Mitigated Inking Impact of Next Generation Optical Fiber Coatings, While Maintaining Robust Draw Processing Capability

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Abstract

Next-Generation primary coatings for optical fibers, are formulated to have less severe in-situ modulus increase upon inking. Specifically, for high-transmittance-colors, next-generation optical fiber coatings have significantly less in-situ-modulus increase, upon inking, than previous generation coatings. In addition, in-situ modulus increase is less sensitive to ink colors, thus more uniform microbending performance among ink colors. At the same time, such coating system is also fit-for-use for modern fiber draw processes, including super-fast draw speed, optimized Helium consumption rate, as well as UVLED curing.

Keywords: Reduced in-situ modulus increase upon inking, less sensitive to ink colors, robust draw process operation window, super-fast draw speed, Helium consumption rate reduction, UVLED curable

1. Introduction

To meet the need of superior microbending performance, next generation optical fiber coatings have been developed [1][2][3][4]. Such coatings are capable of being processed under super-fast draw speed of modern draw towers, with optimized Helium consumption rate, as well as UVLED cure.

Draw Tower Simulator (DTS) has been utilized to monitor and characterize cure kinetics, as well as mechanical property development over time [8].

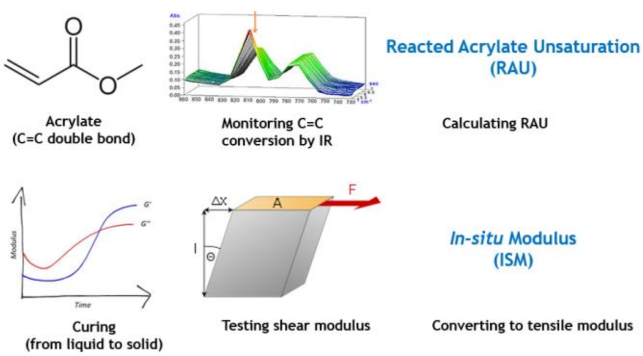

Figure 1. Two Outputs from DTS run – RAU and ISM

Shown in Figure 1 is an illustration of two parameters/outputs from a given DTS run. UV curing (when coating changes from liquid to solid) occurs when acrylate double bond is converted to single bond, upon free radical polymerization. Such chemical reaction process is characterized by Reacted Acylate Unsaturation (RAU). Simultaneously , mechanical property (in-situ modulus, ISM) starts to build up, when crosslinked polymer network forms. Both RAU and ISM are monitored in DTS runs, to evaluate cure behavior of various coatings.

It's interesting to take a close look at the correlation of mechanical property development (i.e. ISM) to the chemical reaction (i.e. RAU) (Figure 2). In the case of Current Coating, ISM increases sharply, when RAU increases from 90% to 100%. In another word, mechanical property is quite sensitive to very last stage of curing reaction. By contrast, when RAU increases from 90% to 100%, Next Generation Coating mechanical property (ISM) remains rather constant, reaching a plateau. Such relatively independence of ISM vs RAU, in the case of Next Generation coating, is believed to benefit a more robust fiber drawing process, enabling a much wider operation window of draw speed and processing conditions.

