

FUNCTIONAL ANALYSIS OF A POLARISCOPE TOOL FOR THE EVALUATION OF STRAIN IN ROLL-TO-ROLL NANOFABRICATION

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ABSTRACT

The use of polymer substrates in roll-to-roll (R2R) manufacturing is an avenue for tremendous cost reduction while also creating robust and flexible products at a high throughput. Yet, this technology has yet to compete with wafer electronics production due to overlay error caused by the deformable nature of the webs when exposed to the processes common in electronics manufacturing. Process control and in-line metrology is critical for reducing measurement uncertainty and maintaining the necessary precision for developing nanoscale devices.

A process control device designed to leverage the photoelastic effect to detect changes in stress is able to improve how tension is monitored in R2R web management. Changes in web alignment, tension direction, and tension magnitude can be consistently detected. The tool is also able to image inconsistencies and stress concentrations in the substrate. By visualizing these processing issues, it is possible to provide recommendations for improvement and reduce error in manufacturing. It will also be possible to analyze these images and calculate exact deformation from the stress distribution captured by the tool.

1. INTRODUCTION

In R2R additive manufacturing, a flexible substrate is tightly stretched between two primary rollers – unwind and rewind – with any processing steps or additional web regulation taking place between the two. The applied tension creates stress in the material, which gets expressed as deformation along the direction of applied stress. Micro and nanoscale deformations can lead to misalignment between expected and real pattern location. In multilayer devices, this overlay error between patterns can result in catastrophic device failure.

The constructed tool leverages a unique optical property of polymer substrates common to R2R manufacturing known as the photoelastic effect. This effect occurs in transparent, optically isotropic materials that become optically anisotropic under stress [citation]. Because of this, the stressed material then changes the properties of the light passing through it, and those changes are based on the magnitude and direction of the applied stress. These changes can then be imaged using variations of a tool known as a polariscope. An

example of a material experiencing the photoelastic effect can be seen in Figure 1.

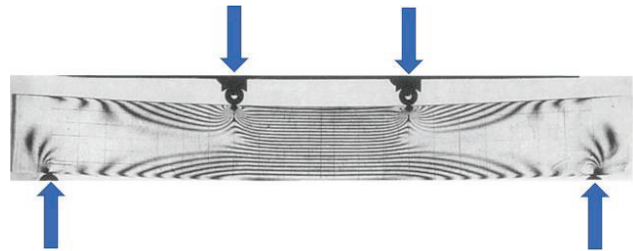


FIGURE 1. Stress lines in a thin film under a bending load [3]

2. TOOL FUNCTION

By measuring the change in polarization of light through the stressed substrate caused by the photoelastic effect, it is possible to create a map of the local strain and account for the deformation when adding features to the material or measuring fabricated patterns. This is done by building a plane polariscope, which is made using a linear polarizer to polarize the incident light source, followed by the material to be imaged, and then a second polarizer at 90 degrees offset to the original for analyzing the change in polarization after the light has passed through the material. This basic setup can be seen in Figure 2.

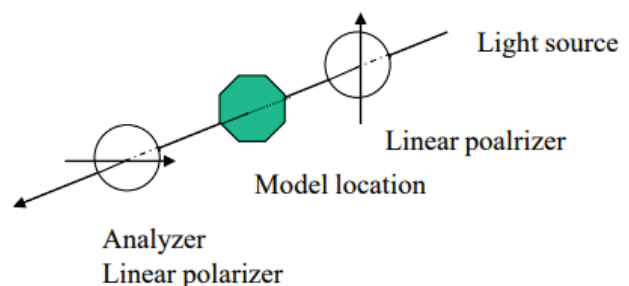


FIGURE 2. Progression of light through a plane polariscope [4]

The full tool consists of a light source, a polarizer to polarize the laser light, another polarizer to analyze the light that has been changed by passing through the substrate, and an optical column with an objective lens and a camera to magnify and capture the results. A pair of stages move the polarizers and optical column to scan across the substrate to capture measurements over the

entire web. Figure 3 illustrates the full polariscope tool design such that the web may be tensioned between the stage containing the majority of the optical devices and the lofted stage containing the camera and optical column.

