Dry Film Lamination Process: Effects of Lamination Parameters on Wrinkling and Dimensional Properties of Dry Film and Copper-Clad Laminate

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Abstract
The dry film lamination process involves adhering a composite structure of photopolymer and polyester film to a metal-clad dielectric laminate. This paper covers the effects of this process on wrinkles in the dry film resist and on the dimensional stability of clad laminate. Further discussed are the techniques for avoiding wrinkles and dimensional changes while maintaining good conformation and yields.

Introduction

One of the evolutionary developments in dry film photoresist technology in recent years has been a trend to thinner polyester coversheets and thinner photoresist layers[1]. The thinner polyester coversheet enhances conformation in hot roll lamination and results in improved resolution in proximity printing. The thinner resist layer can also contribute to improved resolution and better etch uniformity. On the other hand, defect free hot roll lamination of these thinner structures has become more difficult.

Fig.1 shows the layers of materials the radiation has to pass through in the exposure step and illustrates how the distance between the phototool and the resist adversely affects resolution due to the presence of non-collimated light or light scatter. Some radiation reaches non-exposure areas where it causes some degree of polymerization[2]. This unintended partial exposure can be minimized by bringing the phototool in very close contact with the resist, for example through the use of a thin polyester coversheet and a thin photoresist layer.

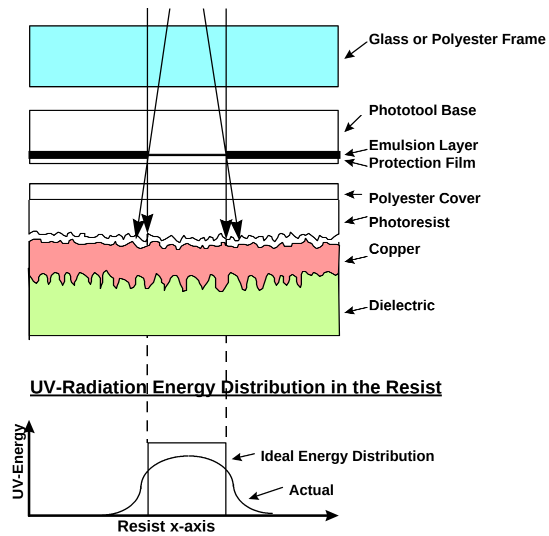

Fig. 1: Exposure Schematic

However, these thinner resist architectures will make it more difficult to avoid wrinkling of the resist during lamination. The thickness of the polyester coversheet has been reduced in recent years from 25 microns to about 18 microns. This made the resist more prone to wrinkles introduced during hot roll lamination, and lamination parameters had to be controlled more tightly. At 16 microns polyester thickness, a cut sheet laminator needs to be well aligned and tuned to avoid resist wrinkling. With a 12 microns thick polyester base, we found it impossible to avoid resist wrinkles on a standard laminator in a lab environment.

Photoresist layer thickness has also been reduced in recent years. The thickness range of commonly used dry film resists is 25-50 microns (1-2 mils). On average, dry film resist thicknesses have come down for print & etch, tent & etch, and pattern plating applications. One major driver has been the need for higher resolution, but productivity through exposure, development and stripping, as well as reduced processing costs, through waste treatment, also played a role in this development. Enabling technologies to support this trend are improved electroplating processes yielding better metal thickness uniformity, and factors contributing to improved conformation of thinner resists, such as improved laminate quality and resist rheology.

The Basics of Lamination: Pressure and Temperature.

In lamination, good contact between the resist and the substrate surface is achieved by making the resist flow to conform to the surface topography. Flow is achieved by lowering the resist viscosity through heat, and by applying a pressure differential for a certain time to cause the flow (see Fig.2 and Table 1). The pressure may be transmitted to the lamination rolls pneumatically, hydraulically, mechanically, or a combination of these means[3].

