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Intra-Roll and Intra-Jumbo Roll Variation of Duct Tapes

ABSTRACT

In forming opinions regarding duct tape examinations, the forensic community has relied primarily upon empirical observations from analyzing case samples or reference rolls, information obtained from industry/manufacturing representatives, and research projects that were relatively limited in scope. This study was designed and undertaken to expand on this body of knowledge by 1) evaluating the within-roll variation of duct tapes, specifically the physical characteristics of scrim count, warp yarn offset, width, and thickness; as well as the chemical composition of the adhesives via Fourier transform infrared (FTIR) spectroscopy; 2) assessing whether rolls removed from the middle and both edges of a jumbo roll have any observable or measureable differences; and 3) determining the association/discrimination criteria that should be used for the forensic analysis of duct tapes. The results indicate that warp yarn offset should not be used to discriminate samples due to variations in this feature along the length of a roll, but that scrim count, width, thickness, and adhesive composition vary to a limited extent along the length of an individual roll of tape. Aside from width, minimal variation in these characteristics occurs between different rolls cut from the same jumbo roll. Statistical analysis of the thickness and adhesive composition via FTIR indicate that

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some statistically significant differences are observed, but these differences are minor and would not likely have resulted in an exclusion/elimination in a forensic comparison case.

Keywords: duct tape, variation, stereomicroscopy, scrim count, width, thickness, Fourier transform infrared spectroscopy, statistical analysis, jumbo roll

INTRODUCTION

Duct tapes are the most common type of tape submitted as evidence to forensic laboratories in North America, and the variations exhibited between duct tape products make the material amenable to comparative analyses. There are generally between five and ten duct tape manufacturers in North America at any given time, and the amount of duct tape produced between manufacturers can vary substantially. Each manufacturer makes a variety of duct tape products that meet certain specifications depending upon their intended/advertised use. Individual duct tape rolls are cut from a much larger roll, referred to as a jumbo roll, using slitting knives pre-set at fixed distances (nominally 2" apart for a standard-width duct tape). The number of jumbo rolls needed to make a given product depends on a variety of market-driven factors (e.g., anticipated demand).

Certain differences between two tape samples can indicate that they are not from the same product and therefore did not originate from the same roll. Similarities between tape samples may suggest commonalities in the manufacturing process. If there are no observed differences between two tape samples, an analyst can generally conclude that the two originated from the same roll or another roll manufactured in the same manner; for duct tapes, this generally indicates the same tape product (Mehltretter 2012). It can be concluded a piece of tape originated from a specific roll only when two pieces of tape physically refit to each other at their ends (i.e., an end match).

The results of a 2012 Forensic Testing Services (Williamston, MI) duct tape proficiency test highlighted the need for additional studies regarding the acceptable variations in the parameters routinely assessed in duct tape comparisons. For this test, the participants received three duct tape samples: Item 1 was a piece of duct tape representing the roll from the suspect's vehicle, Item 2 was a piece of tape from Victim A, and Item 3 was a partial piece (torn lengthwise) of duct tape from Victim B. Once the test was closed, the test provider indicated Items 1-3 were separate pieces of tape torn from the same roll of Duck® brand tape. All Item 1 samples were prepared sequentially, followed by Item 2 samples, and then Item 3 samples. Therefore, the samples for each individual test were yards away from each other on the original roll.

The test results for the comparison of Items 1 and 2 were as follows: of the 49 respondents, 42 (86%) correctly reported an association and seven (14%) incorrectly reported an elimination (exclusion). For the comparison of Items 1 and 3, 45 (92%) correctly reported an association, two (4%) incorrectly reported an elimination, and two (4%) reported an inconclusive. All four of the test takers that did not correctly report an association between Items 1 and 3 also eliminated Items 1 and 2 from sharing a common source roll. In examining the report wording for each of the incorrectly reported results, several themes emerged. Eliminations appeared to be reported based on scrim count, width, and warp yarn offset. These results suggest that there may be uncertainty in the community as to what constitutes a significant difference between duct tape samples, and further, what is typical for intra-roll variation within a commercial grade product.

According to discussions with industry representatives (Mehltretter 2012), scrim counts of ± 1 are generally acceptable in the manufacturing of duct tape products. Further, a significant difference between pristine tapes (not stretched, deformed, or highly contaminated) is generally considered to be a width difference greater than 1.0 mm or a thickness difference greater than 10%. These tolerances do not appear to have been explored by forensic scientists.