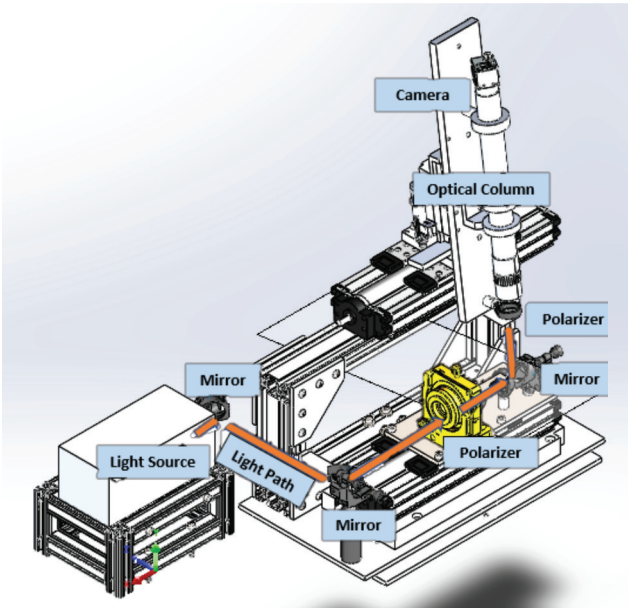


FIGURE 3. Full Polariscope Tool Design

Testing the tool required developing test setups to determine which scenarios of web change result in changes to the color of the web. Four main tests were conducted; these are load angle change, web angle change, alignment angle change, and tension magnitude change. The test setup for the experiments below were conducted on a static simulation of a R2R system built with aluminum and PVC rollers. The position or load applied to the test setup relative to the polariscope was changed to produce the following images.

3. RESULTS

The following four tests seek to produce color change in the web by applying a series of test loads in various web conditions. Load angle change tested how the orientation of the load relative to a perfectly aligned web would affect results. Web angle change rotated the orientation of the entire web relative to the stationary polariscope tool. Alignment angle change forced the ends of the web to be offset relative to each other. Tension magnitude change applied various load magnitudes to an aligned web to produce results.

3.1 Load Angle Change

Figure 4 shows images of the web taken by the tool at the five different load conditions, with arrows that indicate the drawing direction of the polymer chains due

to the different directions of applied load. These images are unedited as captured by the machine with the exception of superimposing the polymer chain directionality indicators. It is immediately obvious to the naked eye that the different load conditions indeed affected the polarization direction of the light and the resulting differences in color are visible to the naked eye. As the polymer chain direction changes in the clockwise direction, different colors dominate the image.

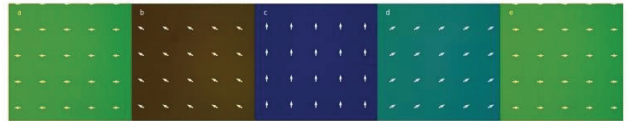


FIGURE 4. Images taken by the polariscope tool with indicators of stress orientations at (a) -90° , (b) -45° , (c) 0° , (d) 45° , and (e) 90° from the standard load orientation.

An RGB analysis of the images from the tool show that each image had a unique and significant combination of average RGB values that could be used to distinguish applied force directions. Table 1 tabulates the average RGB values with their corresponding load orientations.

Direction	Avg. R Value	Avg. G Value	Avg. B Value	Dominant Color(s)
-90	77	153	31	Green
-45	77	57	0	Red, Green
0	34	42	105	Blue
45	32	120	119	Green, Blue
90	73	150	37	Green

TABLE 1. RGB values with respect to load direction

These results show a clear dependence of color on stress orientation. At 0 degrees from the web direction, blue significantly dominates the image. As the load increases toward a negative angle from the standard web direction, the blue cancels almost completely, leaving only red and green present, resulting in an image that appears brown. As the load angle departs from the central angle, different colors dominate. As the load increases towards a positive angle from the standard web direction, the presence of green increases and blue remains dominant as well. Once the load orientation reaches 90 degrees from the standard web direction, green completely dominates. The color distributions for -90 and 90 degrees appear to be identical because at this load orientation, the polymer chains are aligned, and the load is effectively in the same direction.

Fig. 5 shows a greyscale image of the dominant green channel taken by the tool with a load orientation 90 degrees from the standard web orientation. Careful analysis of this image shows defects in the substrate that were not visible to the naked eye in the full-color version

of this image. In particular, this image features a pair of exceptionally light scratches that intersect at an X on the lower half of the image. This image type can be used to identify patterns corresponding to substrate defects like scratches and changes in thickness as well as intensity calculations outlined in the Background and Motivation section. By splitting each color image into its RGB channels, it is possible to run three intensity calculations to get an accurate stress calculation instead of taking several images at different phase angles.

