WEB HANDLING FOR FLEXIBLE DISPLAY MANUFACTURE

by

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ABSTRACT

Flexible displays manufactured in a continuous roll-to-roll fashion are the "Holy Grail" of the display industry. This paper offers an assessment of the development efforts related to web handling, which are required to achieve this goal.

NOMENCLATURE

None.

INTRODUCTION

In this paper, the term "display" means an electronic device for the display of information, usually in the form of images, numbers, or text. Examples include televisions, computer monitors, calculators, digital wristwatches, digital camera viewfinder devices, and the like. This talk will focus on the manufacture of such displays on flexible media, such as plastic webs, using roll-to-roll conveyance techniques.

Currently, flat-panel display electronics are fabricated on glass or silicon substrates using technology developed by the semiconductor industry to manufacture integrated circuits. Because the substrates are brittle and fragile, these displays are easily damaged and cannot be mounted to follow a curved product shape nor can they be placed on a portion of a product that bends significantly. The machinery required to manufacture these displays is quite expensive, and the rate at which the displays can be manufactured is slow, measured in minutes per display. For all of these reasons, the manufacture of similar displays on flexible substrates using web conveyance equipment is attractive. Creating such a manufacturing line has some substantial obstacles, including many related to web-handling technology. Those latter obstacles are the focus of this paper.

Here is an outline of potential obstacles:

- Web cleanliness
- Web surface quality
- Web thickness variations
- Robustness of display patterns, including partially formed patterns, to web conveyance over rollers
- Robustness of finished (or partly finished) displays in wound roll storage
- Registration of a pattern to a previously generated pattern
  - Dimensional changes of web caused by:
    - Tension and Poisson's ratio effects
    - Temperature changes
    - Humidity changes
    - Creep of web material when stored in wound roll form
    - Residual shrinkage caused by high processing temperatures
  - Speed/position variation in web transport
  - Web lateral positioning errors
    - Rotation of the web as the lateral position changes

WEB CLEANLINESS

Cleanliness requirements for semiconductor fabrication are very high—typically class 10 (10 particles 0.5 μm or larger per cubic ft) or better inside the manufacturing equipment. Owing to the very fine line widths and thicknesses involved, a single particle can cause a device to fail. For displays, the requirements are even higher—even large semiconductor devices, such as microprocessors, are no larger than a few square centimeters. If such devices have a yield of, e.g., 90%, with the failures attributed to particulate contamination, then a display with equivalent circuitry that is 0.35×0.5 m^2 in size will be expected to *never* yield a good display (technically, one out of $\sim 10^{40}$ displays would be defect-free, which is a very good approximation of "never"). Consequently, the display industry faces a more difficult cleanliness problem than the semiconductor industry. The industry is successfully dealing with this on glass or silicon plates. Dealing with it on webs will be very challenging. Webs are not (and probably cannot be, because of operations such as edge scrim removal) manufactured in plants with very stringent cleanliness requirements nor are they packaged and shipped in such environments. Thus, it will be necessary to devise a means of cleaning webs to be used for display manufacture.

For the purposes of display manufacture, it is necessary to accomplish the following:

- Specify the cleanliness requirements for display webs
- Devise a means of meeting these cleanliness requirements

WEB SURFACE QUALITY

Going hand-in-hand with web cleanliness is the issue of web surface quality. Even webs with optical-quality surfaces, such as those used for photographic film, might not have sufficient surface quality upon which to build a display. In many ways, surface quality defects will have similar effects to particulate matter on the web. Thus, the development tasks ahead are similar:

- Specify the surface quality requirements for display webs
- Devise a means of meeting these surface quality requirements

WEB THICKNESS VARIATIONS

Depending upon the processes used to manufacture a display, web thickness variations could be a problem. Optical or laser processes might have a depth of focus that is less than the variation in web thickness, for example. While auto focus systems could correct for this, the spatial frequency of web thickness variations coupled with web and beam motion may exceed the frequency response bandwidth achievable with an auto focus system. It will be necessary to characterize more completely the surface topography of typical webs and also determine what is required for web thickness control for display webs. This generates the following list of development activities:

- Devise better methods of measuring and specifying web thickness variations
- Determine specifications for web thickness variations in display webs
- Devise manufacturing technology capable of meeting these specifications

ROBUSTNESS OF DISPLAY PATTERNS

The patterned features of a display are miniscule, and might be made of materials necessarily optimized for their display features rather than for mechanical robustness. Thus, they might be soft, brittle, lack robust adherence to underlying layers, or possess other undesirable attributes that lead to damage during web conveyance. This will be true during the entire web-based manufacturing process, with all of the layers and substances involved. This leads to a list of questions for each layer:

- Can the material in its current form during manufacture sustain contact with a conveyance roller without damage?
- Can the material sustain the strain and resulting stress as the web is bent around a conveyance roller?
- Can the material sustain the strain and resulting stress if the web corrugates into draw lines between rollers?
- Can the material sustain the airflow required to float the web on air if that is necessary?

To some extent, it will be necessary to adjust display materials to be more robust to accommodate web conveyance requirements. And, to some extent, it might be necessary to alter web conveyance methods to avoid damaging delicate display layers. The interplay of these disparate requirements will be at the core of the development effort.

ROBUSTNESS OF DISPLAYS IN WOUND ROLL STORAGE

If a display is to be considered "flexible," it must certainly be flexible enough to be able to bend and be wound into a stock roll. There are additional factors that will occur in wound roll storage:

- Interlayer pressure will dwarf the roller contact pressure that occurs during web conveyance
- In-roll tension will relax as a result of web creep as the roll is stored, resulting in dimensional changes in the web
- If there are longitudinally persistent up features in the display pattern, these might lead to hard streaks in the wound roll, which will greatly increase the

local interlayer pressure and the local creep—which will result in local buckles in the web as it is subsequently unwound, almost certainly ruining the entire roll

Depending on the magnitude of these problems, it might be necessary to develop winding methods (or, more generally, web storage methods) that will significantly reduce interlayer pressure and in-roll tension.

REGISTRATION OF A PATTERN TO A PREVIOUSLY GENERATED PATTERN

During the first patterning pass of a fresh web, the pattern will be put down without regard to the detailed position of the web, since there are no features on the web at that point. On subsequent passes, however, the subsequent patterns need to line up accurately with the previous pattern(s). The current state of the art in accomplishing this task is performed on printing presses, which seem to have registration accuracies in the 50 to 100 μm range. This is sufficient for printing quality color pictures, but it is over an order of magnitude less accurate than what is required for display manufacture. With a moving web, there are three degrees of freedom that need to be controlled: the machine direction (web speed/position), lateral and rotational position. Note that the lateral and rotational positions are coupled; if the web has a rotational error, it will move laterally because it is not at right angles to the roller axis.

Temperature Variations

In addition, the web will expand or shrink with temperature variations. With typical plastic webs, this variation will be several times more than the variation of a typical display glass sheet (for polyethylene terephthalate [PET], it is about 18e-6 m/m/degC). For a large display, though, just a few degrees of temperature variation can alter the length of the web by far more than the registration requirement. Even though the pixels on a large display can be larger than those on a smaller display, displays of interest incorporate thin film transistor (TFT) devices. The manufacture of a quality TFT devices requires sub-micrometer registration, at least for some of the layers. Thus, temperature control becomes a critical issue.

Humidity Variations

Furthermore, plastic webs are hygroscopic to a degree. PET, for example, changes dimensionally about $8 \cdot 10^{-6}$ m/m/% RH. This hygroscopic behavior occurs slowly, taking three or more hours for a 100 μm web exposed on both sides. Various coatings on the web might radically alter this behavior. Nonetheless, this behavior is a problem when using such webs for dimensionally critical purposes. Humidity will need to be controlled tightly. The problem is further compounded because the web is manufactured "dry." The bulk of a stored roll will not significantly absorb moisture, even when stored for many months in an environment with the desired relative humidity. A humidity conditioning process might have to be developed.