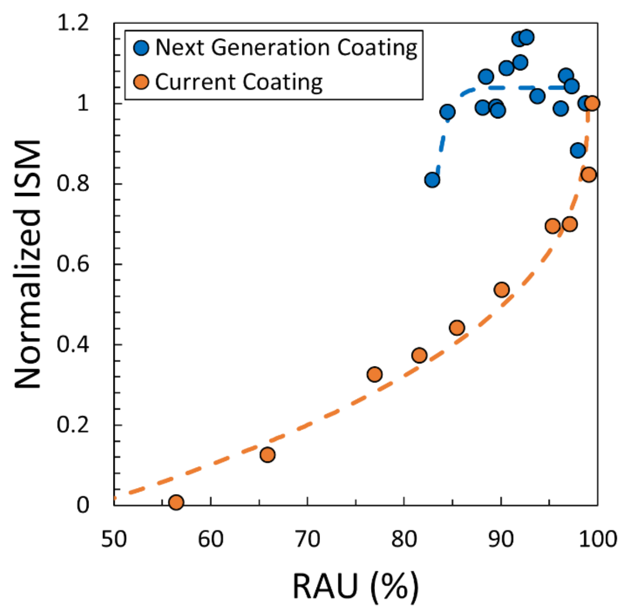

Figure 2. Normalized ISM vs. RAU [4]

It’s been recently reported [5] that, due to additional cure in inking process, in-situ modulus of primary coating increases, resulting in higher (hence undesired) microbending sensitivity. In addition, the extent of added microbending sensitivity is dependent on ink color, causing variation of microbending sensitivity among ink colors.

In this paper, the impact of inking on primary coating in-situ modulus is studied. Of particular interest is the comparison of next generation primary coating vs. previous generation coating.

Recently, UVLED curable ink product line has been developed [6]. The inking experiments in this paper used such UVLED curable inks, and were conducted using both conventional microwave (MW) mercury lamps and UVLED lamps, giving us insight w.r.t. cure behavior between these two processes.

2. Experiments

2.1 In-house Inking Experiments

The inking experiments were conducted in house, using an OFC 52 inking machine (Figure 3).

Figure 3. Inking Machine

Die used in the experiment was supplied from Sancliff, and was 275µm over 260µm in geometry; Nitrogen purge was at a rate of 40L/min, and the pressure was 2.9 bar.

Summarized in Table 1 are inking conditions for both MW curing and UVLED curing.

Table 1. Inking Conditions

	Draw speed	# of Lamp	Lamp Type	Wavelength
MW Curing	1500 m/min	1	D Lamp	Broadband Emission
UVLED Curing	1500 m/min	1	UVLED	395 nm

UVLED curable inks, introduced in previous paper [6], were used in inking experiments.

2.2 *in-situ* Modulus (ISM)

A detailed description of the test method and data processing methodology of primary coating in-situ modulus on glass fiber has been introduced in a previous paper [7].

2.3 Reacted Acrylate Units %RAU (%RAU)

%RAU was measured by Nicolet 4700 FT-IR spectrometer with a diamond ATR attachment. Detailed description of the test method was included in a previous paper [8].

3. Results and Discussion

3.1. Selecting Colors for Inking Experiment

Due to the presence of pigments, depending on the color of an ink, various amount of light is absorbed through the ink layer, resulting in varying amount of transmitted light. An illustration of such effect was published in a previous paper [6] (Figure 4).

In this paper, 3 colors of yellow, blue and white were chosen, representing low/medium/high amount of transmitted light.

It's worth noting that the data of transmitted light were based on the assumption of a UVLED wavelength of 395 nm. For conventional MW lamp with broadband emission spectrum, the exact amount of transmitted light is not going to be the same as that of 395nm UVLED, however, the relative trend should still hold.

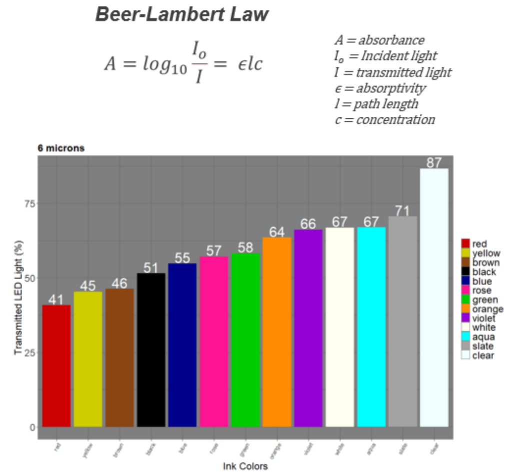

Figure 4. Screening Effects of Ink Colors [6]

3.2. Inking Experiments, MW Curing

First of all, to examine the impact of inking, two set of nature fibers were selected, one set of fiber was coated with Previous Generation coating, and the other was coated with Next Generation coating.