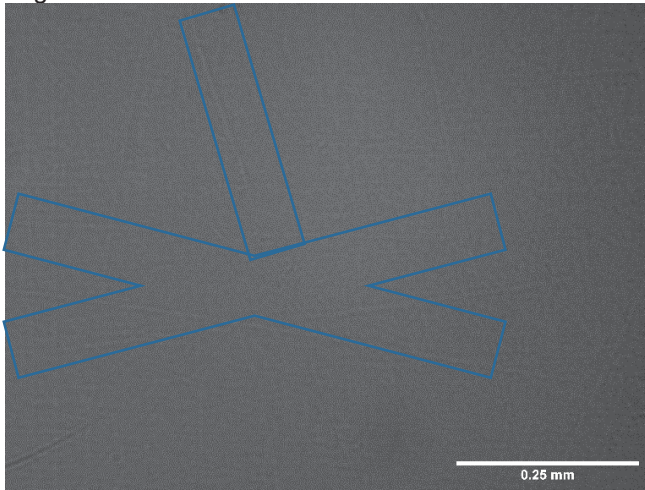


FIGURE 5. Greyscale intensity map of green component of image taken at load applied 90 from standard web orientation with scratches outlined.

3.2 Web Angle Change

The data acquired in web angle change experiments can be seen in Fig. 6. Fig. 6 (b) is a blue dominated image, as expected from the load angle change experiments, although darker than the first set of experiments. This difference could be explained by the significant length of time between the experiments, during which the experimental setup was located in an uncontrolled laboratory space. Further testing would be necessary to determine how the age of a substrate and how minute changes in experimental conditions such as light, temperature, and alignment affect the experimental results.

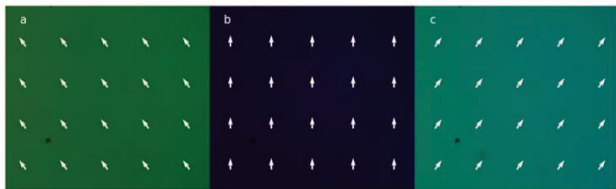


FIGURE 6. Images taken by the polariscope tool with indicators of stress orientations at (a) -10° , (b) 0° , and (c) 10° from the standard web orientation.

After analyzing the RGB color distribution of each image, the results of which are tabulated in Table 2, we can see that differences in the coloring follow a trend in

the dominance between blue and green. As the angle of web position changes in the clockwise direction, the blue values increase approximately linearly. Similar to the results of the load angle experiment, the presence of green is highly dependent on the angle of the web away from the standard web position. The red values did not appear to change significantly with changes in web angle.

Direction	Avg. R Value	Avg. G Value	Avg. B Value	Dominant Color(s)
-10	48	101	40	Green
0	39	25	67	Blue
10	42	120	108	Green. Blue

TABLE 2. RGB values with respect to web direction

Because of the nature of the experiment, the polymer chains do not change orientation within the web itself, but as the web is rotated, the polymer chain orientation rotates with it. Therefore, the images do reflect polymer chain orientation and stress direction, but color changes may be attributed to changes in web direction as well as load direction.

3.3 Alignment Change

As expected, small angle alignment changes resulted in small color changes, but Fig. 7 shows that the color change is still noticeable to the naked eye, and therefore well within the realm of detection by a high-quality camera in a controlled environment. Fig. 7 (a) appears to have far more red than Fig. 7 (c), which is confirmed in Table 3.

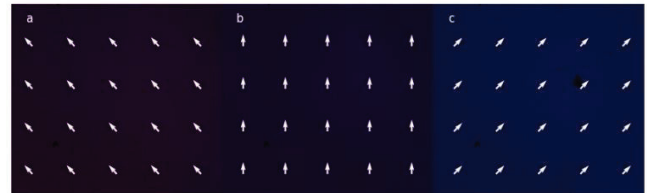


FIGURE 7. Images taken by the polariscope tool with indicators of stress orientations at (a) -20° , (b) 0° , and (c) 20° from the standard roller alignment.

Direction	Avg. R Value	Avg. G Value	Avg. B Value	Dominant Color(s)
-2	51	28	62	Blue, Red
0	41	25	68	Blue, Red
2	27	32	85	Blue

TABLE 3. RGB values with respect to misalignment angle.

Based on the results in table 3, alignment changes do not result in significant changes in green values, but red and blue value levels change to indicate the misalignment. As the alignment is altered from negative to positive, the value of red decreases and blue increases. Because of the change of alignment angle,

the web does have a change in angle, but it also experiences a change in shear stress that changes the principal stress direction. These may both be a cause of the color change captured in the images.

3.4 Tension Magnitude Change

Since the stress direction across the substrate did not change in this test, RGB color change is not expected. As seen in Fig. 8, the results reflect the expectation. An important observation is the change in color intensity as the tension is increased. Lower tension resulted in a visually darker image, reflecting lower intensity light. Higher tension resulted in a brighter image, reflecting higher intensity light. This makes sense, as higher tensions result in stronger pulling of the polymer chains, so there is more chain alignment along the principal stress direction. With more aligned chains, a higher percentage of the light passing through the web will be altered and captured by the camera, resulting in progressively brighter images as demonstrated in Figure 8.

