Thoughts on Undercut

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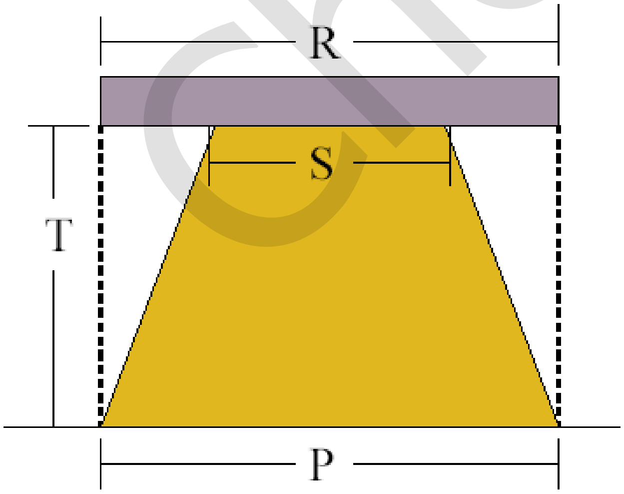
The gradual but growing recognition of photochemical machining as an alternative to stamping for the production of small, burr free, stress free parts and the inevitable trend towards ever smaller and more complex designs has brought the problem of undercut, the ratio of sideways etch to downward etch, to the forefront once again. I say once again because this problem arises every few years with each new generation of design specifications that call for more features to be crowded into less and less available real estate. For instance, the demand in lead frames 10 years ago was for 208 pins with an 8 to 9 mil pitch. Today the demand is for 256 pins with a 5.3 mil pitch in the same space. This, along with an influx of new personnel, has again focused attention on the problem of undercut (I assume that undercut is a problem since, in over thirty years of experience in the PCM business, I cannot recall anyone asking how to get more undercut). Many things have been tried over the years to control or reduce undercut, some based on testing and experience and others based more on gut feelings and intuition. This article will cover the major factors that affect undercut along with test results showing how they affect undercut.

Definitions

Before beginning the discussion, however, it would be a good idea to make sure we have our terms and definitions straight. For the most part we will be discussing etching that goes completely through the material to be etched from one or both sides. Etching that only goes part way through the material uses slightly different calculations although the principle is the same (thank you, David Allen).



$$\text{Undercut} = R - S$$

$$\text{Etch Factor} = \frac{\left(\frac{P-S}{2}\right)}{T} \times 100\%$$

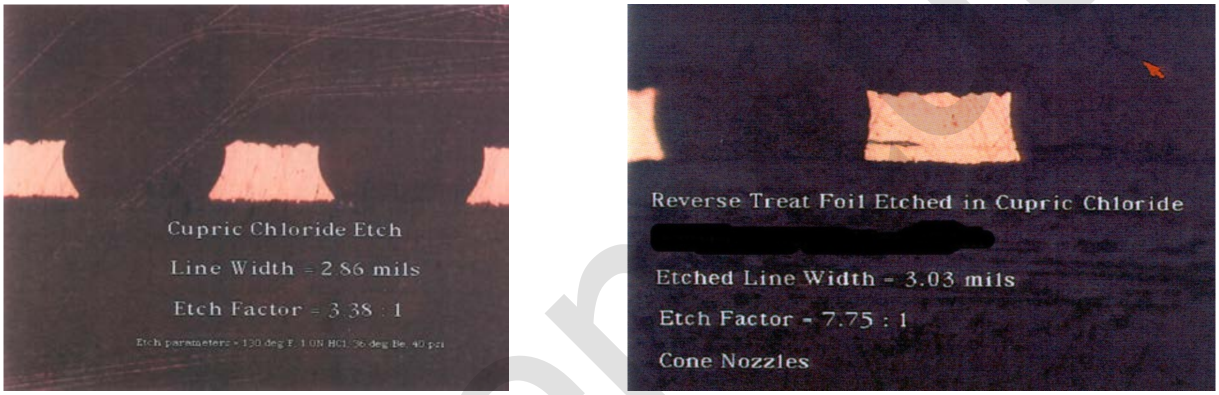
or

$$\text{Etch Factor} = \left[\frac{T}{\left(\frac{P-S}{2}\right)}\right]:1$$

Figure 1 – Calculation of Undercut and Etch Factor

As seen in Figure 1, **Undercut** is the difference between the width of the developed resist line (R) and the final width of the etched feature across the top (S). The **Etch Factor** is the ratio between the difference in the widths of the widest and narrowest parts of the feature after etching is completed and the thickness of the metal etched. This can be expressed as a percentage as shown in the first equation or as a ratio as shown in the second. An etch factor of 3:1 (1 unit of sideways etch for every three units of downward etch) can also be expressed as an etch factor of 33% (the sideways etch is 33% of the downwards etch). The etch factor can also be thought of as an indication of how straight the sidewall of the feature is after the etching has been completed.

There are several things that need to be taken in consideration when using these definitions. Most importantly, undercut and etch factor are different entities, although we tend to use them interchangeably which can cause some confusion. Secondly, neither definition says anything about the relation of the widest part of the feature after etching is completed (P in figure 1) to the width of the resist (R). Giving a number for undercut or etch factor without an indication of the relation of P to R after etching can be confusing or misleading as shown by figure 2.



