Optimization of UV-Curing Multiple Elements by On-line Measurements

By Rick Chamberlain, Paul Schmugge, Bob Stulpin, Harri Turunen and Tim Dougherty

The efficient manufacture of quality optical fiber ribbons using in-line coloring is achieved by the measurement and control of key process parameters to assure product performance. Typical quality assurance procedures that test product end samples do not assure quality along the entire length of the product.

Prysmian (formerly Pirelli) and Nextrom have developed key on-line measurements and controls for ribbon lines with in-line fiber coloring. These include the selection and integration of relevant sensors into the line and the development of models to predict the final cure of UV inks to control fiber breakout performance from the ribbon matrix. This approach guarantees that the ink cure is sufficient along the entire length of ribbon (including ramping up and down) to reduce off-line sampling and the potential for scrap.

During development trials to increase production capacity via increased line speeds, poor ribbon "break out" was observed. Poor ribbon break out is defined as either ink transfer from the fibers to the matrix material, or worse, sticking of the fibers to each other or the matrix material when attempting to remove individual optical fibers from the ribbon. In the most severe cases, the sticking is such that the fiber coating is completely removed leaving bare glass. This result could be catastrophic with modern mid-span access techniques used to splice single fibers.

The integration of optical fiber coloring into a ribbon line resulted in a single manufacturing operation producing cost savings and efficiencies of operation. These included simplified logistics and fiber handling.[1] Operating parameters were developed to produce acceptable products[2] and the tandemized ribbon product was used in new cable designs.[3] A tandem coloring/ribboning line is shown in Figure 1. The unit consists of three coloring modules. Each module contains four fiber supplies, a die with four-color ports to produce four individual colors and a series of UV lamps to cure the four fibers within a single quartz center tube. The 12-colored fibers are then gathered and fed into a ribbon die and

Figure 1

Tandem coloring/ribboning line

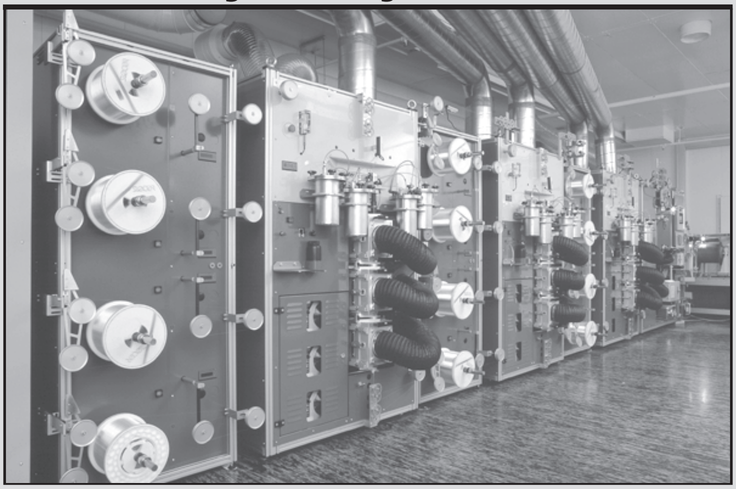
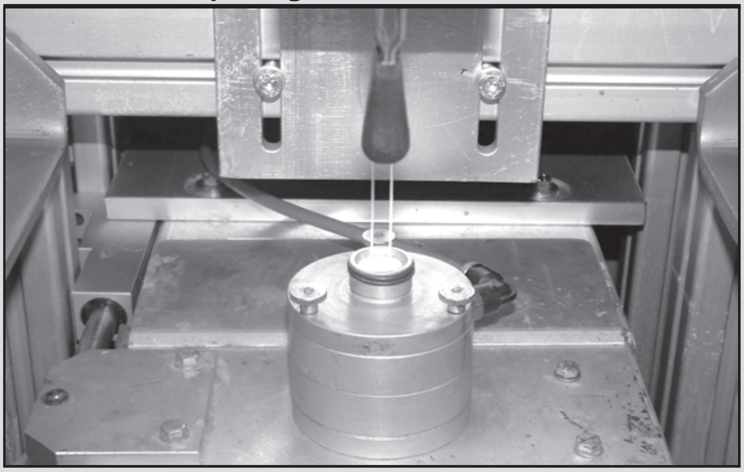


Figure 2

Colored fiber spacing



then passed through another series of UV lamps to cure the ribbon. The product is then wound on a spool.