Inking experiments were conducted under two conditions: (1) "re-cure" by running the natural fiber through inking process without applying any ink layer; (2) inking the nature fiber with three colors (yellow/blue/white), individually.

%RAU results are included in Figure 5.

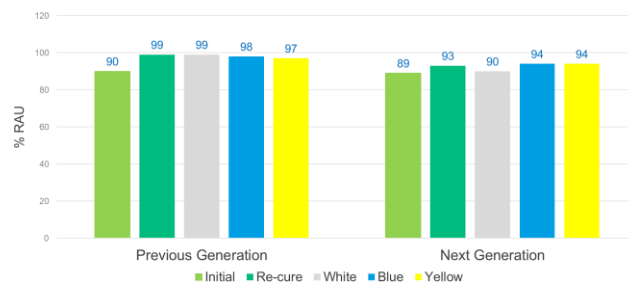

Figure 5. %RAU of Primary Coating, after Re-cure and Inking (MW Curing)

In case of Previous Generation coating, initial %RAU was 90%, and %RAU reached almost full cure of 99% when re-cured. It's interesting that %RAU values of inking with white, blue and yellow colors follow the trend in amount of transmitted light, at 99%, 98% and 97%, respectively.

In the case of Next Generation coating, % RAU increase was less, from initial %RAU of 89% to re-cure of 93%. And, %RAU of three colors were between 90% to 94%.

To understand the fact that Next Generation coating appears to have less amount of %RAU increase than Previous Generation coating, it helps to re-visit Figure 2. Next Generation coating reached mechanical property plateau, starting from around 85% RAU. In another word, the crosslinked polymer network becomes less dependent on %RAU, or additional chemical reaction. The possibility is, in case of Next Generation coating, crosslinked polymer network limits the mobility of residual free radical, and prevents %RAU from reaching complete conversion. Moreover, this less %RAU increase is correlated to the content of UV active functionalities in cured primary coating. All primary coatings still have some UV active functionalities left behind after being cured on fiber. The UV active functionalities include the ones from acrylate and photo initiators, which will continue to react when more UV is applied such as what's coming from inking process. The continued reaction would increase %RAU and in turn modulus level of primary coating. From formulation design perspective, Next Generation coating has less content of UV active functionalities than Previous Generation after being cured on fiber, thus, %RAU increase tends to be less than Previous Generation coating. While in case of Previous Generation coating, higher content of UV active functionalities, combined with a crosslinked polymer network allowing more mobility of residual free radical, resulted in nearly full conversion, with additional cure upon inking.

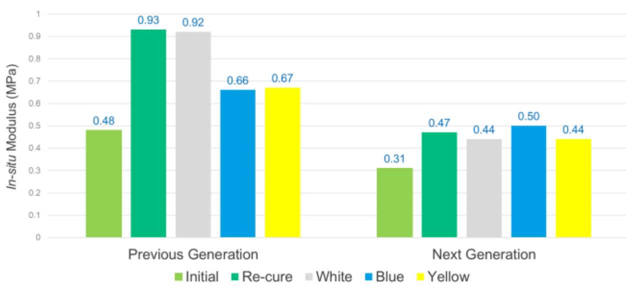

Figure 6. ISM of Primary Coating, after Re-cure and Inking (MW Curing)

ISM data of these inking experiments are shown in Figure 6.

In case of Previous Generation coating, initial ISM was 0.48 MPa. Upon re-cure, ISM nearly doubled to 0.93 MPa. When inking with white, blue and yellow, ISM increases by quite varying amount, to 0.92 MPa, 0.66 MPa, and 0.67 MPa, respectively. Despite of similar %RAU upon inking, ISM demonstrated strong correlation to amount of transmitted light, with white ink giving rise to ISM that is essentially the same as re-cure (0.92 MPa vs. 0.93 MPa), while fibers with blue and yellow inks only reached ISM level of 0.66 MPa and 0.67 MPa, about half way between initial ISM and recure/white ink ISM.