Undercut = 0.94 mils (24 µm)

Etch Factor = 3.38:1 or 29.6%

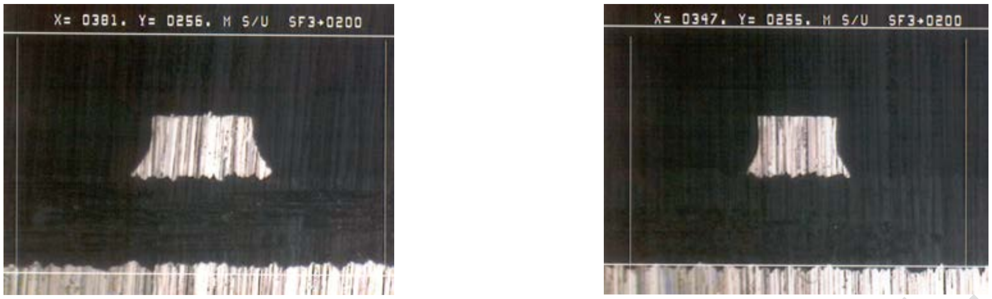
Undercut = 1.33 mils (34 µm)

Etch Factor = 7.75:1 or 12.9%

Figure 2 – Etch Factor vs. Undercut

Both pictures show a cross section of a 3 mil (75 µm) line etched in 1 oz. (35 µm) copper foil. The section on the left has an etch factor of 3.38:1 while the one on the right has an etch factor of 7.75:1 and an obviously much straighter sidewall. What’s the difference? The line at the left started with a 3 mil resist width while the line shown at the right started with a 4 mil (100µm) resist width and was etched until the etched line width was 3 mils. A glance at the undercut numbers quickly shows that, while the line on the right had a much better etch factor, it also has much more undercut. As you can see, using the term undercut when you mean etch factor and vice versa can lead to some confusion while claiming an etch factor of 7.75:1 for a 3 mil line in 1 oz. copper without mentioning that the line started with a 4 mil wide resist might be considered misleading. However, the above example does illustrate the fact that straight sidewalls, a very desirable trait in the PCM business, can be achieved at the cost of more undercut and etch time, as shown in the next series of cross sections.

Starting with a 5 mil (125 μm) line on 2 oz. (70 μm) copper foil the following cross sections show how the undercut and etch factor are affected by increasing etch time.



Etch Time = 2 min. 54 sec.
Undercut = 0.87 mils (22 μm)
Etch Factor = 3.0:1 or 33%

Etch Time = 3 min. 24 sec.
Undercut = 1.77 mils (45 μm)
Etch Factor = 4.8:1 or 20.8%

Etch Time = 3 min. 54 sec.
Undercut = 2.2 mils (56 μm)
Etch Factor = 8.7:1 or 11.5%

Etch Time = 4 min. 24 sec.
Undercut = 2.87 mils (73 μm)
Etch Factor = 10.7:1 or 9.3%

Figure 3 – Trading Time and Undercut for Etch Factor

As can be seen, increasing the etch time will give a straighter sidewall at the expense of a narrower line. By increasing the width of the resist it is possible to end up with a fairly straight sidewall (high etch factor) at a specified finished etched line width. This is a fairly common practice in the industry and can solve a lot of what people refer to as an undercut problem. Unfortunately, as features get closer together, the increased widths of resist necessary to insure straight sidewalls begin to overlap each other so this approach to increasing etch factor is no longer possible. Moreover, as the space between the features narrows there comes a point, even before the edges of the resist overlap, where making the space any narrower in order to increase the resist width becomes counterproductive, as shown in the next test example.

A lead frame manufacturer wished to try and increase the lead width by increasing the width of the developed lead, leaving less developed space between the leads for the etchant to act upon. The design called for a 135 μm (5.3 mils) pitch at the tips of the leads with a width of at least 80 μm (3.14 mils) across the tops of the leads after the etched spaces were cleaned out with no bridging. The first photo-tool design left a 30 μm space between the leads for etching and they were able to achieve their goal, but just barely and with a high percentage of rejects. By widening the developed lead and narrowing the developed space between the leads they hoped to increase the width of the etched lead and decrease rejects. They sent three sets of samples with spaces of 30, 27, and 24 μm between leads. The results of the etch tests are shown in the table below.

Table 1 – Lead Frame Etch Tests

Space between leads	30 μm (1.18 mils)	27 μm (1.05 mils)	24 μm (0.95 mils)
Etch Time	3 min. 34 sec.	3 min. 53 sec.	4 min. 34 sec.
Final Lead Width	79.5 μm (3.13 mils)	78.4 μm (3.09)	78.3 μm (3.08 mils)

You will note that, even though the width of the developed resist leads was increased by narrowing the space between the leads, the final etched lead widths were all pretty much the same although it took a minute longer to reach the same width when the space between the leads was decreased by 6 μm. Keep in mind that by decreasing the developed space between the leads we are also increasing the developed width of the lead by 6 μm. Increasing the etch time by one minute to get the same results certainly can be defined as counterproductive but the point at which it becomes counterproductive has yet to be determined.

We have now reached the limit of what can be done with artwork compensation to increase etch factor at the expense of undercut yet we still need to improve etch factor without increasing undercut. What other factors might influence undercut and what are their effects on undercut?

Factors Affecting Undercut

The factors affecting undercut are grouped into three broad areas, etching chemistry, etching equipment and miscellaneous effects that are not due to either chemistry or equipment.

It should be noted here that most of the data presented in this section come from a testing series done on copper lead frames etched in cupric chloride. In general, ferric chloride, whether etching copper or iron alloys, follows the same trends as seen in the cupric chloride tests.

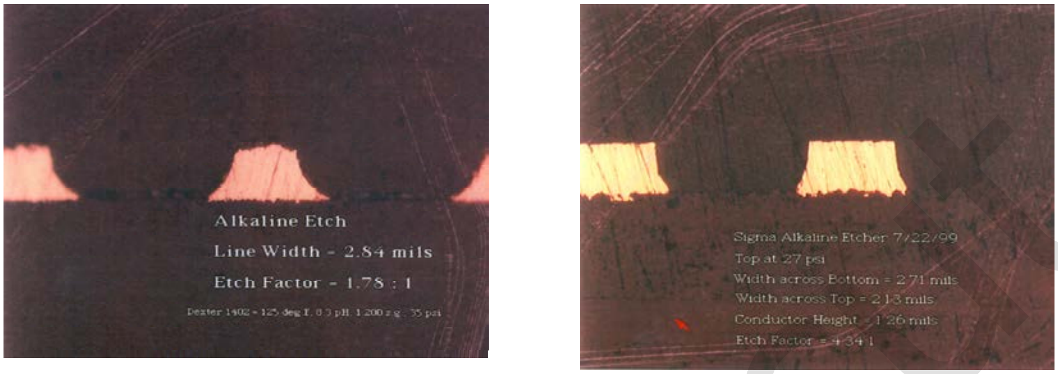
All the graphs shown are from those tests and a brief description of those tests will help in understanding the data presented. The tests were done on 208 pin lead frames with an 8 mil pitch in 6 mil copper. The goal was to have 4 mils across the top of the lead and a minimum of 3 mils between the leads.

