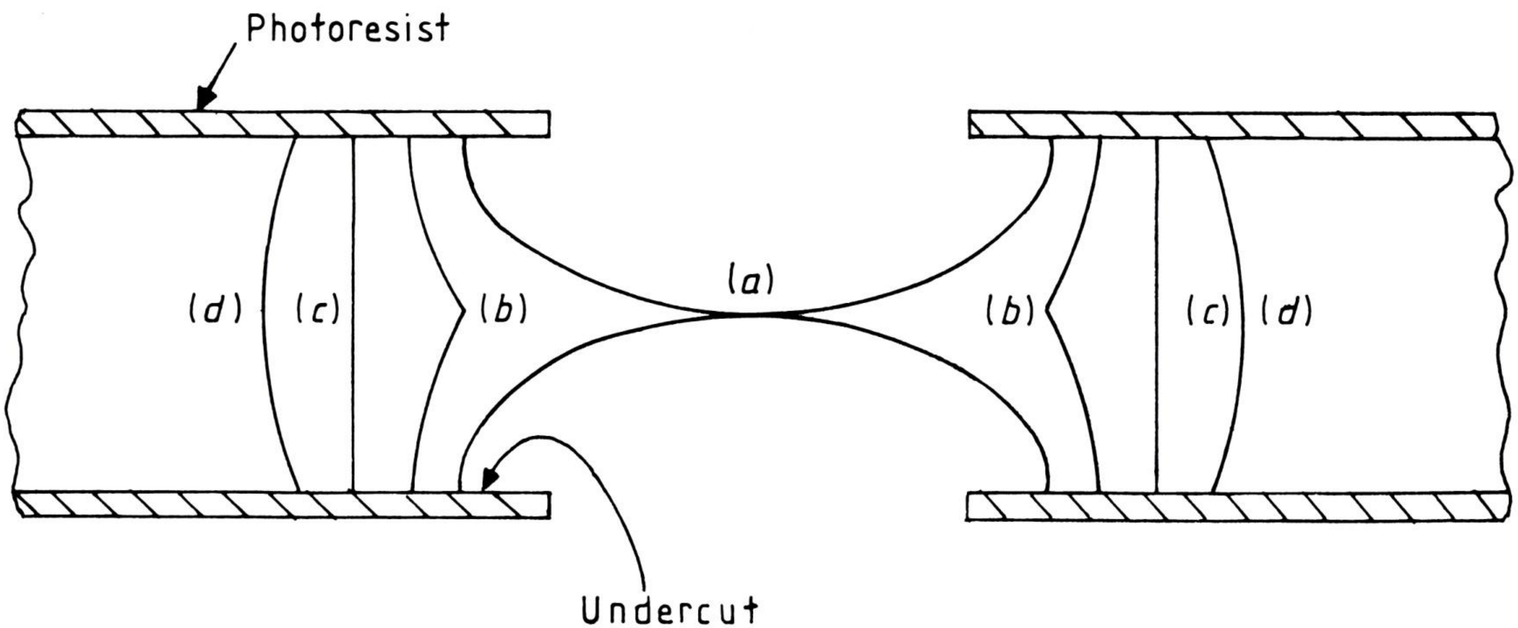
Note that as etch time increases, depth of etch and undercut also increase

Cross-section of a surface-etched part showing Undercut (U) =½(B-A)



The etch factor is the ratio of the depth of etch (D) to the undercut (U). Etch factor should be as high as possible to achieve small holes in thick material.

Development of etched edge profiles when etching from two sides through identical resist stencils (a) Breakthrough point;(b) biconvex profile; (c) ‘straight profile; (d) biconcave profile



Usually, deviation from a ‘straight’ profile is controlled to be <0.2T