Few publications have addressed if physical and chemical properties are consistent throughout a roll of tape: one addressed electrical tapes (Keto 1984), one considered elemental analysis on duct tapes (Jenkins 1984), and one was a review article (Blackledge 1987), which referenced the other two. In Keto's work, three rolls from each of six different electrical tape manufacturers were examined by X-ray fluorescence and FTIR; no statistically significant differences were found within a roll or between rolls of the same manufacturer. All six of the analyzed brands were clearly different. Jenkins reported no significant variation in elemental composition between the beginning, middle, and end of a duct tape roll when analyzed by energy dispersive X-ray spectrometry. The number of rolls analyzed and the sampling procedure were not noted in this latter work.

To date, no studies have been found that address the intra-roll variation of the physical characteristics or chemical composition (via FTIR) of duct tapes. These analyses (physical and FTIR) are the most widely used techniques for the analysis of duct tapes and have been found to yield a very high degree of discrimination between duct tape products (Mehltretter 2012). Additionally, no studies have been found which examined the variation between different rolls produced from the same jumbo roll or manufacturing batch.

This study was designed and undertaken to address this knowledge gap through 1) evaluation of the within-roll variation of duct tapes, specifically documenting the observed and measured physical characteristics as well as the chemical composition via FTIR spectroscopy, 2) assessment of whether rolls removed from the middle and both edges of a jumbo roll have any observable or measureable differences, and 3) determination of the appropriate association/discrimination criteria for the forensic analysis of duct tapes.

MATERIALS AND METHODS

Tape Collection

The major North American manufacturers of duct tape were contacted and asked to submit three rolls of a popular, commodity-grade duct tape product. These three rolls were to come from the left, middle, and right side of the same jumbo roll of their selected product. In total, five products were received from four different manufacturers, totaling 15 rolls of tape. All were silver-backed, nominally two inches wide, placed on manufacturer or brand name labeled cores, and 55 or 60 yards in length.

These rolls were unwound, cut into five yard increments, and placed on plastic tubular roll stock. This process resulted in twelve or thirteen pieces of tape for each roll.

The nomenclature used for each piece of tape was as follows:

Character	Comments
1	Product identifier (B, C, I, M, or S)
2	Collection time (0 indicates time=0, a single collection time)
3	Individual roll (A=left, B=middle, C=right)
4-5	Number of yards cut from the leading edge of the tape roll.

For instance, B0B15 indicates that this particular piece of tape originated from product B, at the initial collection time (this study represents only a single collection time for each product), from the middle roll on the jumbo roll, and that the piece was cut beginning at 15 yards from the leading edge of the roll. Each piece was then prepared and analyzed as described herein.

Scrim Count

A portion of the adhesive was removed as needed with suitable solvent and cotton swabs/Kimwipes® to expose enough of the fabric to measure one square inch. The scrim count was measured using an English/Imperial ruler, in which the number of warp yarns (machine direction) and the number of fill or weft yarns (cross direction) were counted per inch in each direction, and recorded as a measure of warp/fill (w/f). To ensure consistency of measurement, the zero point of the ruler was lined up with a yarn, and that yarn was not counted. If a yarn lined up with the 1" point of the ruler, that yarn was counted. Since variations in scrim count are expected to be minimal at any given location, one measurement was taken near the leading end of each five yard piece of tape. Any variations in scrim count values over the length of the tape were noted.

Warp Yarn Offset

The warp yarn offset is defined as the distance from the machine edge of the tape to the first warp/machine-direction yarn. This offset was evaluated one of two ways for each product, depending on what was most amenable for a particular tape. One method was to examine the warp yarn closest to the machine edge of the tape and follow it along the length of the tape to determine whether the offset changed in an observable way (e.g., from at-edge to off-edge). The second method was to visually examine the piece of tape at various points along its length and observe whether there were noticeable variations in offset (e.g., from at-edge to off-edge).

Width

With a metric ruler, a single width measurement (again because variation at a given location is expected to be minimal) was taken at each five yard increment and recorded to the nearest 0.5 mm (ruler gradations were 1 mm). Any variations in width over the length of the tape were noted.

Thickness (Overall and Film)

For thickness measurements, the sample was placed between the two faces of a Mitutoyo digital micrometer, model number 293-348 (Mitutoyo, Aurora, IL). For film thickness measurements, the adhesive and fabric were first removed with hexane or chloroform. Five overall thickness and five film thickness measurements were taken within approximately the first two inches of each five yard piece, and the values were recorded to the nearest 0.05 mil (1 mil = 1/1000 inch). To avoid possible drift of the mean measurement from one piece to the next, one measurement of each piece from a roll was taken before taking the second measurement of each piece, and so forth. All measurements for a particular product were taken on the same day.