A designed experiment was set up to test several different parameters. There were thirty-two separate test runs in the design and the experiment was run twice for a total of sixty-four test runs. For each test run the lead frame was etched until the space across the top was 4 mils. The lead was then cross-sectioned and the minimum space between the leads was measured. The number shown on the Y-axis of the graphs is the space across the top (4 mils) divided by the space across the center of the lead (minimum). The goal was 4 mils / 3 mils or 1.33. The actual number is not as important as the trend, a lower number meaning better undercut characteristics.

This type of designed experiment is called a screening test because it allows a large number of parameters to be tested against each other in a relatively short time to find out which ones have the most effect on the process. Time can then be spent further testing on these parameters and not wasted on parameters that have little effect on the process. The other advantage of this type of test is that interactions between parameters may also be spotted. Two parameters taken separately may individually have little effect but together may have a much larger effect, something that may be hard to spot during a traditional test schedule.

Chemistry Parameters That Affect Undercut

For those who might think that chemistry parameters do not have much affect on undercut Figure 4 should provide some food for thought.



Etchant pH = 8.3, sg = 1.200
Etch Rate = 2.5 mil/min
Undercut = 1.71 mils (43 μm)
Etch Factor = 1.78:1 or 56%

Etchant pH = 7.9, sg = 1.230
Etch Rate = 1.9 mil/min
Undercut = 0.87 mils (22 μm)
Etch Factor = 4.34:1 or 23%

Figure 4 – Chemistry Effects on Undercut
Alkaline Etch, 3 mil line, 1 oz. copper

The lines above were etched in the same etcher with the same etchant. The cross section on the left obviously has more undercut and a poorer etch factor than that on the right. Why? The etchant for the section on the left was adjusted to run at high pH and low specific gravity for high etch rate. For the section on the right the etchant was adjusted to run at low pH and high specific gravity for best undercut performance. Note the difference in etch rate and keep it in mind. The improvement in undercut came at the expense of about a 25% decrease in etch rate. This will be a constant theme in all of the following discussions.

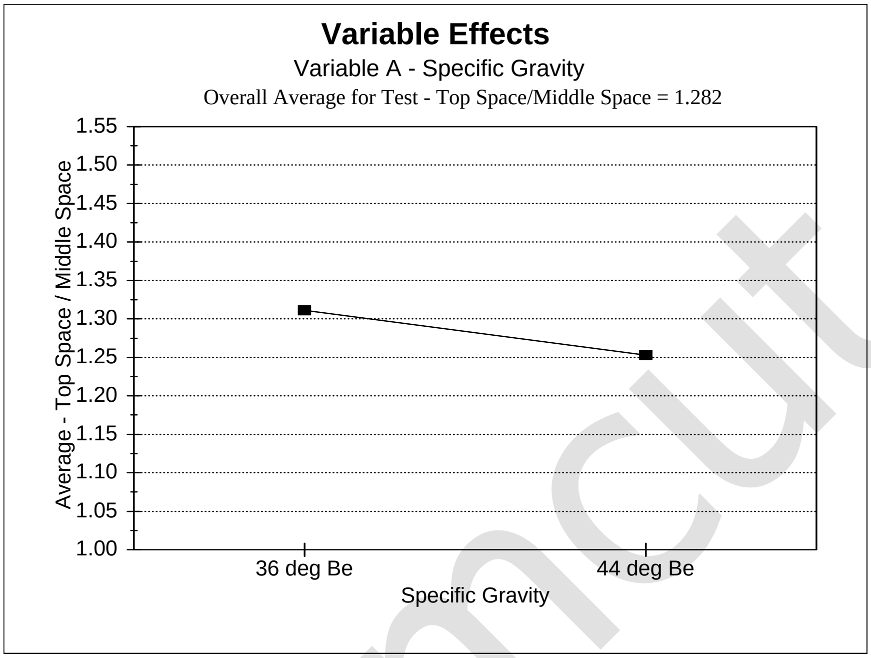
The chemistry parameters that affect undercut are: 1) Type of etchant, 2) Specific gravity, 3) Temperature, 4) Acid content, and 5) Oxidation-Reduction potential.

<u>Type of etchant</u>

Copper and copper alloys can be etched with cupric chloride or ferric chloride. If possible, most choose to etch copper with cupric chloride since it can be regenerated which greatly reduces etchant costs associated with obtaining new etchant and disposing of old. However, ferric chloride shows less undercut when etching copper than cupric chloride. Typically the etch factor for copper etched in cupric chloride is 3:1 while the etch factor for copper etched in ferric chloride is usually around 4:1. Many lead frame manufacturers chose to etch their copper lead frames in ferric chloride because this advantage in undercut performance is the difference between good product and rejects.

Ferric chloride is the only economical choice for etching iron and iron alloys. Undercut here is dependant on the type of alloy and the other chemistry parameters listed above.

Specific Gravity



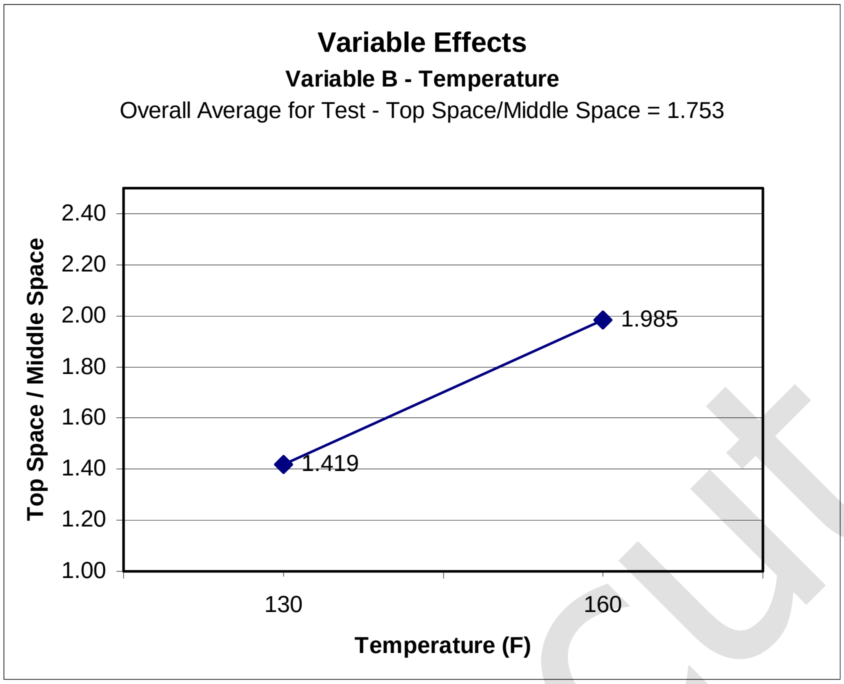
Graph 1 – Effect of Specific Gravity on Undercut

