Challenges for Scaling UV NIL to Production Speeds using Roll-to-Roll Manufacturing[1]

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Roll-to-roll (R2R) manufacturing methods have existed for over 200 years. This manufacturing method remains one of the most productive in existence. Products that cannot be made in discrete form and result in profit can be made cheaply with better repeatability with R2R methods. R2R methods are used to make and coat substrates called webs. Coatings can be continuous or discrete by the gravure process and may be used to print graphics, text or even electronics. What coating processes have in common is that they must be at least partially cured or dried prior to contact with a roller surface in the R2R machine or coating defects will result. They must be completely cured or dried prior to winding the web at the end of the R2R machine. The coated web is wound in rolls, to date this is the only efficient means for storing web lengths on the industrial scale of kilometers for subsequent processing. While multiple processes can occur on one R2R machine it is unusual. These processes run optimally at unique web velocities and tensions.

Moving UV-NIL from discrete embossing to continuous R2R production has unique challenges. Uncured resins are coated onto a web. This coated web enters a convergence between an imprint roller and a backup roller as shown in Fig.1 in schematic, the R2R imprinter is shown in Fig. 2. The backup roller is required to force the resin to fill the nanoimprint mold which is mounted on the surface of the imprint roller. Then, while the resin/web remains in contact with the imprint roller, the resin must be sufficiently cured with UV light such that the cured resin/web can be peeled from the roller with no damage to the imprinted nano features. Although the backup roller is a necessity for overcoming the fluid dynamics of mold-filling there are additional effects that may be unobvious to those practiced in UV-NIL processes. Scaling to higher velocities requires the elasto-hydrodynamics of coating to be considered. Sufficient resin must be provided to fill the imprint mold but excess resin thickness will result in mold fouling and requires higher UV power intensity to ensure curing sufficiently prior to peel [1].

In R2R manufacturing there is an entire field dedicated to the contact mechanics of webs entering nips such as the convergence of the imprint/backup rollers used in UV NIL. What is known is that not only a contact pressure distribution forms that assists the mold filling operation but also tension stresses and shearing forces are induced that cause contact shear stresses to form between the molded resin and imprint roller while subject to UV exposure [2]. Such shearing could be disastrous if the result is shearing or distortion of the nano imprinted features in the resin. In the current research imprint speeds of 20 mpm have been achieved. At this speed, the resin coated web has ~1/6 second residence time in contact with the imprint roller while UV curing prior to peeling. We have found that light curing photo chemistry versus dark curing aspects of UV resins[2] may be a factor that will limit the speeds of UV-NIL R2R production (Fig. 3). We are finding the shear strength of the light cured resin may be but a fraction of the dark cured strength. If the shearing stresses due to nip mechanics exceed the shear strength of the resin, imprint damage is expected. With knowledge of the tensile (Fig. 4) and shearing stresses, especially in the vicinity of the peeling region (Fig. 5), the web/resin tension at the exit of the imprint roller can be used to attenuate slippage and prevent damage. UV resins will continue to dark cure after peeling from the imprint roller and the mechanical strength of the resin will continue to rise over periods of minutes to hours. While additional UV curing is possible in unsupported web spans downstream from the imprint roller the imprinted surface will become subject to contact pressure when transiting a roller and more so when wound where contact pressures in the MPa range are possible.

Scaling discrete UV-NIL stamping and curing processes to R2R manufacturing processes often requires detailed analysis of fluid mechanics, contact analysis on the imprint roller, properties of UV curable resins while curing and control of pressure on imprinted surfaces downstream of the imprint roller. Note with increased speeds these analyses become critical and can result in partial mold filling (Fig. 6). Means of characterizing the moving imprinted surface are necessary such that web and gravure roller velocities, nip force and web tensions upstream and downstream of the imprint can be controlled to maintain the quality of an imprinted surface. While such analyses can be challenging, the potential reward is immense for producing nanoimprinted surfaces continuously at web velocities of 20 mpm or faster.