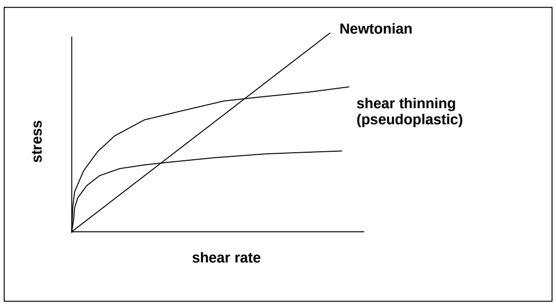

Fig. 2: Viscosity/ Pressure Relations

Table 1 - Actual Lamination Times

Time in nip (secs) for different speeds and pressures			
Speed\Pressure	3 bars	4 bars	5 bars
1 mpm	0.72	0.82	0.91
2 mpm	0.36	0.41	0.45
3 mpm	0.24	0.27	0.30
Figures are for an ASL-24 laminator			

The actual force on the resist depends on the design of the roll loading system, taking into account the actual area of the cylinders and the mechanical leverage, if any, of the system. Since the force is applied to the resist through an elastomeric roll covering (see Fig.3), the deformation of the rubber forms a roll nip contact zone or "footprint". The actual pressure (force per unit area) on the resist is dependent on the length and width of this footprint.

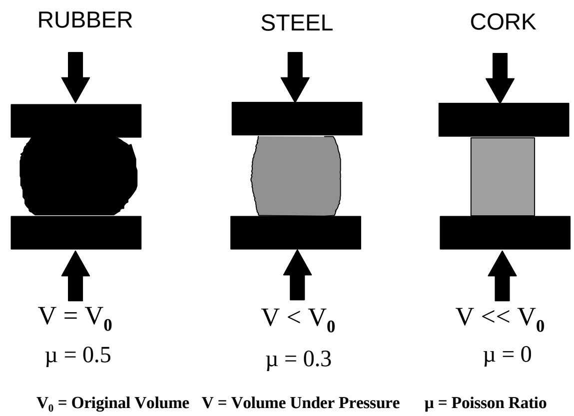

Fig. 3: Volumetric Compressibilities

The footprint is influenced by the total force applied, the roll diameter, and the thickness and durometer of the roll covering. The pressure across the footprint width varies from zero at the edges to some peak pressure at the center of the nip where the roll covering is compressed the greatest. The average of this pressure profile (roughly described by a parabola) is about 2/3 of the peak pressure. When referring to nip pressure, we usually mean this average pressure instead of peak pressure, because it is simpler to determine.

When pressure is transmitted to straight lamination rolls, they tend to bend and form an uneven roll footprint on the resist (see Fig. 4). The footprint is narrow at the center of the rolls and wider at the ends. This means that the pressure on the resist at the center is less than at the ends. The result is poorer resist conformation at the center and a tendency for the dry film to wrinkle (see discussion on wrinkles). Laminator suppliers are aware of this phenomenon and try to build the rolls as sturdy as is practical. Residual roll bending can be compensated for[4] with rolls that are "crowned" (see Fig. 5). A crowned roll has a rubber covering which is thicker in the center than at the edges and changes gradually from center to edge, resulting in a curved profile.

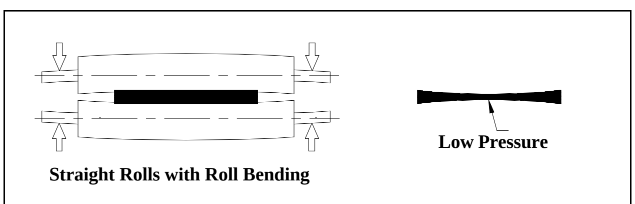

Fig. 4: Nip Pressure Profile with Straight Rolls

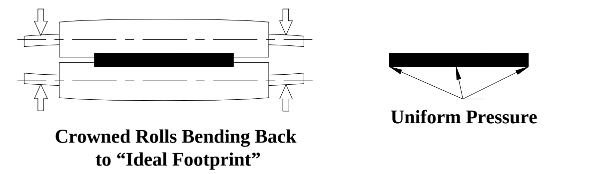

Fig. 5: Nip Pressure Profile with Crowned Rolls

In hot roll lamination, the resist is heated to lower its viscosity so that it can flow and conform to the substrate surface. Heat is applied to the rolls and transferred through the polyester film coversheet and the resist to the resist/copper interface. This is often supplemented by preheating the boards directly.

