Flexible Manufacturing—How Design and Cost Can Influence Processing

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The use of flexible circuits has progressed from relatively low volume, high price, high technology applications into everyday life and therefore lower cost, high volume applications. However, technologically, flexible circuits and assemblies have grown in complexity. Designers must be aware of all factors affecting the finished product to avoid difficulties with cost, manufacturability or functionality.

Flexible circuits—including single-/double-sided, sculptured circuits and flex-rigid-multilayers—can be produced in part or totally by two basic routes: panel processed or continuous roll web or reel-to-reel (R2R) processing. For thin laminates (e.g. 12.5 micron dielectric and 5 micron copper foil thickness), severe difficulties can arise from panel processing through etch and post-etch process equipment. When R2R processing is utilized many of these difficulties are reduced as the web handling equipment is designed to ensure a uniform web tension is applied at all times during the processing.

Additionally, early R2R equipment tensioned the web directly between unwind and rewind stations. This can result in serious problems with the carryover of solutions from the wet process stages and thus create the potential for poor yields. To eliminate these issues, modern R2R web handling systems utilize machine conveyors and tension balancing or "dancers" at the unwind and rewind. This has resulted in the development of R2R facilities that can process very thin web materials with fine conductor geometry. During continuous roll processing, the chemistry is applied to the web using sprays. In some cases "puddling" of the etchant can occur. This reduces the capability of the etching process but can be avoided by taking the "copper down" approach, or for double-sided laminates, using narrow webs and the use of relief holes to allow for the drainage of any puddles that form.

Figure 1. A modern continuous web/R2R manufacturing facility.

Primary imaging is undertaken using photoresists that can be applied as a dryfilm or as a roller-coated liquid resist. The dryfilm material is supplied with an accurately controlled thickness which is optimized to the imaging process. Its application via hot roll lamination is also a continuous roll process.

Successful photo imaging of fine circuit geometry relies upon a clean environment (Class 100 inside the exposure frame), automatic web handling, very high levels of process control, e.g., exposure time, UV light energy, and vacuum between the exposure frame and web. As the photoresist is a polymer film cross-linked under the influence of UV energy, the wavelength of this energy needs to be carefully controlled to ensure crisp feature definition. Theoretically, to achieve straight sidewalls on etched tracks full collimation, i.e., zero light contact angle is required. However, any particulate material present within the incident light path will also be resolved onto the resist, thus causing a defect in the etched circuit pattern. The optimum degree of light collimation is where a light contact angle of 4° from the normal is achieved to eliminate the risk of resolving particulate but achieve a very good sidewall profile.

There are many choices of photoresist and special purpose resists are available for fine feature definition and even compatibility with Laser Direct Imaging (LDI) photo imaging processes. Where phototools are used their control and care are critical.

Excellent etching control can be achieved using an electrolytic closed loop control system with a copper chloride ($CuCl_2$) etchant. This type of system provides superb track profile control but is very cost effective with respect to replenishment and is environmentally friendly with very little waste produced.

DESIGN

The aim today of flexible circuit manufacturers is to increase the level of understanding at the outset of design level to ensure fast and accurate design for manufacture (DFM). To achieve this designers must work closely with development, product, and process engineers as soon as possible in the product design phase.

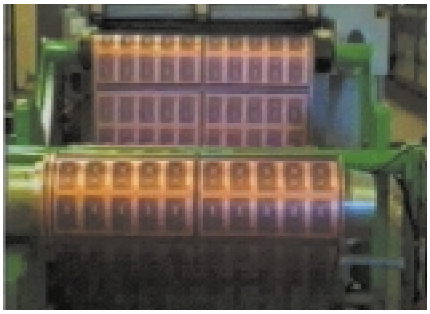

Figure 2. A typical web/R2R processed product.

Factors on which design has an effect:

1. Cost
2. Material choice and utilization
3. Physical shape, size, and weight
4. Construction
5. Manufacturing process routes
6. Test and inspectability
7. Electrical performance
8. Mechanical performance—bend to install or dynamic
9. Physical performance—dimensional stability, temperature/environmental resistance
10. Assembly technology

All of the above need to be considered as soon as possible within the product design cycle. Often the reverse can be the case, with flexible circuits being an after thought to solve other design problems. In either case, the use of design Failure Mode and Effect Analysis (FMEA) is extremely useful in eliminating potential issues. There is no reason why this could not include the manufacturing process detail at this stage or shortly afterwards.