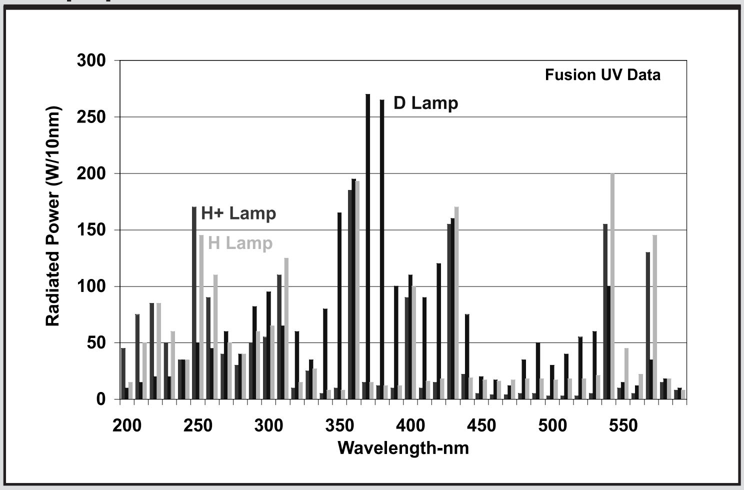
Because optical fibers are colored and ribbonized in a single operation, the assurance of adequate ink cure is vital to guarantee acceptable ribbon performance. In addition, the spatial distribution of the fibers within the UV lamps, as shown in Figure 2, means that the fibers are located close to, but not at, the focal point of the elliptical reflector system contained within the lamps. This factor makes optimization of the ink cure operation even more critical.

Uncured fibers in ribbons and completed cables can be a significant problem because customers are no longer doing only mass fusion splicing on long lengths of ribbon cables. Now cables are often cut into 100 foot pieces and handled along their entire length during connectorization, thus increasing the exposure to problems of marginal cure of fibers within ribbons.

This work focuses on two main concerns of UV-curing. The first is achieving adequate UV energy to fully cure the colored fibers before applying the ribbon matrix. UV energy is a function of UV lamp length, lamp power, line speed plus the efficiency of UV reflections and absorptions within the lamp assembly. The second concern is the control of the atmosphere within the quartz center tube during curing to not only minimize the presence of oxygen, but to also flush the volatiles released during the curing process to minimize center tube clouding.

Figure 3

Lamp spectra



Oxygen inhibits surface cure, which affects fiber breakout from the ribbon matrix. Clouded center tubes absorb UV energy minimizing the UV to targeted fibers.

Critical Process Parameters

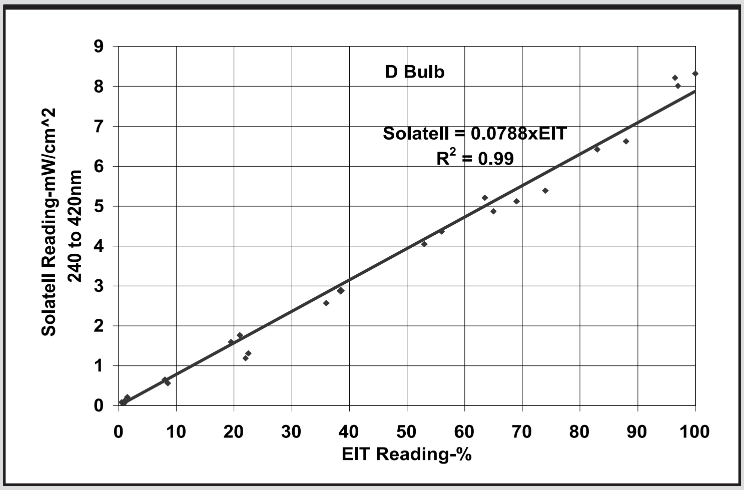
UV Energy

High-speed cure is possible because of UV-curable materials. Adequate cure cannot be achieved without enough energy. Current commercially available materials for fiber and ribbon manufacturing are cured most effectively at wavelengths in the 250-500 nm range. Shorter wavelengths are either absorbed right at the material surface or not able to penetrate the quartz tubes used to seal out oxygen. Longer wavelengths approaching the visible part of the spectrum may have some minor benefit, but were not measured. Fusion UV ovens with VPS power supplies were used as the UV source for all experiments. Three different bulb types are commercially available for these ovens, Type D, H and H+.