The actual temperature at the resist/copper interface depends on a variety of factors:

- the contact time of the resist with the heat source,
- the temperature of the heat source,
- the heat transfer coefficients of the materials between the heat source and the resist/copper interface,
- and the thermal mass and temperature of the board.

The contact time, in turn, is a function of the lamination speed and of the roll/film "footprint" in the lamination roll nip. This time in the nip is only a fraction of a second (see Table 1), and therefore good resist <u>flow</u> and flow <u>volume</u> is needed to conform to the recessed areas of the copper topography.

Lamination Wrinkles: Causes and Cures

One advantage of dry-film photoresists is the uniform thickness provided by a carefully controlled coating process. This advantage may be forfeited if the film cannot be laminated without wrinkles. Two different forms of wrinkles can occur: those which form in the lamination nip, and those which appear some time after lamination (also known as post-lamination wrinkles). Both of these wrinkles are closely associated with the polyester base film which supports the photopolymer layer but are caused by factors independent of the base film.

Nip-generated Wrinkles in Cut-Sheet Laminators

The most prevalent and most damaging form of wrinkles are nip-generated wrinkles. These are severe wrinkles, usually causing imaging defects because they result in creases or folds in the polyester base. These creases cause off-contact in proximity printing and can distort the light path (lens effect). The following are the main sources of these wrinkles; the numbering is only used to reference the subsequent list of explanations, not to indicate the severity or frequency of the event. Note that an ASL-24 cut-sheet laminator is the basis for the list. Most of the featured sources of wrinkles will directly apply to all laminators, or can be related to a generic equivalent on other laminators.

1. Misalignment between resist supply rolls and lamination rolls.
2. Misalignment between panel input conveyor and lamination rolls.
3. Poorly wound, distorted, or cocked polyethylene take-up rolls.
4. Uneven drag on film passing over vacuum holding plate.
5. Resist rolls not centered on laminator rolls or panels not centered in rolls.
6. Distortion of cut sheet edge at trimming.
7. High electrostatic charge on unwinding film.
8. Uneven leading edge sealing or tack-down to panels.
9. Lamination rolls running at different surface speeds.
10. Unequal drag between top and bottom supply roll brakes.
11. Worn lamination roll bearings.
12. Roll bending.
13. Uneven air cylinder pressures (clamp pressures).
14. Difference between temperatures of lamination rolls.
15. Different rubber compression between top and bottom lamination rolls.
16. Non-parallel lamination rolls.
17. Roll covering (rubber) too thick.
18. Varying laminate thickness, particularly on multilayers.
19. Poorly wound dry film resist.
20. Non-uniform dry film resist thickness.

The following parameters can aggravate the wrinkling propensity introduced by the above mentioned causes:

21. Resist with a thin polyester base.
22. Wide dry film resist and panels.
23. Thin resists.
24. Thin laminate.

Explanation of wrinkle sources for cut-sheet laminators.

It should be noted that a properly aligned and maintained laminator is the first step towards wrinkle-free lamination.

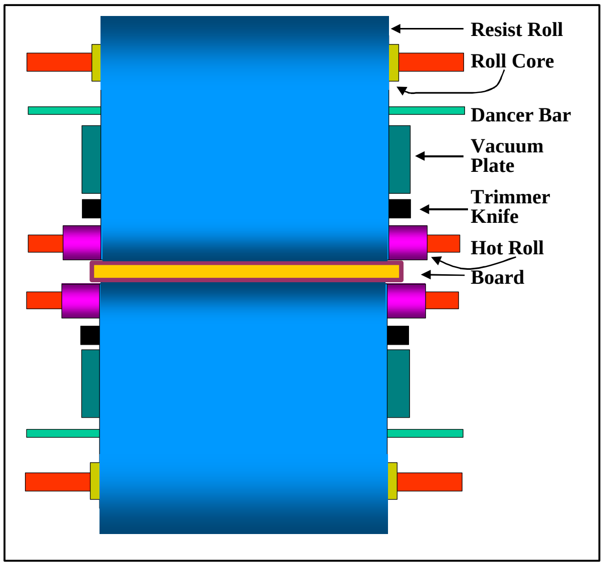

Fig. 6: Properly Aligned Laminator

Many of the sources mentioned contribute to wrinkling problems but may not actually result in wrinkles if the laminator is adequately aligned and maintained.