Graph 1 shows that the undercut decreases as the specific gravity increases. However, the effect is small and as specific gravity increases past 36^{o} Be (1.33) the etch rate begins to drop off substantially. At specific gravities higher than 36^{o} Be the gain in undercut performance is generally not worth the loss in productivity. For ferric chloride the cutoff point where gains in undercut performance are not worth the loss in etch rate is around 48^{o} Be (1.495).

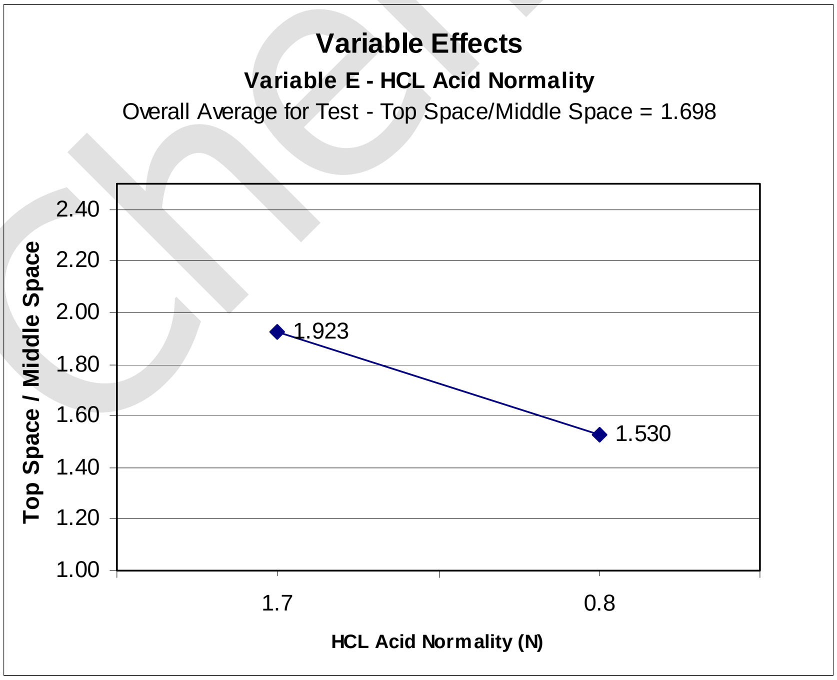
Temperature

Graph 2 shows that temperature has a significant effect on undercut in the test range with lower temperature giving better undercut performance. The trend continues as the temperature goes below 130^{o} F (54^{o} C) but, as we've come to expect, the increase in undercut performance comes at the expense of lower etch rates. (As a rule, the chemical activity of a reaction drops by about half for every 10^{o} C drop in temperature). Most cupric chloride and ferric chloride etching is already run at 130^{o} F so noticeable gains in undercut performance aren't seen until the temperatures of the etchants are reduced to 115^{o} F or below. Again, the gain in undercut must be factored against the loss of etch rate.

Acid Normality



Graph 2 – Effect of Temperature on Undercut



Graph 3 – Effect of Acid Normality on Undercut

The amount of free acid in the etchant also has a significant effect on undercut as shown in Graph 3 with decreasing acid levels giving better undercut performance. As usual, this is also accompanied by a loss in etch rate. For cupric chloride the etch rate loss versus undercut gain is less than that of either specific gravity or temperature changes. Below 0.8N the undercut performance begins to worsen again. Acid levels for ferric chloride tend to be lower in comparison to cupric chloride so further decreases in acid level don’t show as dramatic increases in undercut performance. Decreasing the acid level of ferric lower than 0.5% by weight slows down the etch rate much more than any increase in undercut performance can usually justify.

Oxidation/Reduction Potential (ORP)

Tests on ORP showed a small gain in undercut performance at the cost of an enormous loss in etch rate (approaching 50%). Generally, any gains in undercut performance are far outweighed by the loss in productivity.

In summary, the tests done on the chemical factors affecting undercut for cupric chloride showed that reducing the free acid level gave the largest gains in undercut performance with the least loss in etch rate in proportion to the gain in undercut performance. Increasing the specific gravity up to 36^{o} Be also gave a boost in undercut performance, although not as great as shown in reducing free acid levels. Reducing free acid levels below 0.8N or raising specific gravity above 36^{o} Be are counter-productive in terms of gain in undercut performance versus loss in etch rate.

Ferric chloride follows the same trends as cupric chloride but the greatest gain in undercut performance comes from increasing the specific gravity since the free acid levels tend to much lower already than those in cupric chloride. Raising specific gravity above 48^{o} Be or lowering acid levels below 0.5% again tend to be counter-productive.