Type D bulbs emit the most UV energy overall, but output in the

FIGURE 4

EIT vs. Solatell measurements

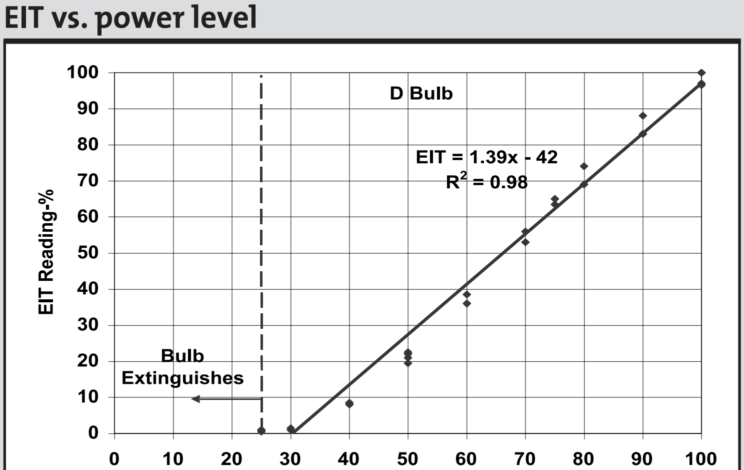


shorter wavelengths is limited. The H and H+ bulbs emit more energy at the 310 nm wavelength and below, but their overall energy output is less than the D. Figure 3, supplied by Fusion UV Systems, shows the energy output by lamp type.[4]

Original production lines were supplied with type D bulbs in all of the lamp curing assemblies. This was based on recommendations of equipment and raw material suppliers. However, after experiencing some cure-related difficulties other alternatives were investigated. More energy is always better may be a common thought process, but is not necessarily true. Type D bulbs provide more energy, but lack output in the shorter wavelengths. Type H and H+ bulbs have more output in the shorter wavelengths, but less overall energy.

FIGURE 5

EIT vs. power level



Nitrogen Atmosphere and Oxygen Content

Oxygen inhibits cure, especially on the surface where good cure is critical for satisfactory ribbon breakout. Oxygen is removed from the cure environment by introducing a nitrogen purge into one end of the quartz tube and vacuuming it out on the other end. Good cure results were obtained at most of the nitrogen flow rates tried. Only when a certain low threshold was crossed did breakout become a problem. The presence of oxygen in the quartz tube causes the fibers and matrix to stick together, making breakout difficult or impossible. When low cure is due only to insufficient power (no oxygen is present) the fibers will breakout fine from the matrix, but color will transfer from the fiber to the matrix as it is removed. It was discovered during trials that nitrogen flow alone is not a good indicator of oxygen content. The oxygen analyzers supplied with the machines were the only valid indicator of the inertness of the cure environment.

Good cure and ribbon breakout can be achieved with oxygen levels at several thousand parts per million. In practice, lower oxygen levels were easily attainable. Although specific settings will not be shared here, suffice it to say that, the in-line coloring ribbon lines routinely run with oxygen levels in the hundreds of PPM or below.

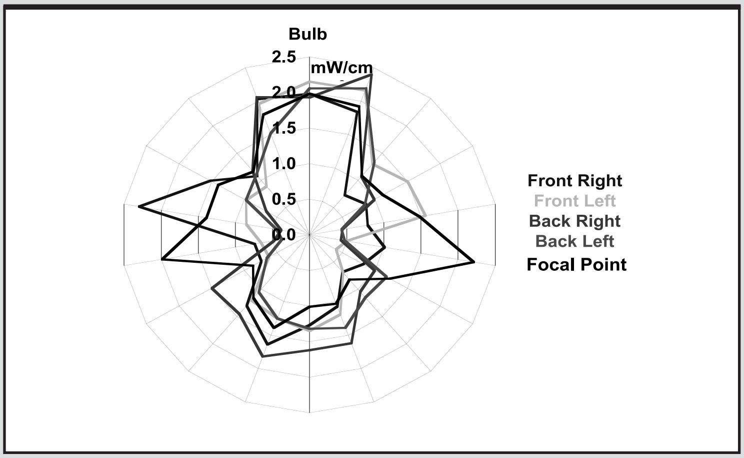
Trials and Results

UV Measurements

A variety of UV measurements were made using a portable Solatell Solascope I® and on-line EIT® sensors. The Solatell probe was 4 inches long and had a 2 mm diameter. It measures the UV spectra between 240 nm and 425 nm wavelengths. The area under these spectral curves was used to define total UV intensity over the