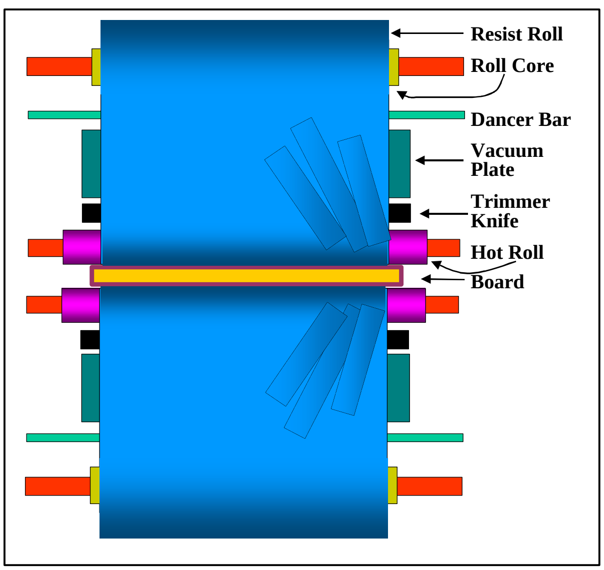

Fig. 7: Lamination Wrinkles (possible causes: Lamination Rolls Closing on Right Side before Left Side; Closing Force Grater on the Right Side)

A general rule is that wrinkles, on a reasonably maintained laminator, are a problem only when laminating wide (>510mm; >20") resist or when laminating very thin (< 0.2mm;<0.008") laminate.

Source 1. Misalignment between supply rolls and lamination rolls.

The resist supply rolls are held by roll chucks on the supply roll shafts. Over-tightening these chucks can distort the plastic cores of the rolls from round to oval shape. This can cause an intermittent wrinkling of the film as it unwinds. While these wrinkles usually "iron out" on the way to the lamination rolls, they occasionally make it to the nip or cause drag at the trim knife, resulting in problems with the next panel.
Another cause of misalignment is a loose or worn shaft chuck on the supply roll unwind. If there is play between the clamp and the shaft, the roll of resist will orbit the centerline at that end of the roll, resulting in wrinkles which oscillate from one direction to the other. It can also cause the shaft to jump when the shaft end drops within the looseness of the chuck. With a full roll of resist on 150 mm (6") cores, this can cause wrinkles which slant one way on panel and the other way on the next.

All the idlers between the supply roll and the nip are important. If an idler is mis-aligned, it can have the same effect as having the supply roll and the nip rolls mis-aligned.

Source 2. Misalignment between panel input conveyor and lamination rolls.

The panels must be fed with the leading edge parallel to the lamination rolls. If the input conveyor is angled to the rolls, the panel will either skew as it first enters the nip or will begin to rotate as one edge moves closer to the center while the other edge moves farther from the center. Distance from center of the two sides is very important. Because of roll bending, off-center panels will rotate slightly as they are laminated, resulting in distortion or wrinkling of the resist. If the sides of the sheet of cut film are not parallel to the sides of the panel, adjust the input conveyor until they are.

Another cause of misalignment occurs principally with laminators that feature "Thin Panel" and "Thick Panel" settings, and the "Thin-Panel" setting is mistakenly chosen for thick panels. When set for thin panels, the rolls are closed too tight for the thicker panels and can cause the panels to skew when they enter the nip.

Source 3. Poorly wound, distorted, or cocked polyethylene take-up rolls.