Repeat film thickness and overall thickness measurements were taken for each piece in order to subject the results to statistical analyses using an Analysis of Variance (ANOVA) scheme. Because the tape samples necessarily followed each other sequentially and came from the same individual and jumbo roll of tape, the sampling design was not fully randomized. Rather, the sampling methodology employed approximated a standard, Two-Way, Repeated Measures ANOVA design. Accordingly, that model was assumed and was used to perform the initial ANOVA analysis using MINITAB (State College, PA) Version 13 software.

In addition, a One-Way ANOVA analysis was conducted and Tukey's Honestly Significant Difference (HSD) test (with overall $\alpha=0.05$) was applied to the individual rolls to conduct pairwise comparisons among all of the tape samples known to be from the same individual roll. Similarly, Tukey's HSD test with overall $\alpha=0.05$ was applied to identify significant differences in mean thickness among the set of three rolls that originated from the same jumbo roll.

FTIR

Between five and seven adhesive samples were physically removed with a scalpel at each five yard increment. They were smeared onto a KBr disc and analyzed in the transmission mode using a Continuum microscope attached to a Nicolet Nexus 6700 FTIR E.S.P. spectrometer with a MCT/A detector (4000-650 cm^{-1}) (Thermo Nicolet, Madison, WI). The resolution was 4 cm^{-1}, the aperture was approximately 100x100 µm, and the number of scans was 128. Intensity was recorded at a total of 1738 wavenumbers.

Raw spectra were first normalized to a common baseline by taking the first derivative. MATLAB (The MathWorks, Inc., Natick, MA) was used to generate a heat map image of the first derivative spectra. To identify outlying samples for visual comparison, statistical analysis of the FTIR spectra (made possible through the replicate analyses) was conducted by first reducing the number of variables (wavenumbers) to a few principal components (PCs), which describe a large portion of the information contained in the spectra. Unscrambler X (CAMO Software, Oslo, Norway) was used to perform principal component analysis (PCA) for reduction of the number of variables to a few important PCs. A multivariate form of ANOVA, multivariate analysis of variance (MANOVA), was used with the values of the first four PCs in JMP Pro (SAS, Cary, NC) to separately detect statistically significant differences 1) along the length of a single roll and 2) across the width of a jumbo roll. Pillai's Trace was used as the p-value estimate as recommended in the JMP Pro software documentation. If statistically significant differences were detected, visual comparison of the spectra that appeared most different was conducted by an experienced duct tape examiner to determine if the difference would lead to an exclusion in a forensic examination.

RESULTS

Scrim Count

Table 1 provides the scrim count measurements for each piece of tape. Within a single roll of tape, scrim count did not vary on most rolls. However, exceptions did occur in rolls from two of the products. For product C, the warp count varied on one of the rolls (roll A) up to two yarns per inch ranging from 19 to 21 (there was no variation in the fill yarns). The other two rolls from the same jumbo roll did not demonstrate this variation. For the roll with variation, however, it was observed that there was an unusual pattern to the fabric (see Figure 1a). The fill yarns were curved across the tape width rather than perpendicular to the warp yarns, and the warp yarn count appeared higher on one side of the tape than on the other. For product I, the fill count varied between 11 and 12 for two of three rolls (rolls B and C); however, for those with an 11 count, the 12th yarn was located just outside of the measurement window.