MATERIAL

For many years flexible circuits have been manufactured mainly using polyimide as the base and coverfilm laminate. However, as use has increased and applications have become more cost sensitive, the choice of materials has diversified. Today the number of materials available has increased to include:

- Polyimide—Adhesiveless
- Polyimide—Adhesive
- Poly Ethylene Napthalate (PEN)
- Poly Ethylene Teraphthalate (PET) or Polyester
- Thin FR4 epoxy/glass

These materials vary in their cost and performance, and Figure 3 shows a comparison of the material costs using adhesive based polyimide laminate as the reference.

Individual material performance data can either be obtained from the raw material supplier or developmental testing to suit the application. As applications expand across industry sectors this data is key to ensuring robust manufacturing and product performance. Much of the material supplier's data is focussed around the IPC or MIL standard test criteria. As yet there is further work to be completed and published to satisfy newer areas such as automotive across the full range of available materials.

PROCESS ROUTING

Process routing is key to ensuring that the critical features of the product, i.e., dimensions and performance, are met in a repeatable and cost effective manner. As discussed already there are fundamentally two process routes for circuit production.

The R2R route is preferred with respect to cost and repeatability being a continuous manufacturing technique. However, there are product types that have to follow the panel route due to material availability, circuit design, R2R line capability and/or cost. One of the most interesting phenomena is when a product starts its production utilizing the R2R approach but then at some point divides into panels. Today it is becoming popular for customers to require the final product in roll form, particularly where high levels of automatic assembly are employed to achieve high volumes at lower costs, e.g., the telecom antenna and smartcard markets.

Figure 4 indicates the mix of process options available for products produced via pure R2R or R2R/panel processing. Often cost is the prime factor in deciding which route is optimum for a particular product. Other factors which influence the process route are technical and can, with a well thought out process flow, provide optimum yields and lower costs for products not traditionally associated with R2R or part R2R production.

For example, the economies of scale provided by R2R production can be used to reduce the cost of single or non-plated through hole (PTH) double-sided flex circuits that could later in panel production processes be incorporated into multi-layer flex, sculptured flex, flex-rigid-multilayers or Regalflex circuits.

R2R production lines generally provide more capable print and etch processes due to the inherent feedback systems employed compared to panel processing equipment.

The use of continuous web processing is compatible with automatic electrical testing and optical inspection. Provided side-to-side

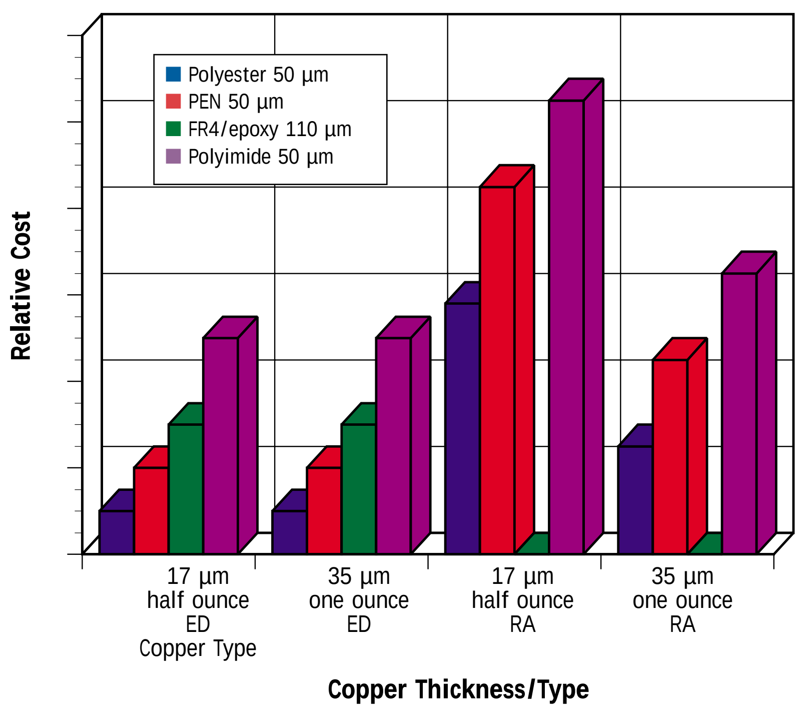

Figure 3. Flex laminate material cost comparison for two common copper types and weights.