It is advisable to strip off the polyethylene from the take-up rolls before starting a new roll of resist. Check that the start of the new polyethylene on the take-up core is smooth, so the roll remains in contact across the whole width of the film. Make sure that the roll is not cocked on the supply roll that drives it. Remove the polyethylene any time the polyethylene wrinkles or folds over.

Source 4. Uneven drag on film passing over vacuum holding plate.

The vacuum plate on an ASL-24 keeps the film from moving during trimming. If the vacuum is not even across the plate, the film can be displaced such that the next panel will wrinkle. Plugged or partially plugged vacuum holes in the plate could be the cause. If the problem persists after cleaning the holes, clean or replace the vacuum supply tubing. Volatile components of the resists will accumulate in them and reduce the effective vacuum.

Source 5. Resist rolls not centered on laminator rolls or panels not centered in rolls.

Lamination rolls bend due to the loading on them (see Fig. 4). This bending tends to drive the edges of the film faster than the center. If the resist is not centered, it will feed in faster on one side than on the other, causing wrinkles which are angled slightly from the machine direction.

Source 6. Distortion of cut sheet edge at trimming.

Dull trimmer blades can cause the sheet edge to move when they cut. The film needs to be held firmly during trimming, and the blades have to be sharp enough to avoid dragging the film. Wrinkles which change direction each panel can be an indicator of this type of problem.

Source 7. High electrostatic charge on unwinding film.

Static charges can cause the film to cling to surfaces and can cause high separation forces when trying to remove the polyethylene separator sheet. Relative humidity below 50% will aggravate this problem. Ionizing static bars are installed to counteract the problem, but they need to be maintained clean to be effective. Additional air ionizers may be required if the relative humidity is too low. This problem can be worse on laminators which do not have a seal bar and which rely on direct roll tacking or sealing of the leading edge.

Source 8. Uneven leading edge sealing or tack-down to panels.

Uneven tacking of the leading edge of the resist is the most likely cause of leading edge wrinkles and of severe wrinkling in the first half of the panel. The resist must be uniformly tacked across the whole width if leading edge wrinkling is to be avoided. The causes of poor sealing are incorrect seal temperature and worn seal strips.

The seal temperature can be checked with a contact thermocouple to ensure the temperature agrees with the controller gauge. Both the seal tip heater and thermocouple can be dislodged so that the gauge-indicated temperature is not the true tip temperature. Worn seal strips are a frequent cause of poor leading edge tack. Replace seal strips frequently and check to make sure the sealing pressure is equal across the whole width of the panel. Look for “blisters” in the resist which are actually bubbles of trapped air on the leading edge of the panel. This is a good indication that the seal tip pressure is too low and the seal tip should be replaced. Another indicator of poor sealing is a crooked leading edge. On an ASL, poor sealing can be detected by watching the leading edge of the panel just prior to closure of the laminating rolls onto the panel.

Source 9. Lamination rolls running at different surface speeds.

The lamination rolls are geared together to run at the same angular speed. If the rolls are not the same diameter, however, the surface speeds will be different. The difference in surface speeds can cause wrinkling on thick panels and curling of thin panels. The diameters themselves are not the only dimensions determining the surface speed. The diameters of the underlying steel rolls are equally important. If these diameters are different, and the outside diameters of the rubber covering are equal, the roll with the smaller steel diameter has more rubber than the other roll. The difference in steel core diameters is caused by the removal of a small layer of metal each time a roll is recovered. If the rolls are not kept in pairs, it is possible to have significantly different diameter rolls on the laminator together.

This difference will cause a difference in compression and, in effect, will cause the surface speed to be different. This will result in more stretch of the photoresist and polyester base on one side than on the other. This difference in stretch will result in wrinkles on rigid panels and may cause curling and post-lamination wrinkles on flexible substrates.

Source 10. Unequal drag between top and bottom supply roll brakes.

The supply roll brakes should provide enough drag on the supply rolls to prevent overshooting when the resist is stopped on the vacuum plate for shearing (trimming). Unequal drag will cause problems similar to Source 9 but will not be limited to thick panels.