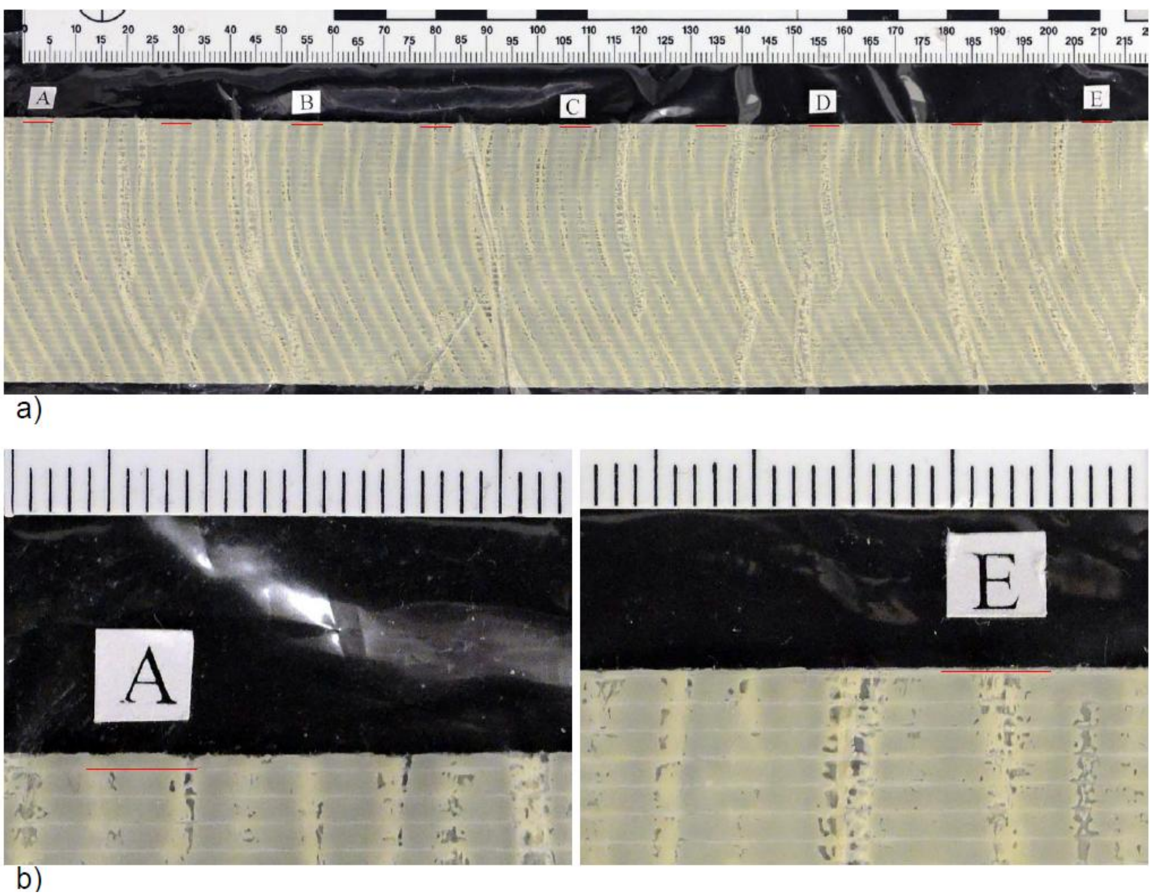

Figure 1 a) Photograph depicting how the fill yarns curve across the width of the tape piece and how the edge warp yarn shifts along the length of the piece. In this example, the shift is observed over approximately 8" in length, and the warp yarn of interest is emphasized with a recurring thin red line. b) Higher magnification photographs of areas A and E.

Table 1 Scrim count and width measurements for each piece of tape.