Creep

As has been previously mentioned, the in-roll web tension in a stored wound roll will also make plastic webs creep, or relax, over time. If partially completed displays are stored in wound roll form, it is expected that the dimensions of the stored displays will have changed (longer in the machine direction, narrower in the cross-machine direction).

Furthermore, given that the in-roll tension is not uniform, the resulting dimensional changes will not be uniform either. This phenomenon will give a powerful incentive to complete the manufacture of displays in a single pass.

Residual Shrinkage

Finally, if the web is an oriented polymeric substance such as PET, there will be further difficulty, in that some desirable processing steps for displays will locally and temporarily elevate the temperature of the web surface past its heat relaxation temperature. In an oriented polymeric web, residual shrinkage will occur, at least in the local small portion of the web that was heated. This might cause small puckers of distortion in the web; and, if there are many such local distortions, the overall dimensions of the web may be affected, and it may curl or buckle. This phenomenon may severely limit the materials and techniques that can be used to form display elements on roll-to-roll plastic webs.

Speed and Position Control

Continuous conveyance is required to obtain the required throughput. If the web motion is intermittent, the advantage over existing sheet processes is lost. Because the web is continuously running, the speed/position accuracy of the web as it is transported through the patterning apparatus will be critical to registration. Using a high-accuracy encoder pulse train for pattern timing, rather than a timed pulse train, can reduce this problem. Speed and position control will nonetheless be a critical development area if this is to succeed.

Summary of Registration Control

Pattern registration will require a huge development effort. It will likely necessitate improved web conveyance techniques for registration, improved machine and storage environmental controls, and novel new methods of adaptive pattern generation that can compensate for the unavoidable small dimensional changes and misalignments of the substrate upon which the pattern is being manufactured.

SUMMARY

The development effort to generate a roll-to-roll display manufacturing line is enormous. But so is the market—and it's growing rapidly. Large advances in the following technologies are required to make it happen:

- Web cleaning
- Web surface quality
- Web thickness variation
- Gentle or non-contacting web conveyance techniques
- Gentle wound roll or alternate web storage techniques
- Pattern registration techniques for moving webs

One of the most important items to note regarding this effort is the diversity of disciplines involved. It will require experts in the fields of: semiconductor fabrication, display materials, web handling, optics, lasers, registration, polymers, environmental control, adhesion, and others.

Web Handling for Flexible Display Manufacture — **R. L. Walton**, Eastman Kodak Company, USA

Name & Affiliation	Question
Bob Lucas GL&V USA, Inc.	I have a question. This term flexible web in this sense. Is it fair in as far as your anticipated product to insist that the web be flexible to the same extent that a web is presently, maybe for conveying purposes, you might have to have rollers that are maybe 1 meter in diameter, or the core size that you wind on might also have to be very large so that you physically limit the curvature of these multi-laminent structures. That way the stresses that they are exposed to will not destroy the integrity. Maybe the roll that you wind may have to be limited to the number of wraps that will prevent excessive layer to layer pressure build-up and some sort of a paradigm shift in the type of equipment that's involved with handling these sensitive webs.
Name & Affiliation	**Answer**
Bob Walton Eastman Kodak	I totally agree with you.
Name & Affiliation	**Question**
Claude Faulkner DuPont	You were referring to polyester and some of its properties. The talk earlier discussed the use of triacetates. Are we thinking we're going to have to have a whole new film structure to be able to meet some of these requirements?
Name & Affiliation	**Answer**
Bob Walton GL&V USA, Inc.	Well, obviously the selection of the material is very important. You never, for example, consider triacetate for extreme hygroscopic environments.
Name & Affiliation	**Comment**
Keith Good Oklahoma State University	Sometimes the decision may need to be made where to stop using web handling or roller-to-roller manufacturing. After these panels are built-up, maybe they are never wound but are cut to size at the end of the machine. So these panels might be stored in layers rather than rolls. This conference and the WHRC are dedicated to minimizing the losses associated with roll-to-roll manufacturing. So the key might be to determine where not to do web handling as well.
Name & Affiliation	**Answer**
Bob Walton GL&V USA, Inc.	Winding rarely improves webs.