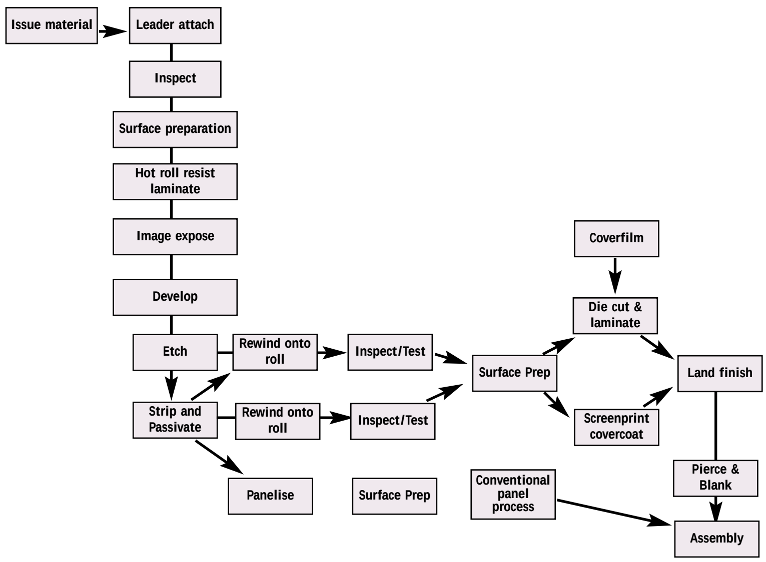

Figure 4. Flow chart indicating the process routes available from single- and double-sided non-plated through hole (PTH) continuous roll processing to component assembly.

alignment requirements are achieved, there is no reason why plated through hole (PTH) products cannot be produced via R2R plating processes.

For many companies the capital investment and space requirements of R2R hole generation and PTH plating facilities are significant. However, there are new hole generation and plating technologies emerging that may dramatically reduce the space requirements and dramatically improve speeds to make such lines more viable.

In a pure R2R process, covercoat printing or coverfilm bonding would be done in line as a continuous operation. Equipment exists today to achieve this and new materials/adhesives are being developed to facilitate lower temperature in-line bonding. If this route is not available then panel processing using existing equipment has to be used and tooling positions to accommodate this must be considered to provide adequate alignment for the circuit to the coverfilm.

For printed covercoats material type is very important, as they are cured by either heat or Ultra-violet (UV) energy. Additionally, it is feasible to “flood print,” roller or spray coat a photo-imagable covercoat (PIC). This is part cured and apertures are then photo exposed using similar equipment to that as for primary imaging. Surface mount assembly often requires rectangular apertures in covercoats, and this is a cost effective and elegant alternative to a fully tooled coverfilm. For certain materials with lower melting points, e.g., polyester, the temperatures required for either cure method can have a dramatic effect on the laminate. For this reason care must be taken when choosing equipment, materials, and process routing.

Most circuits after covercoat or coverfilm processing will require some form of land finish to protect the copper prior to shipment to the customer (e.g., Organic Surface Protectant or OSP) and/or to provide a suitable surface for the customer to assemble to (e.g., electroless nickel/immersion gold). Care must be taken to ensure that the materials are compatible with the temperatures and chemistries used within these processes. For R2R coating, OSP finishes are very compatible as they rely on surface modification, can be run at high speeds, and offer relatively low costs. For the electroplated finishes significant investment is required for R2R processing, the metal deposition times can be long and the equipment large. In many cases the panel processing route is chosen today for the application of plated finishes but there are systems currently being developed which utilize higher current densities and innovative equipment design.

Stiffeners and rigidisers are often required for component support. There are a wide variety of materials available for both the stiffeners (e.g. FR4, FR3, CEM1, aluminum and polyimide) and the attachment adhesives (e.g. thermally bonded or pressure sensitive). From the materials we will derive the attachment process and this can vary from multiple stiffener bonding in a lamination press to auto or manual attachment on individual circuits. For high volume applications, the tooling approach for profiling is an important consideration.

Once the raw circuit has been finished it is common for some form of component assembly to take place. This is usually performed in the panel or part panel format and allowance must be made at the design stage for this processing. In the future it will be more common for large volume applications to facilitate component assembly in the continuous roll or R2R form. Again, special consideration will be required to allow for optimum circuit definition for both the circuit and assembly manufacturers.

SUMMARY

We have shown that there can be a flexible approach to flex circuit design and manufacture. It is therefore important that the design authority involve the circuit manufacturer and assembler as early as possible in this process. This will lead to the most cost-effective and successful interconnect solution and clearly identify the optimum routing from all of those available as shown in Figure 4.

With the widespread use of control systems inherent in continuous roll processing, both capability and product quality can be significantly improved. Better use of chemistry can also be achieved as the speed and amount of material processed is better understood. Similarly, material utilization is key in understanding product cost for high volume applications. The relationships between the individual circuits, i.e., borders and spacing, can be minimized due to the reduced handling provided by continuous roll compared to panel processing.

As indicated in this article, it is possible to extend the range of linked R2R processes, but this must be balanced against the practicality of achieving this and the likelihood that different stages of the overall process could run at dramatically different speeds. The most effective and flexible configuration can therefore be achieved with superb results by considering the process flow in conjunction with the circuit design as early as possible. ■