Equipment Parameters That Affect Undercut

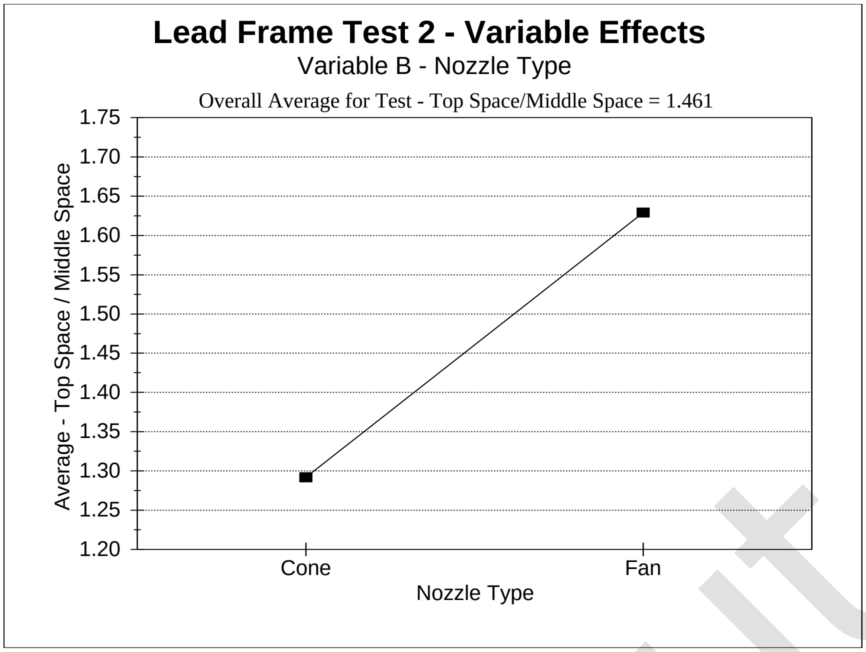
The equipment parameters tested were 1) Nozzle type, 2) Nozzle placement, 3) Spray Pressure, 4) Nozzle flow rate, and 5) Oscillation.

Nozzle Type and Nozzle Placement

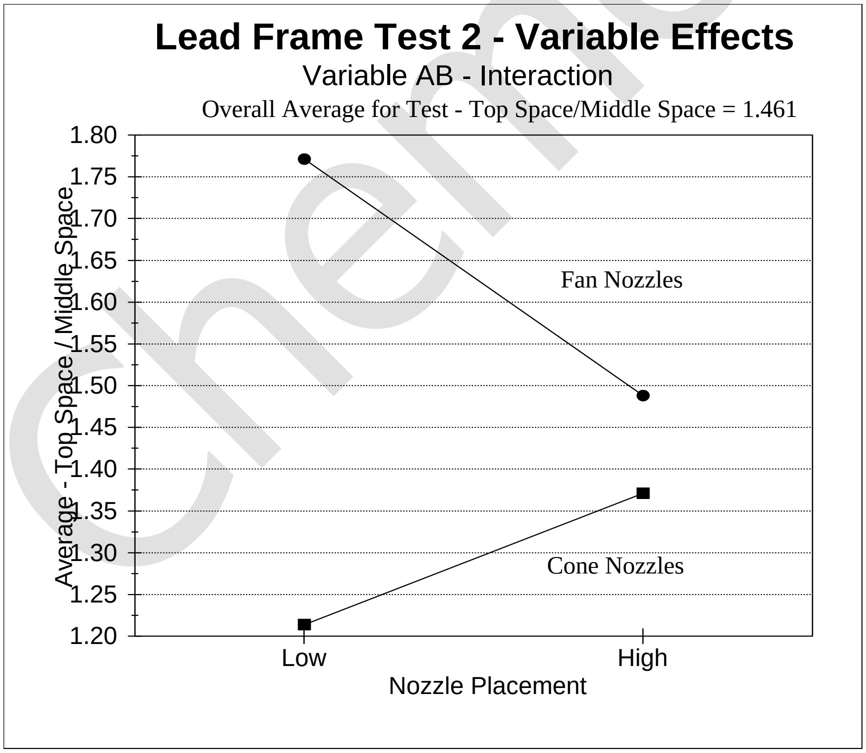
These two parameters are being discussed together since the relationship between the two are so intertwined that it is difficult to talk about one without including the other. Nozzle type refers to fan and cone nozzles while nozzle placement refers to the nozzle distance from the work surface.

There are two types of nozzles generally used in both PCB and PCM etching, cone nozzles, which spray in a circular cone pattern and fan nozzles, which spray in a flat fan pattern. When undercut improvements are considered the first idea that seems to occur to most people is changing the type of nozzle being used in their equipment. Also, most people seem to be under the impression that fan nozzles have better undercut performance, mostly due to claims made by equipment manufacturers using the different types of nozzles. In reality, there is very little difference in undercut performance but the perception lingers.

We have used cone nozzles in our equipment for almost fifty years and the first results from the designed experiment seemed to vindicate our choice. Graph 4 shows that cone nozzles gave significantly better results in terms of undercut performance than the fan nozzles. The numbers for each nozzle are