In case of Next Generation coating, first, the amount of ISM increase was less than Previous Generation. Initial ISM was 0.31 MPa, and re-cure ISM increased to 0.47 MPa. In addition, ISM of primary coating after inking were 0.44 MPa, 0.50 MPa and 0.44 MPa, with white, blue and yellow inks. Unlike Previous Generation, Next Generation coating appear to be insensitive to ink colors, thanks to its rapid-developing ISM profile (Figure 2). In another word, Next Generation coating ISM reached more complete cure during fiber manufacturing process, in terms of mechanical property, leaving less room for additional ISM increase, upon inking.

Such insensitivity toward ink colors means more uniform mechanical properties among fibers inked with various colors, resulting in more predictable and reliable microbending performance.

3.3. Inking Experiments, UVLED Curing

UVLED curing has become more widely adapted by fiber manufacturers in recent years. In addition to coatings, UVLED curable inks were developed as well [6]. After MW curing inking experiments (results in the previous section, in this paper), inking with UVLED curing was conducted on the same two sets of fibers, as well. Two conditions, re-cure and yellow ink, were evaluated.

%RAU results are included in Figure 7.

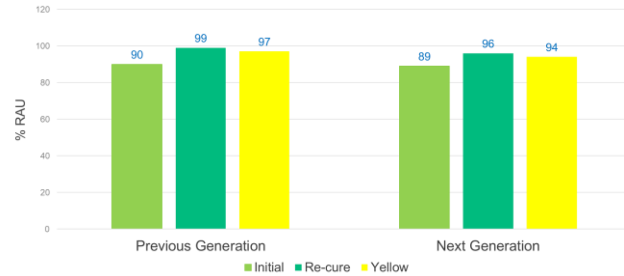

Figure 7. %RAU of Primary Coating, after Re-cure and Inking (UVLED Curing)

Similar to MW curing, Previous Generation coating had more %RAU increase, from initial %RAU of 90% to re-cure and yellow ink of 99% and 97%, respectively, while Next Generation coating %RAU increased from initial %RAU of 89% to re-cure and yellow ink of 96% and 94%, respectively.

It's interesting, from %RAU data, UVLED cure appears to reach slightly higher level than MW cure, particularly in the case of Next Generation coating (96% UVLED vs 94% MW).

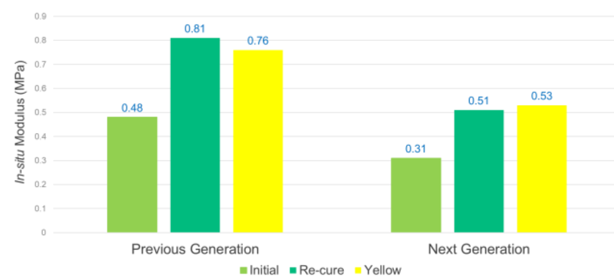

Figure 8. ISM of Primary Coating, after Re-cure and Inking (UVLED Curing)

ISM data of UVLED curing are compiled in Figure 8.

In the case of Previous Generation coating, re-cure ISM increased from initial ISM of 0.48 MPa to 0.81 MPa, much smaller change than MW curing (0.48 MPa to 0.93 MPa). In addition, ISM of yellow inked fiber was 0.76 MPa, similar to re-cure ISM, indicating ink color insensitivity, upon UVLED curing.

In the case of Next Generation coating, it's observed again the ink color insensitivity, evidenced by similar ISM of yellow ink (0.53 MPa) to that of re-cure fiber (0.51 MPa). It's worth noting, in both re-cure and yellow ink conditions, ISM values are higher than those of MW curing (0.47 MPa and 0.44 MPa, respectively).