Source 11. Worn lamination roll bearings.

Worn roll bearings will cause severe wrinkles which cannot be eliminated. Movement of the roll shaft in response to loading causes one side to drive faster than the other, resulting in very long wrinkles at a slight angle to the machine direction.

Source 12. Roll bending.

Laminator rolls bend when subjected to lamination loading. The bending causes higher driving speeds at the edges than in the center of the panel. While it usually does not affect the panels, except for very thin laminate, it can drive the resist film in a way that the film edges tend to move toward the middle, resulting in lamination wrinkles. If the loading is high enough to "iron out" the wrinkles during the time the film is being held by the vacuum bar, the wrinkles may not appear until the very end of the cut sheet when the film is dropped by the vacuum bar. At this point there is no restraint of the trailing edge and the last inch or so is likely to gather and wrinkle. Frequently, "comet tails" on tooling holes are caused by a combination of roll bending and poor control of the resist trailing edge.

Source 13. Uneven air cylinder pressures (clamp pressures).

The clamp pressures (these are the air cylinders closing the rolls) must be set at the same pressure for wrinkle-free lamination. This source may be one of the biggest causes of long wrinkles starting mostly at the middle of the panel and moving back at a small angle to the lamination direction. The gauges are not always reliable indicators for the actual pressure. A periodic independent pressure check is advisable.

Source 14. Difference between lamination roll temperatures.

Differences between the two roll temperatures can cause different stresses in the polyester base. These, in turn, will tend to cause wrinkles in panels.

Source 15. Different rubber compression between top and bottom lamination rolls.

This source of wrinkles can be caused either by differential speed (Source 9) or by differences in the hardness of the rubber. Standard silicone rubber covered rolls are 70 Durometer. Mixing durometers can also cause wrinkling problems by changing the effective speed of the rolls.

Source 16. Non-parallel lamination rolls.

This is a structural problem that can only be solved by having the machine aligned using alignment templates. Non-parallel rolls can cause a fluctuating problem which sometimes appears on the top of the panel and sometimes on the bottom side.

Source 17. Roll covering (rubber) too thick.

Rubber roll covering for the ASL-24 is usually about 2 mm (.080") thick. When rolls are recovered, the underlying steel core is machined slightly to remove all the rubber. Since the rolls are machined to the same outside diameter after recovering, the actual rubber thickness increases each cycle. Besides the danger of differential speed (Sources 9, 15) from mixing rolls with different steel core diameters, there is a problem with wrinkling associated with thicker rubber covering. On a continuous (non cut-sheet) laminator, rolls of 2.7 mm (.106") rubber caused fewer wrinkles than rolls having 4.0 mm (.157") of rubber covering.

Source 18. Varying laminate thickness; particularly on multilayers.

Variable thickness results in panels skewing as they are laminated which will cause the resist to wrinkle. It seems to be a bigger problem on multilayer panels because of the likelihood of varying thickness. Print-through of innerlayers to the outer surface are another problem source.

Source 19. Poorly wound dry film resist.

Loosely wound resist can create problems because the drag brake cannot keep uniform drag forces on the roll of resist. Rolls can telescope during handling if they are not tightly wound and/or they are stored on end. This will make them virtually unusable.

Source 20. Non-uniform dry film resist thickness.

Resist which is consistently thicker along one side than the other will tend to move sideways as it is unwound.

This condition can usually be detected by checking for soft spots when pressing against the surface of the resist roll. This has been seen on rolls of resist which were stored on end instead of the recommended horizontal position.

Source 21. Thin polyester base.

Wrinkling problems increase inversely to the thickness of the polyester base. Thinner base has imaging advantages, but the laminator must be in excellent condition and well aligned to avoid wrinkling with such films.

Source 22. Wide dry-film resist and panels.

Films which are greater than 510 mm (20") wide are more susceptible to wrinkling than narrower films. At the limit of the machines, usually 610 mm (24"), the film is very sensitive to all of the sources of lamination wrinkles. Roll bending is probably the major cause of this sensitivity, so wide films almost always require crowned rolls to minimize wrinkling.