Piece	Scrim Count	Width (mm)	Piece	Scrim Count	Width (mm)	Piece	Scrim Count	Width (mm)	Piece	Scrim Count	Width (mm)	Piece	Scrim Count	Width (mm)
B0A00	17/5	48.0	C0A00	20/7	49.0	I0A00	18/11	50.0	M0A00	29/8	47.5	S0A00	19/7	49.0
B0A05	17/5	48.0	C0A05	20/7	49.0	I0A05	18/11	50.0	M0A05	29/8	47.5	S0A05	19/7	49.0
B0A10	17/5	48.0	C0A10	20/7	49.0	I0A10	18/11	49.5	M0A10	29/8	47.5	S0A10	19/7	49.0
B0A15	17/5	48.0	C0A15	20/7	49.0	I0A15	18/11	49.5	M0A15	29/8	47.5	S0A15	19/7	49.0
B0A20	17/5	48.0	C0A20	20/7	49.0	I0A20	18/11	49.5	M0A20	29/8	47.5	S0A20	19/7	49.0
B0A25	17/5	48.0	C0A25	21/7	49.0	I0A25	18/11	49.5	M0A25	29/8	47.5	S0A25	19/7	49.0
B0A30	17/5	48.0	C0A30	20/7	49.0	I0A30	18/11	49.5	M0A30	29/8	47.5	S0A30	19/7	49.0
B0A35	17/5	48.0	C0A35	21/7	49.0	I0A35	18/11	49.5	M0A35	29/8	47.5	S0A35	19/7	49.0
B0A40	17/5	48.0	C0A40	20/7	49.0	I0A40	18/11	49.5	M0A40	29/8	47.5	S0A40	19/7	49.0
B0A45	17/5	48.0	C0A45	21/7	49.0	I0A45	18/11	50.0	M0A45	29/8	47.5	S0A45	19/7	49.0
B0A50	17/5	48.0	C0A50	19/7	48.5	I0A50	18/11	50.0	M0A50	29/8	47.5	S0A50	19/7	49.0
B0A55	17/5	48.0	C0A55	20/7	48.5	I0A55	18/11	49.5	M0A55	29/8	47.5	S0A55	19/7	49.0
			C0A60	20/7	48.5	I0A60	18/11	50.0	M0A60	29/8	47.5	S0A60	19/7	48.5
B0B00	17/5	48.5	C0B00	19/7	48.0	I0B00	18/11	47.5	M0B00	29/8	47.5	S0B00	19/7	48.5
B0B05	17/5	48.5	C0B05	19/7	48.0	I0B05	18/11	47.5	M0B05	29/8	47.5	S0B05	19/7	48.5
B0B10	17/5	48.5	C0B10	19/7	48.0	I0B10	18/11	47.5	M0B10	29/8	47.5	S0B10	19/7	48.5
B0B15	17/5	48.5	C0B15	19/7	48.0	I0B15	18/11	47.5	M0B15	29/8	47.5	S0B15	19/7	48.5
B0B20	17/5	48.5	C0B20	19/7	48.0	I0B20	18/11	47.5	M0B20	29/8	47.5	S0B20	19/7	48.5
B0B25	17/5	48.5	C0B25	19/7	48.0	I0B25	18/11	47.5	M0B25	29/8	47.5	S0B25	19/7	48.5
B0B30	17/5	48.5	C0B30	19/7	48.0	I0B30	18/12	47.5	M0B30	29/8	47.5	S0B30	19/7	48.5
B0B35	17/5	48.5	C0B35	19/7	48.0	I0B35	18/11	47.5	M0B35	29/8	47.5	S0B35	19/7	48.5
B0B40	17/5	48.5	C0B40	19/7	48.0	I0B40	18/12	47.5	M0B40	29/8	47.5	S0B40	19/7	48.5
B0B45	17/5	48.5	C0B45	19/7	48.0	I0B45	18/11	47.5	M0B45	29/8	47.5	S0B45	19/7	48.5
B0B50	17/5	48.5	C0B50	19/7	48.0	I0B50	18/11	47.5	M0B50	29/8	47.5	S0B50	19/7	48.5
B0B55	17/5	48.5	C0B55	19/7	48.0	I0B55	18/12	47.5	M0B55	29/8	47.5	S0B55	19/7	48.5
			C0B60	19/7	48.0	I0B60	18/12	47.5	M0B60	29/8	47.5	S0B60	19/7	48.5
B0C00	17/5	47.5	C0C00	19/7	48.0	I0C00	18/11	48.5	M0C00	29/8	48.0	S0C00	19/7	47.5
B0C05	17/5	47.0	C0C05	19/7	48.0	I0C05	18/11	48.5	M0C05	29/8	48.0	S0C05	19/7	47.5
B0C10	17/5	47.0	C0C10	19/7	48.0	I0C10	18/12	48.5	M0C10	29/8	48.0	S0C10	19/7	47.5
B0C15	17/5	47.0	C0C15	19/7	48.0	I0C15	18/11	48.5	M0C15	29/8	48.0	S0C15	19/7	47.5
B0C20	17/5	47.5	C0C20	19/7	48.0	I0C20	18/11	48.5	M0C20	29/8	48.0	S0C20	19/7	47.5
B0C25	17/5	47.0	C0C25	19/7	48.0	I0C25	18/12	48.5	M0C25	29/8	48.0	S0C25	19/7	47.5
B0C30	17/5	47.5	C0C30	19/7	48.0	I0C30	18/12	49.0	M0C30	29/8	48.0	S0C30	19/7	47.5
B0C35	17/5	47.0	C0C35	19/7	48.0	I0C35	18/11	48.5	M0C35	29/8	48.0	S0C35	19/7	47.5
B0C40	17/5	47.0	C0C40	19/7	48.0	I0C40	18/12	48.5	M0C40	29/8	48.0	S0C40	19/7	47.5
B0C45	17/5	47.5	C0C45	19/7	48.0	I0C45	18/11	48.5	M0C45	29/8	48.0	S0C45	19/7	47.5
B0C50	17/5	47.0	C0C50	19/7	48.0	I0C50	18/11	48.5	M0C50	29/8	48.0	S0C50	19/7	47.5
B0C55	17/5	47.5	C0C55	19/7	48.0	I0C55	18/12	48.5	M0C55	29/8	48.0	S0C55	19/7	48.0
			C0C60	19/7	48.0	I0C60	18/12	49.0	M0C60	29/8	48.0	S0C60	19/7	47.5