Figure 6

UV directional distributions



wavelength range of interest. Custom fixtures were designed and used to accurately position the probe within the UV lamp quartz center tube.

Compact EIT® UV sensors were also installed within each lamp housing and were positioned to look through a hole in the elliptical secondary reflector, through the center of the quartz center tube toward the bulb. This measurement is sensitive to the bulb output and clouding of the center tube. The EIT spectral sensitivity was selected to match the type of lamp being measured.

The UV measurements made using these instruments correlated well with each other over the full range of UV lamp power levels as shown in Figure 4. A plot of EIT readings vs. Fusion power supply settings is shown in Figure 5 to demonstrate the linearity of the lamp output over its operational range. This data was used to accurately program UV lamp power levels during line acceleration and deceleration to assure the proper cure of colored fibers along their entire length.

UV Spectra

The spectra of the D, H and H+ bulbs were measured using the Solatell Solascope I over the 240 nm to 420 nm wavelength range and the data were similar to the data shown in Figure 3.

The shorter wavelength output in the H and H+ bulbs is particularly helpful in providing good ribbon breakout properties. Most of the energy from the shorter wavelengths is absorbed near the surface of the ink. So using only H type bulbs would normally lead to poor bulk cure of the ink. Using the type H or H+ in combination with type D provides the best overall results for in-line coloring ribbon lines. The H+ bulb provides a good "kick" at the last lamp to dramatically improve surface cure and hence, ribbon breakout. The trials proved that less overall power could be used while ensuring good cure when a combination of bulb types was utilized.

UV Distribution Measurements

The Solatell was also used to measure the UV intensity at the actual fiber locations within the center tube. The fibers, and hence the probe, were offset approximately 4.3 mm from the focal point. Since the probe measurement is highly directional, the probe was rotated in 20˚ increments to develop an understanding of the directional nature the UV energy impinging on each of the four offset fibers. Typical 360˚ distributions for each fiber position are shown in Figure 8 in colors, which can be compared to the distribution at the focal point shown in black. Each 360˚ distribution was then averaged to estimate the total UV energy impinging on each fiber. These averages were approximately 80% of the energy at the focal point. This 80%

Figure 7

Center tube clouding

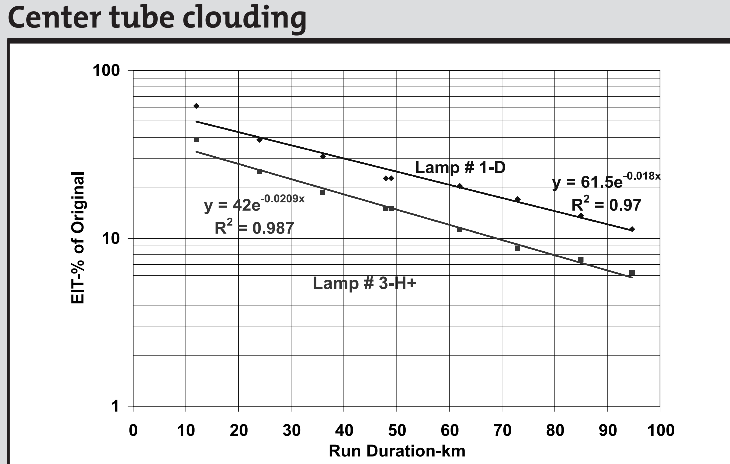
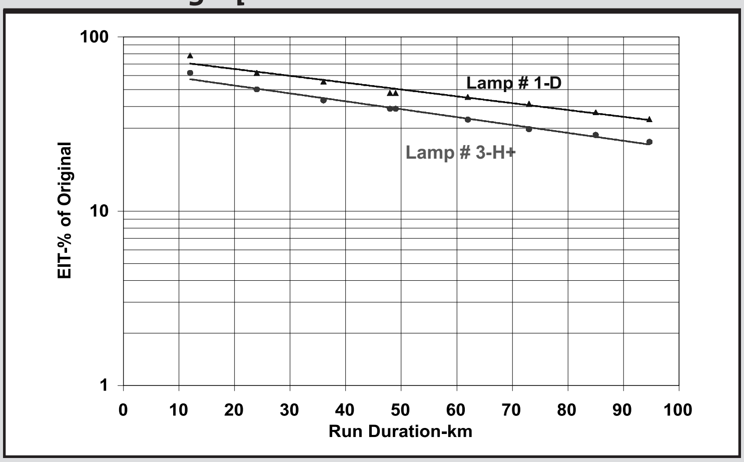