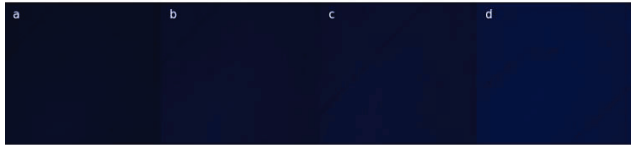


FIGURE 8. Images taken by the polariscope tool at (a) 1 lbf, (b) 6 lbf, (c) 9 lbf, and (d) 16 lbf in a lit room.

Environ- ment	Tension (lbf)	Avg. R Value	Avg. G Value	Avg. B Value	Color Trend
Illuminated	1	18.51	23.26	66.877	B ~3x RG
	6	21.13	26.51	73.69	B inc. ~2x RG
	9	22.14	27.77	76.30	B inc. ~2x RG
	16	25.76	31.64	84.55	B inc. ~2x RG
Dark	1	18.96	23.74	67.91	B ~3x RG
	6	21.69	27.24	75.21	B inc. ~2x RG
	9	23.29	29.01	78.85	B inc. ~2x RG
	16	26.08	32.02	85.30	B inc. ~2x RG

TABLE 4. RGB value comparisons across tensions and environmental effects.

After image processing it was possible to compare images taken in an illuminated room to those taken in a dark room. Since these images are very dependent on intensity of light, it was critical to know if environmental conditions had a significant effect on the results. Figure 8 depicts the images taken in an illuminated room. The experimental results from the dark room are visually identical to the naked eye and have therefore only been compared in Table 4.

Based on Table 4, there are several interesting trends that occur as tension increases in both environments. Firstly, it is important to note that the dominant color captured by the tool is blue, which was roughly 2.5 to 3 times larger in value than the red and green values. As tension increased, the B value increased, as expected. However, the R and G values also increased, but the B value generally increased at roughly twice the rate that the RG values did. This data shows that monitoring the dominant color is a viable method from monitoring tension.

Between the lit environment and the dark environment, it is apparent that the dark environment had marginally higher RGB values. While the difference is not apparent to the naked eye, this could be a critical difference. However, this increase in brightness in a darker environment is counter to the expected results. The setup uses a long tube lens and collimated light in order to reduce ambient light from reaching the camera, but this does not explain why there would be an increase in light reaching the camera in a darkened environment. Therefore, this comparison will require further testing before any conclusions can be reached.

4. CONCLUSIONS AND FUTURE WORK

These results support the experimental hypotheses that load orientation, web orientation, tension magnitude, and roller alignment stretch polymer chains in a polycarbonate web from an amorphous optically isotropic state to an optically anisotropic state, where change in polarization angle of transmitted light results in detectable RGB color changes that correspond to expected simulated stress distributions. These results are useful for demonstrating the feasibility of creating a reference library of RGB combinations and their corresponding load orientations. Therefore, instead of running intensity calculations for each RGB component of each pixel in every image taken by the tool, the tool can instead reference color averages of sections of each image to the library and determine the load orientation. Changes in the direction of polymer chain orientation would be almost instantly detectable and diagnosable so that the web may be fixed and returned to its standard applied load.

However, future experimentation is necessary in a more realistic R2R environment. The angular and load changes experimented here are not particularly realistic in terms of the magnitudes of change expected in real-

world systems. Further experimentation on a more robust test mechanism is currently being conducted, where motorized steel rollers are creating a more dynamic system for testing. Additionally, conducting experiments about more realistic surface patterns is also crucial since current tests are run on a blank substrate.

Beyond more robust testing, further work is necessary to bring this tool to the functionality necessary for operation with a fully-functional R2R system. The first necessary step is to create a computer-vision software capable of segmenting the image and performing the necessary optical calculations to convert the image color intensities into stresses, and finally into relative deformation. These calculations can then be used to build a library of corresponding color change to deformation so as to provide real-time error correction suggestions.

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REFERENCES

- [1] J. Lee, S. Park, K. H. Shin, and H. Jung, "Smearing defects: a root cause of register measurement error in roll-to-roll additive manufacturing system," *Int. J. Adv. Manuf. Technol.*, vol. 98, no. 9–12, pp. 3155–3165, 2018, doi: 10.1007/s00170-018-2465-0.
- [2] W.-C. Wang, "Photoelasticity," p. 66.
- [3] G. Cloud, *Optical Methods of Engineering Analysis*, vol. 34. Cambridge University Press, 1995. Accessed: Jul. 26, 2021. [Online]. Available: <http://doi.wiley.com/10.1111/j.1747-1567.2009.00611.x>