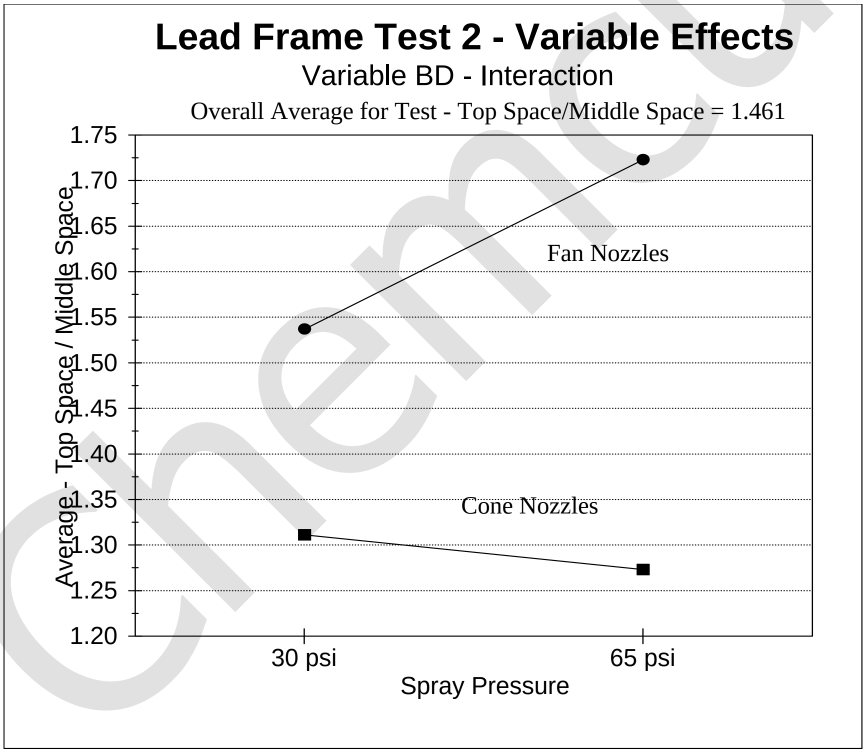


Graph 3 – Effect of Nozzle Type on Undercut



Graph 5 – Effect of Nozzle Type and Placement on Undercut averages of the 32 tests with cone nozzles and the 32 tests done with fan nozzles. However, Graph 5 shows that this conclusion may be misleading. Graph 5 shows the interaction between nozzle type and the distance of the nozzle from the work surface. In this graph the nozzle results are broken down so that, in addition to the nozzle type, the effects of the distance from the work surface of each nozzle is also shown. As can be seen, fan nozzles give better undercut as the distance from the work surface increases while cone nozzles give better performance as the distance decreases. The realization that the two types of nozzles react differently to the same parameters led to some insight on the fan vs. cone nozzle argument on undercut performance. Equipment manufacturers design their equipment to get the best performance from the type of nozzles they use. Since fan nozzles and cone nozzles respond differently to the same parameters the designs for best performance are also different. Cone nozzles in equipment designed for fan nozzles are going to perform poorly as are fan nozzles in equipment designed for cones. Since the etcher used in these tests was designed for cone nozzles, they had an inherent advantage that showed up in Graph 4. When all factors are taken into consideration, there is not much difference in the undercut performance between the two types of nozzle.

Spray Pressure



Graph 6 – Effect of Spray Pressure on Undercut

As Graph 6 shows, the undercut performance of fan nozzles and cone nozzles also go in opposite directions with increasing spray pressures. The undercut performance of cone nozzles gets slightly better as spray pressure increases and, in order to get to pressures in the range of 65 psi or greater, requires major changes in pump design and placement. The cost of modifying the equipment to handle these higher pressures is much more than the increase in undercut performance justifies. This is one of the few instances, however, where an increase in undercut performance also shows an increase in etch rate.

Fan nozzles show more response to spray pressure but the undercut performance gets worse as the spray pressure increases. The trend of increased undercut performance at the expense of etch rate is faithfully followed in this case.

Since these tests were run in the mid-nineties we have done some more work with fan nozzles and found we could match the undercut performance of cone nozzles at closer distances and higher pressures by reducing the flow rate of the fan nozzles used and increasing the densities of the nozzles to compensate. Figure 5 is a photograph of a cross section of a lead frame etched this past summer (2005). The material is 5 mil (125 µm) copper with a 5.3 mil (135 µm) pitch and a distance of 3.15 mils (80 µm) across the top of the finger.

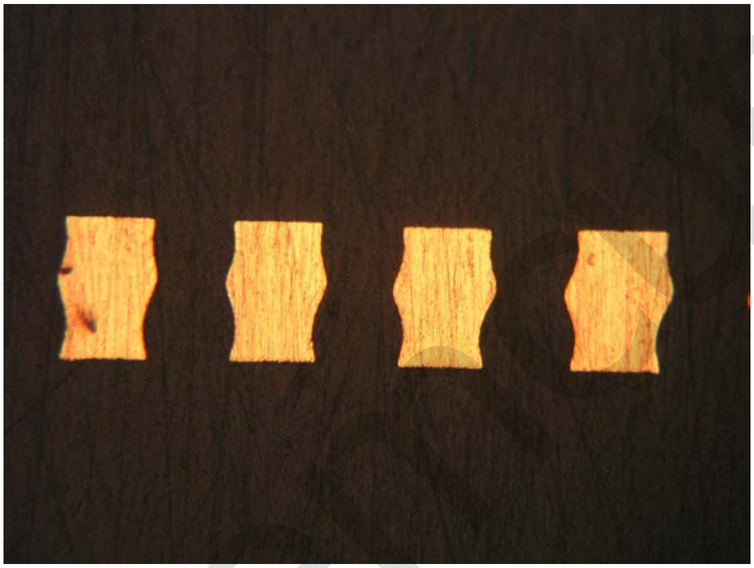
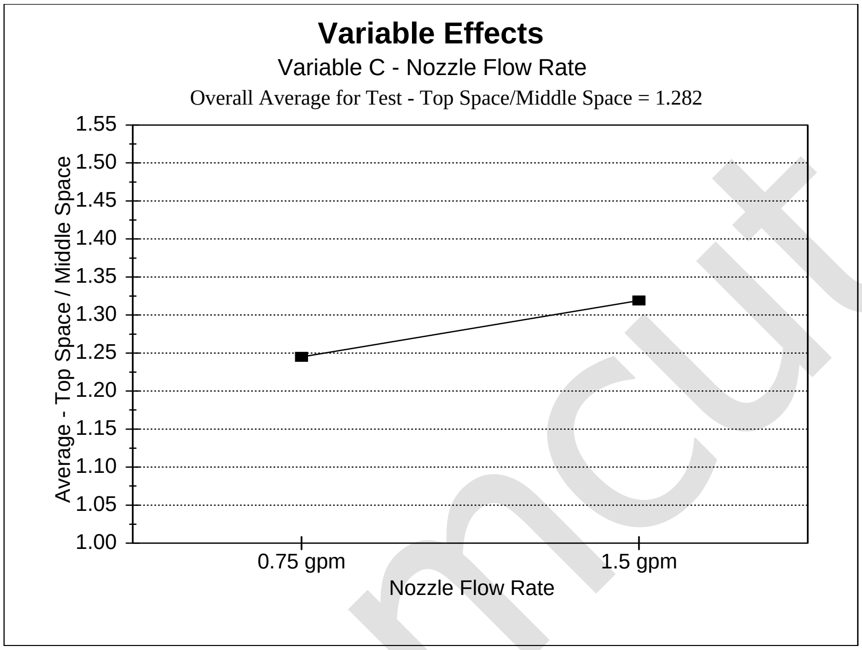


Figure 5 – Fan vs. Cone Nozzles

This was a two sided etch with fan nozzles used from one side and cone nozzles from the other. Can you tell which side was etched with fans and which with cones just by looking at this cross section? Simply switching from one type of nozzle to another is not likely to bring any undercut performance improvement.