Figure 8

Tube clouding square root of EIT



offset correction factor will be used later to calculate the relative UV energy on individual fibers.

Center Tube Clouding

A wide variety of trials were conducted to study the effect of many variables including the number of lamps, type of bulb, line speed and nitrogen flow rate, which effects center tube oxygen concentration. The measured responses included ribbon breakout and the % RAU (i.e., the percent reacted acrylate unsaturation) of the colored fibers and ribbon matrix material. The EIT sensors were used to provide on-line UV measurements. These measurements are sensitive to the bulb output, the reflectivity of the elliptical reflector and the clouding of the center tube. The drop off of measured UV energy due to center tube clouding during a long run is shown in Figure 7. Data for the top lamp containing a D bulb is shown in blue. Data for the bottom lamp containing an H+ bulb is shown in red. All EIT measurements were referenced to 100% at the start with a clean center tube.

A rapid drop off was observed during the first 10 km. Thereafter, the decay occurred at a constant exponential rate as shown by the trend lines. Note that after 70 km, the lamp # 3 reading was less than 10% of the original UV intensity. This dramatic decrease is caused by passage of the UV energy through both walls of the clouded center tube. An estimate of the UV energy within the center tube is obtained by calculating the square root of the normalized EIT readings. These results are shown in Figure 8. In the case of the above example, the value within the center tube would be approximately 32% instead of 10%. This is still a significant decrease, but not as dramatic as the raw reading.

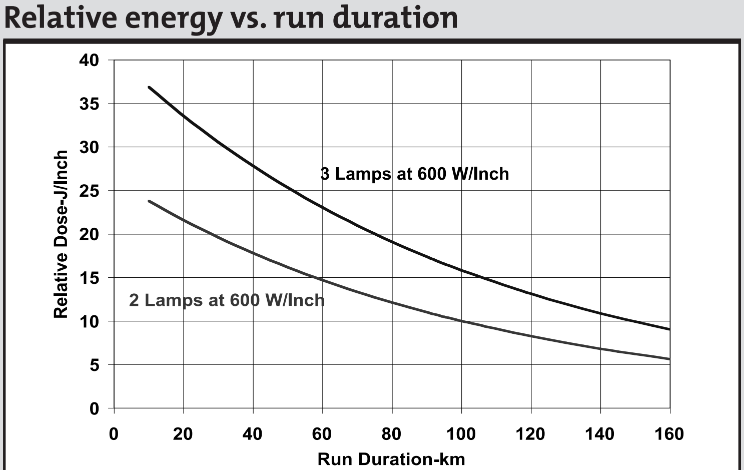
Relative Energy

The relative UV energy that a fiber experiences in its passage through the UV-lamp system is a function of the lamp power levels, center tube clouding, fiber position offset and the line speed. The relative UV energy per unit length was calculated by multiplying the lamp power per unit length in each lamp by the square root of its EIT reading, by the 80% fiber offset factor and by the corresponding residence time in that lamp (i.e., the lamp length divided by line speed). Finally, the energy in each lamp was summed for each lamp in the system. Note the actual energy is significantly lower and is a function of the overall UV power conversion efficiency plus the size and distribution of energy within the lamp sweet spot.

An example of relative energy vs. run duration plot is shown in Figure 9. The trend line equations describing tube clouding in Figure 7 were used to simulate operation with two or three Fusion lamps operating at 600 W/inch.

Figure 9

Relative energy vs. run duration



The minimum value of relative energy must now be determined to assure adequate colored fiber cure.