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[2] UV15, Masterbond, 154 Hobart Street, Hackensack, NJ 07601 USA

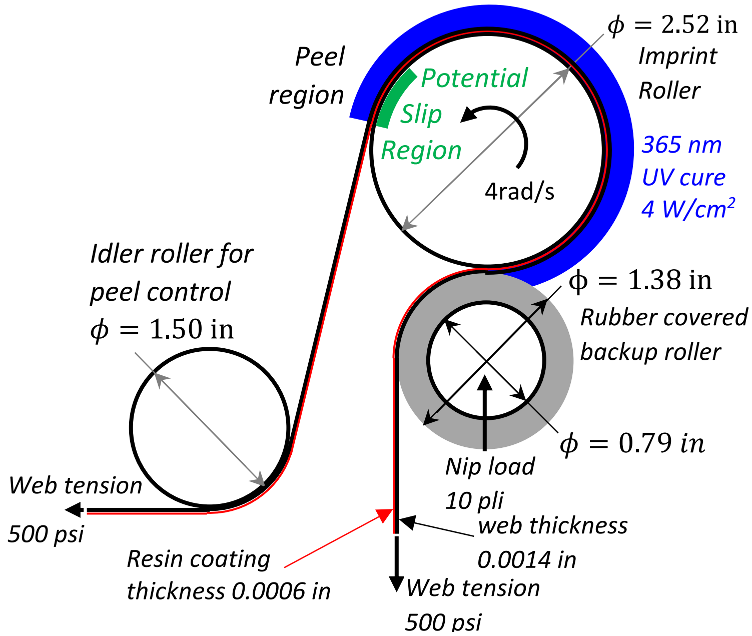

Fig.1 Schematic of UV-NIL Imprinter

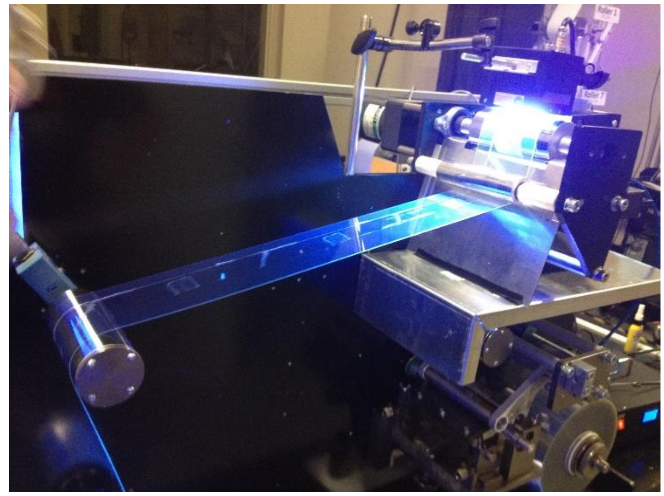
Fig.2 R2R UV-NIL Imprinter

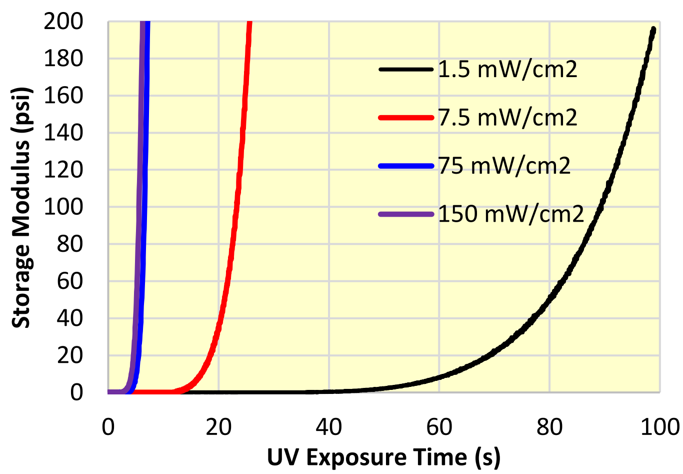

Fig.3 Storage Modulus UV15

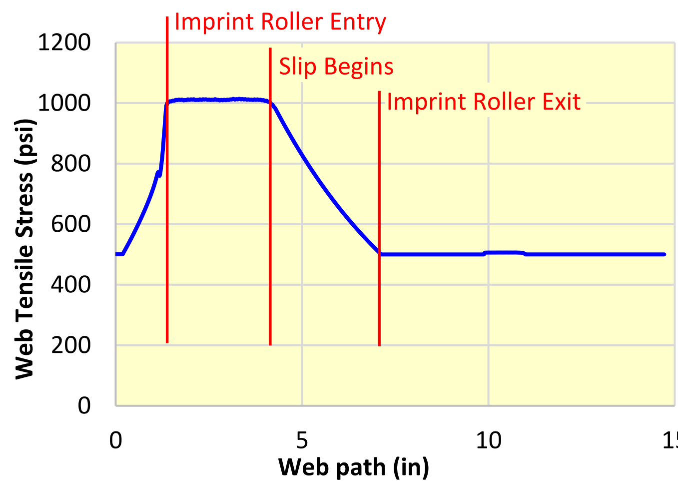

Fig.4 Web Stresses resulting from Nip Contact

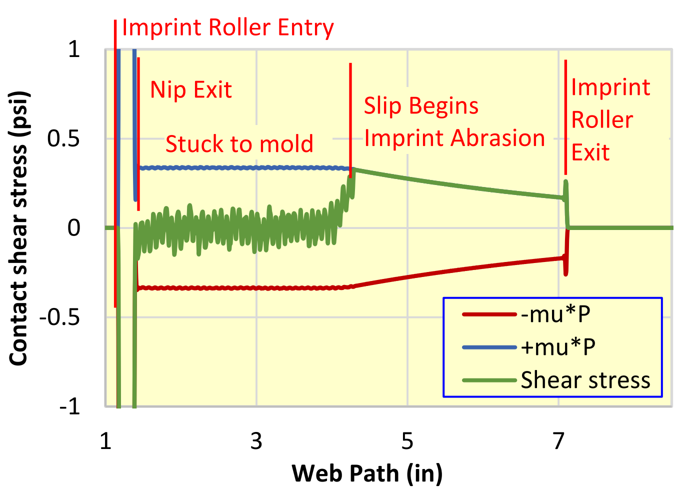

Fig.5 Web Shear Stresses and Slippage

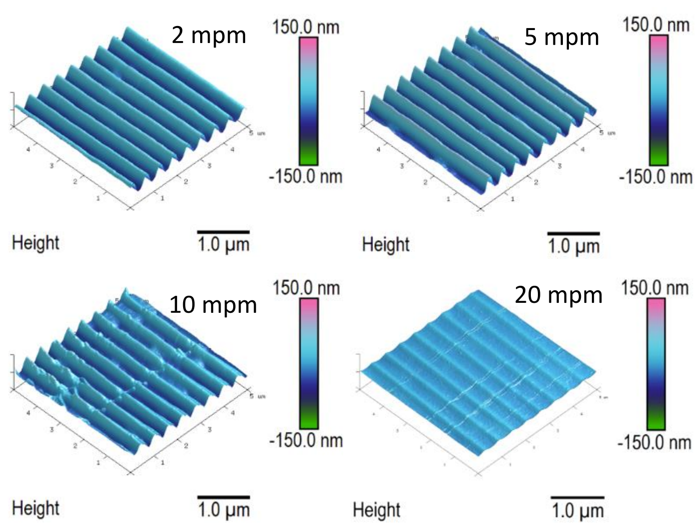

Fig. 6 AFM characterization of replicas from trials at imprint speeds of 2, 5, 10 and 20 mpm

References

1. J. P. Gomez-Constante, P. R. Pagilla & K. R. Rajagopal, "Effect of Process and Transport Parameters on Mold Filling in Roll-to-Roll Nanoimprint Lithography," Fifteenth International Conference on Web Handling, Oklahoma State University, June 2019.
2. Y. Ren and J.K. Good, The Nip Mechanics of Nano-Impression Lithography in Roll-to-Roll Process Machines, Fourteenth International Conference on Web Handling, Oklahoma State University, June 2017.