<u>Nozzle Flow Rate</u>

Another thought that occurs to many people is that reducing the droplet size of the sprayed etchant may have a beneficial effect on undercut especially where the spaces between features is small (3 mils or 75 µm or less). The thinking is that a smaller droplet size will be able to get into the tight spaces and clean them out faster than a larger droplet; resulting in less undercut and higher etch factors. Unfortunately, smaller droplet sizes means going to a lower flow rate nozzle with less impact energy at the etch surface and a slower etch rate (so what else is new?). Graph 7 shows the results of the tests done with 0.75 gpm (2.8 lpm) nozzles against 1.5 gpm nozzles. As you can see, while the 0.75 gpm nozzles show a little bit better undercut performance, the difference is not that much. The reason is that, although the flow rate has been cut in half, the droplet size of the 0.75 gpm nozzle is still rather large when compared to the space left on the surface of the panel for the etchant to react. The mean diameter of a droplet from the 1.5 gpm nozzle is 1200 µm compared to 950 µm for the 0.75 gpm nozzles. While the droplets are smaller for the lower flow rate nozzle they are still large in comparison to the 50 µm space between the fingers for the etchant to get into. To get droplet sizes down into this range requires atomizing nozzles and etch times that will go from the 1.5 to 2 minute range for 1 oz. copper to 20 to 30 minutes. For all practical purposes going to a smaller droplet size without increasing etch times by a factor of ten is not going to affect undercut performance very much.



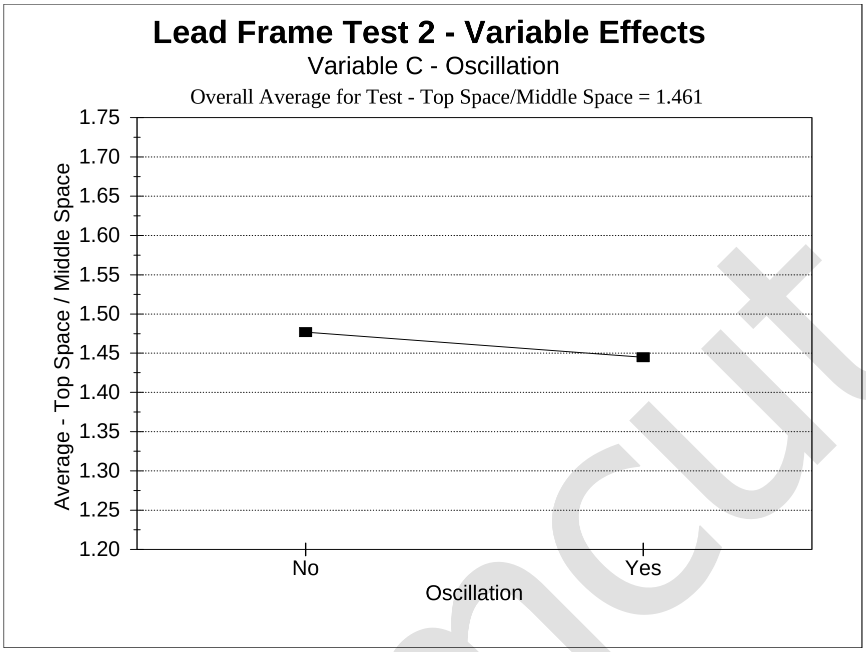
Graph 7 – Effect of Nozzle Flow Rate on Undercut

Oscillation

The purpose of oscillation is to move the solution on the surface of the panel, especially the top; to provide mixing and improve transport of spent etchant from the copper/etchant interface and fresh etchant to the interface efficiently and evenly over a large area. The oscillation on the etcher used in these tests was provided by rotating the spray tubes through a 40° angle perpendicular to the direction of travel. It was thought that moving the nozzles away from a vertical position might increase undercut since more spray might be directed under the resist rather than directly down upon it. Graph 8 shows the results of the tests run without oscillation versus tests run with the oscillation on. This result shows that there was virtually no difference in the undercut performance. The only major difference was that the etch rate for no oscillation was considerably slower. Considering the relatively large size of the spray droplets in relation to the small space for etchant penetration (1200 µm vs. 50 µm) it most likely that the spray droplets themselves are not penetrating directly under the resist as hypothesized.

Summary of Equipment Effects

These tests showed that the most important equipment parameters affecting undercut performance were the nozzles and the nozzle placement. Both types of nozzles tested were equal in undercut performance but the conditions for best performance were considerably different for each type. The most important thing learned was that simply replacing fan nozzles with cone nozzles in equipment designed for fan nozzles or vice versa is not going to improve the undercut performance of the equipment; in fact, the undercut performance is more likely to get worse. The other factors investigated had little or no impact on undercut performance.



Graph 8 - Effects of Oscillation on Undercut

Miscellaneous Factors That Can Affect Undercut

There are several things that can affect undercut performance that are not directly related to etchant chemistry or equipment design. The ones to be discussed briefly here are: 1) crystal structure of the metal, 2) Size of the panel to be etched, 3) feature density, and 4) plated or metallic resists.