3.4. MW Curing vs UVLED Curing

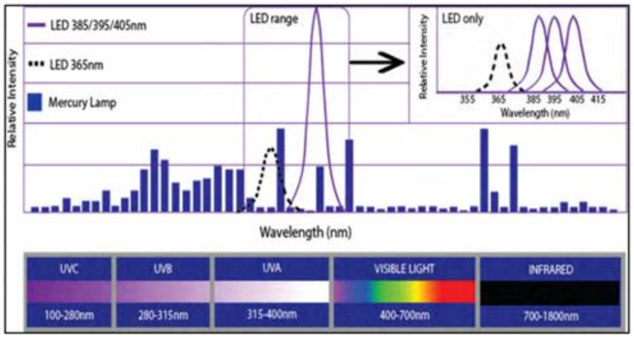

Figure 9. Emission Spectra, Mercury Lamp vs LED Lamp [9]

As published in the past [9], Figure 9, unlike the broadband emission spectrum of conventional MW (Mercury) lamps, UVLED lamp is single wavelength, and monochromatic in nature (395 nm in this study). It's expected that the curing behavior would be different, and the data here shed some light on UVLED curing vs MW curing, particularly about the inking process.

As the main subject of this study, primary coating ISM after re-cure and inking is of great interest, as the level affects microbending performance. Included in Figure 10, are ISM data of re-cure and yellow color inking, under both MW curing and UVLED curing.

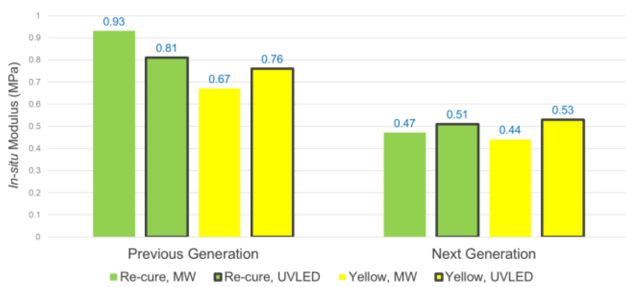

Figure 10. ISM of Primary Coating, after Re-cure and Yellow Color Inking (MW Curing vs UVLED Curing)

Except re-cure of Previous Generation coating (which we don't quite understand), in all other three cases (Previous Generation yellow color inking, Next Generation both re-cure and yellow color inking), ISM were higher under UVLED curing than MW curing. It's well known that 395nm UVLED, due to its relatively longer wavelength, penetrates deeper in material. In this study, in case of re-cure, it appears that 395nm UVLED light is capable of more through-cure than the broadband emission of conventional MW powered mercury lamp, resulting in slightly higher in-situ modulus (i.e. more in-situ modulus increase).

4. Conclusions

In this paper, in-situ modulus increase after inking was evaluated, with both MW curing and UVLED curing. Next Generation coating was compared with Previous Generation coating, w.r.t. severity of impact (the amount of in-situ modulus increase), as well as the sensitivity toward ink colors.

Thanks to more complete mechanical property build-up in fiber drawing process and special design in chemistry, Next Generation Coating exhibits much less amount of in-situ modulus increase, comparing to Previous Generation coating, upon inking, with both MW curing and UVLED curing,

In addition, Next Generation coating also exhibits much less sensitivity towards ink colors, meaning more consistent in-situ modulus across ink colors, than Previous Generation coating. Such consistency in mechanical properties across ink colors would mean consistent and predictable microbending performance.

It was also observed in this study, primary coating in-situ modulus increase after inking is slightly higher with UVLED curing than MW curing, likely due to the fact that 395nm UVLED light is capable of more through cure. Understanding UVLED curing behavior vs. MW curing is quite helpful, as the industry is transitioning to UVLED curing technology, including inking.

5. Acknowledgments

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6. References

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