Source 23 Thin resists

The thickness of the resist affects wrinkles. Resists 25µm (1 mil) or less in thickness require higher pressures to achieve acceptable conformation so roll bending and other mechanical issues result in more wrinkling.

Source 24. Thin Laminate

Wrinkling is a serious problem with very thin laminate under 125µm (5 mil) core thickness, particularly with 0.5 oz copper. First, the laminate is flimsy, which makes accurate alignment and panel feeding difficult. Any misalignment between the film and laminate can cause not only wrinkling of the film, but distortion and wrinkling of the laminate itself. Tack uniformity is crucial, tensions must be controlled carefully to prevent curling of the resist-laminate package, and dimensions of the laminator rolls must be identical. An additional problem is the effect of roll bending, even with relatively narrow film. The main contact area is between the rubber rolls outside the width of the laminate, reducing the actual lamination forces and causing the resist to bunch together as lamination occurs. This results frequently in trailing edge wrinkles which sometimes start as far in as the middle of the panel. Crowned rolls are a must for thin laminate to reduce contact between the rolls outside the width of the laminate.

Post-Lamination Wrinkles

Post lamination wrinkles are rarely visible immediately after lamination. They are caused by excessive stress and heat in the polyester support base. The stresses placed in the base are relieved by movement of the base after lamination, sometimes taking days to equilibrate. The defect looks like furrows or a washboard, with sinusoidal wrinkles running lengthwise in the direction of lamination. They are usually not very pronounced in depth, but can cause contact problems during exposure and overplating problems during plating, if present in multilayer outerlayers. Fig. 8 is an exaggerated illustration of this defect. A 30 micron thick resist might show furrows with a peak to peak distance of 2 mm and a waviness of 5-8 microns.

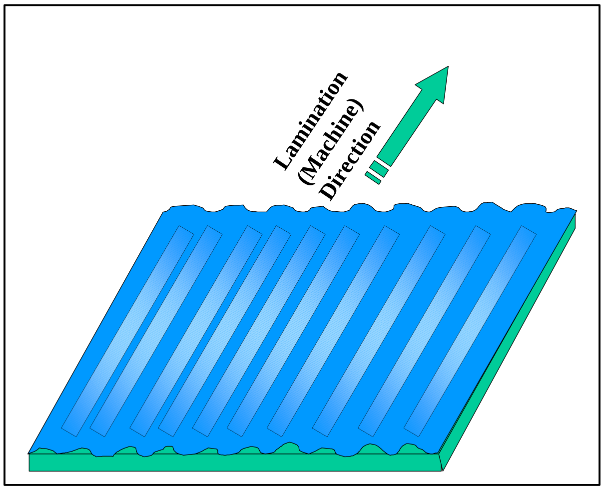

Fig. 8: Post-Lamination Wrinkles (Exaggerated)

The major sources of these wrinkles are:

- Excessive lamination roll temperatures.
- Excessive panel preheat.
- Excessive lamination pressure.
- Thick dry film resists.
- Thin polyester base films.
- Long hold times between lamination and exposure.
- Inadequate, i.e. slow cooling of panels after lamination.
- Stacking panels after lamination while still hot.

Explanation of post-lamination (PL) wrinkle sources for cut-sheet laminators.

Source P1. Excessive lamination roll temperatures.

The rolls contact the dry film support base directly as it enters the nip. If this temperature is greater than 125 degrees C, it may cause PL wrinkles. Whether they form or not is dependent on how many of the other sources are present.

Source P2. Excessive panel preheat.

This is unlikely to cause a problem with thin innerlayer laminate, but is a serious source of problems in multilayer panels because the amount of heat contained in the panel itself is sufficient to keep the resist layer hot for a considerable length of time. While the resist is hot, it flows easily, providing very little resistance to movement of the polyester base as it attempts to reduce the stresses induced during lamination. To minimize the effects of preheating on PL wrinkles, the total amount of preheat should be limited. To do so without adversely affecting lamination, the preheating should be done as close to the laminator as possible to ensure the surface (and not the bulk) of the laminate is still hot.