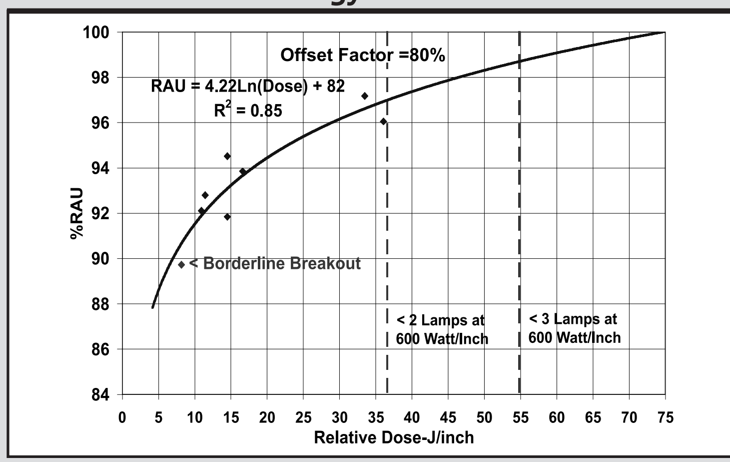
Fiber Cure

The results of the cure studies are shown in Figure 10. The % RAU results represent the average for all 12 colors in each ribbon. A logarithmic trend line fit the data well. The red data point corresponded to a ribbon with marginal fiber breakout performance. Also, shown for reference are the relative energy expected with clean center tubes using two or three lamps operating at 600 W/inch. For reference, each lamp is 10 inches long. Production line speeds were also assumed. As the center tube clouds, initially high-relative energy decreases toward the left along the curve. The higher the initial energy, the longer the duration of the production run before required center tube changes.

In this example, a relative minimum energy of 10 J/inch should assure a minimum % RAU close to 92%. Note that these data and the resulting process limits are dependent upon the characteristics of the particular ink and ribbon matrix materials. Although targets may change for other materials, the methodology used here should still apply.

Figure 10

% RAU vs. relative energy



Finally, the % RAU vs. energy equation in Figure 10 can be combined with the energy vs. run duration calculations in Figure 9 to produce an estimate of % RAU vs. run duration. Curves are shown in Figure 11 for two or three 600 W/inch Fusion lamps operating at full power. The maximum run length would be 100 km using two lamps and 140 km using three lamps. Note that the exponential effect of tube clouding appears to counteract the logarithmic effect of cure to produce a linear relationship between cure and run length. This is why practical run lengths are achievable even though on-line sensors experience dramatic changes.

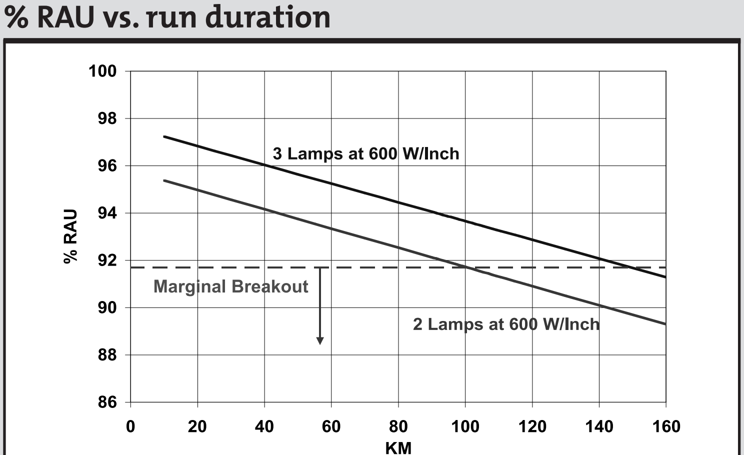
Conclusions

As a result of these detailed studies, the curing of multiple colored fibers in tandem with ribbonizing was optimized. Breakthroughs were made in lamp selection and programming of lamp power levels. The integration of key on-line UV and oxygen sensors into production lines provides early warnings of line problems or process drift. This allows process corrections in time to assure the proper cure of colored fibers and thereby guarantee fiber breakout performance along the entire length of a ribbon.

The development of models assisted in interpretation of data and the establishment of critical process limits.

Figure 11

% RAU vs. run duration



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