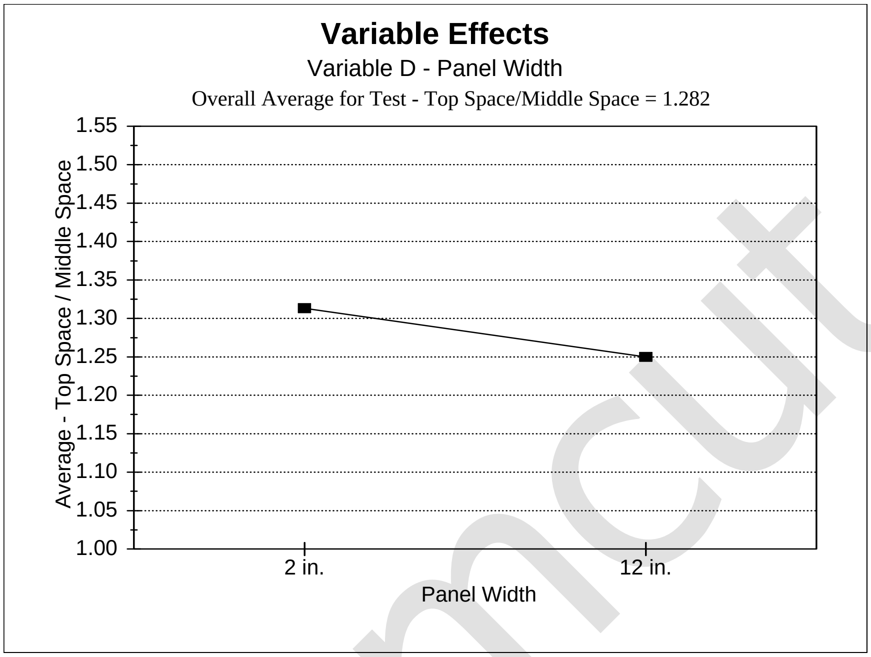
Crystal structure of the metal

The attack of cupric and ferric chloride on the various metals used in the PCM industry is generally along the grain boundaries of the metal in question, so the crystal structure of the metal can be important. I will admit up front that I am not an expert on crystal structure or metallurgy but I do know that the crystal structure of copper can be controlled during formation to provide a foil that has better undercut performance. I also know that this is both difficult and expensive.

I don’t know if the same is possible with iron alloys but it may be something that is worth looking into. There may be ways of improving the undercut characteristics of the metals themselves that are known to the metal suppliers who, in turn, may be unaware that the PCM industry could use them to good advantage.

Panel Size

It was perceived by some of the participants in the lead frame tests that frames made in narrow strips on a reel-to-reel etch line had better undercut characteristics than those etched in panel from in the normal fashion. Graph 9 shows that there is little difference in undercut between a twelve inch wide panel and a two inch wide strip. From the PCB side of etching there has been no observed difference in undercut or etch factor on various sized panels up to 24 x 18 inches.



Graph 9 – Effect of Panel Width on Undercut

Feature Density

It has been noticed that once the space between features begins to fall under 5 mils (125 µm) the etch factor begins to improve when compared to similar isolated features. Figure 6 shows the cross sections of two 3 mil (75 µm) lines. The cross section on the left came from a spot on the panel that had 30 mil (760 µm) spaces between the lines while the section on the right came from a place on the same panel where the spaces were only 3 mils between the lines. The undercuts for both panels were the same but the etch factor for the line etched in the higher density area is obviously better. The narrow spaces slow down the circulation of the etchant between the lines as the etching goes deeper which evens out the etch rate differences between the top and bottom of the feature. This also increases the etch time needed to reach the same feature width compared to an isolated feature (surprise, surprise). In some cases it may be possible to improve the etch factor of isolated features by adding dummy lines or features around it.

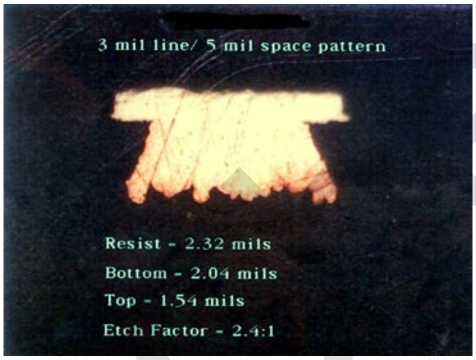
Metallic Resists

The use of plated resists, such as tin or solder, is not widely practiced in the PCM industry but we should be aware of the effects of metallic resists on undercut. Two dissimilar metals in contact with each other in the presence of an acid is essentially a battery, resulting in a large electron flow from the region where the two metals are in contact. Figure 7 shows two 3 mil lines with the about the same undercut but different etch factors. The line on the left was etched with tin/lead as the etch resist while the line on the right was etched with a dry film resist.

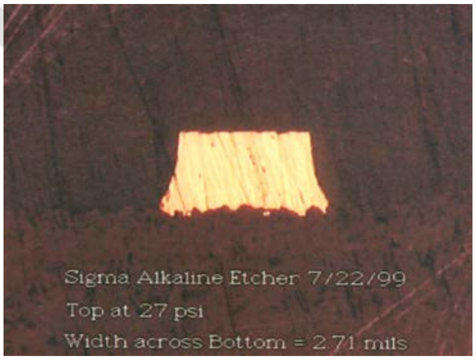
3 mil line, 30 mil space
Undercut = 0.59 mils (15 µm)
Etch Factor = 2.0:1 or 50%

3 mil line, 3 mil space
Undercut = 0.61 mils (15.5µm)
Etch Factor = 4.1:1 or 24.4%

Figure 6 – Effect of Feature Density on Undercut



3 mil line, tin/lead resist
Undercut = 0.89 mil (23 µm)
Etch Factor = 2.4:1 or 41.7%



3 mil line, dry film resist
Undercut = 0.87 mil (22 µm)
Etch Factor = 4.34:1 or 23%

Conclusions

Undercut performance can be improved somewhat by manipulating etchant chemistries and with some other tricks involving equipment and design but it cannot be eliminated entirely. It is something we will have to live with, at least until someone comes up with something that will inhibit sideways etch.

Sidewalls can be straightened by photo tool compensation and over etching until feature density becomes too great. There is a point reached, however, where decreasing space between features is no longer effective.

Most chemical and equipment modifications to improve undercut performance come at the expense of etch speed.

Cone nozzles and fan nozzles give equal undercut performance provided the equipment is designed for that particular nozzle. Simply changing to a different type of nozzle or nozzle flow rate will not lead to large improvements in undercut performance and may, in fact, make it worse. It may be somewhat discouraging to realize that dip etching without nozzles generally gives the same undercut performance.

Most of the equipment factors that were discovered in the course of these tests have been taken into account in new equipment designed since then.