Source P3. Excessive lamination pressure.

PL wrinkles are caused by heat and stress in the polyester base. While the need for good conformation requires as high a lamination pressure as possible, this pressure can add to the stress in the base. It would be better to use two nips set at medium pressures and temperatures than one nip at high pressure and high temperature if PL wrinkles are a problem. The second nip should be directly after the first one to minimize heat loss between nips. Note that this arrangement would be more useful on multilayer panels than on innerlayers.

Source P4. Thick dry film resists.

PL wrinkles are formed by the buckling of the polyester cover film as it tries to grow back to its original width. During lamination it is stretched in the machine direction and narrowed in the transverse direction. After lamination the film attempts to return to its original shape. Since it is connected to the laminate by the resist layer, it must buckle into a sinusoidal wave pattern. This means that some of the photopolymer is thinned out where the wave is depressed and thickened where the wave is elevated. When the resist is thin, 37µm (1.5 mil) or less, the movement occurs very slowly or not at all. With thick resists the movement is easier since the resist can flow more readily. Because of this, PL wrinkles, unlike nip-generated wrinkles, occur more with thick dry film resists than with thin resists.

Source P5. Thin polyester base films.

Thick polyester base cannot be stretched as much as thin base and it cannot buckle easily. Thus thick base films will not be as susceptible to PL wrinkles as thin base films. As needs for finer resolution demand thinner bases, the problem will become more of an issue.

Source P6. Long hold times between lamination and exposure.

PL wrinkles take time to form. If a high-count multilayer panel contains a lot of heat when it is laminated, and is left to relax a long time before exposure, the severity of the PL wrinkles will increase.

Source P7. Inadequate (slow) cooling of panels after lamination.

The panels should be cooled as quickly as possible after lamination to slow down the flow of the resist under the polyester base. However, the resist on a panel with excessive heat inside will continue to flow until all the heat has been removed. Thus, cooling only helps when the bulk of the photopolymer layer can be dropped quickly to room temperature.

Source P8. Stacking panels after lamination while still hot.

This is mentioned only because a stack of multilayer panels containing heat will stay warm for a long time. There are sufficient reasons to avoid stacking aside from PL wrinkles to always avoid the practice.

Wrinkling with continuous (non-sheet) laminators.

Continuous laminators, commonly called hot-roll laminators, have no trimming mechanism and are considerably less complicated than cut-sheet laminators. Wrinkling occurs with these machines as well and many of the sources of wrinkles for cut-sheet laminators apply to hot-roll laminators. Since these laminators are frequently used to laminate on one side of a panel only, using a carrier web to support the panel and keep resist from contacting the opposing lamination roll, some additional sources are possible.

The use of a wide web of polyester film under the panel can aggravate wrinkling because the main driving force is through the web instead of through the panel. This will accentuate roll bending problems. It is best to keep the width of the support web slightly smaller than the width of the panels, and only slightly wider than the width of the resist.

Hot-roll laminators are not as rigidly built as cut-sheet laminators and the rolls are more flexible, so roll bending can be a bigger problem with such machines. Crowned rolls are probably a must as well as steel lamination rolls in place of the less rigid aluminum rolls. If laminating very smooth laminate, particularly non-woven materials, a harder rubber covering of about 80 durometer in place of the normal 70 durometer should help.

Summary

Thinner dry film photoresist constructions, notably thinner polyester cover foils, have contributed to the advancement of resist resolution, conformation, processing speed, cost and waste reduction. However, these thin films are more prone to wrinkling in the hot roll lamination process. Automatic sheet laminators need to be finely adjusted and maintained to minimize sources leading to film wrinkles in the lamination nip such as misalignments, uneven nip pressure, and uneven film web drag, Temperature profiles during board preheat, lamination, and post-lamination hold may have to be adjusted to avoid post-lamination wrinkles.

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