Warp Yarn Offset

For all the rolls in the study, the warp yarn offset was observed to vary along the length of the roll. For example, using the first method described earlier, roll C0A's warp yarn offset was observed to have an obvious shift in the position of the first warp yarn over a distance of approximately 8¼ inches (see Figure 1b). Using the second observation method, the offset for roll S0B was observed to change along the length of the roll (see Figure 2).

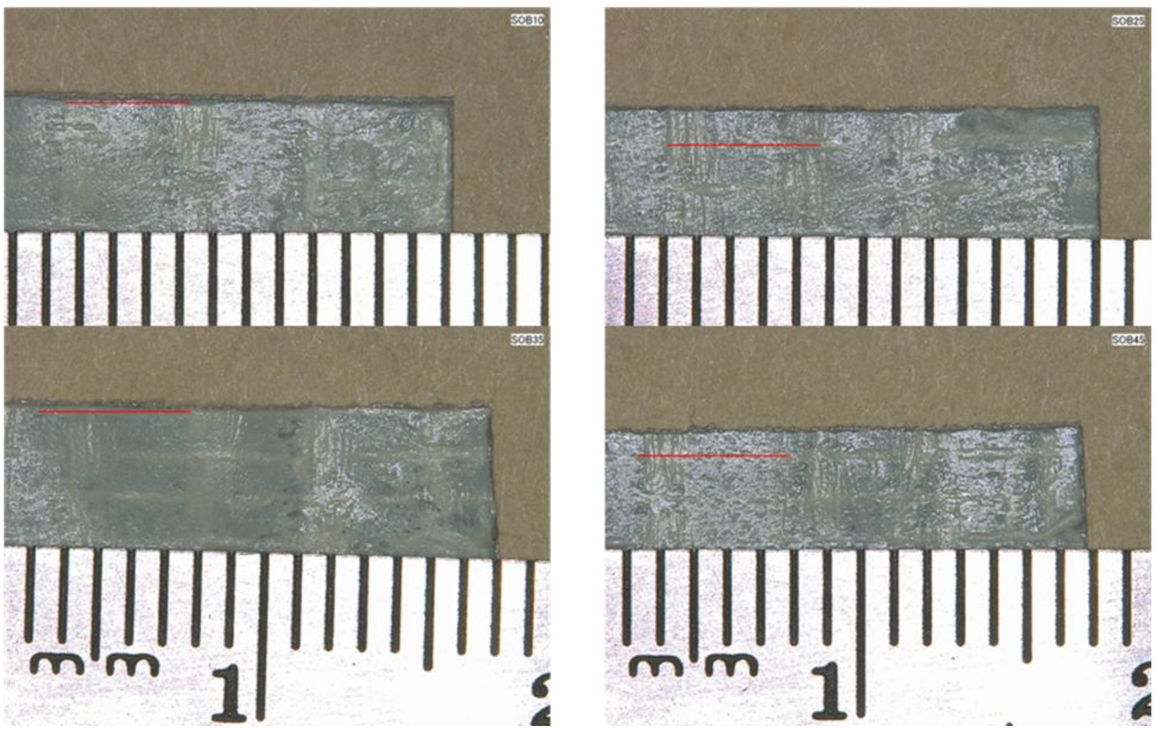

Figure 2 Four different pieces of tape from the same individual roll of tape depicting a variation in warp yarn offset along the length of a roll (clockwise from top left: S0B10, S0B25, S0B45, and S0B35). The warp yarn closest to the tape's machine edge is marked by a red line.

Width

Table 1 provides the width measurement for each piece of tape. The largest difference in width observed along the length of a single roll was 0.5 mm, which was observed in six of the 15 rolls included in the study (four different manufacturers). For a majority of the rolls, the width did not vary when recorded to the nearest 0.5 mm. The largest difference in width observed between pieces cut from the same jumbo roll of tape from the same product was observed for product I and was 2.5 mm (47.5 mm versus 50.0 mm).

Thickness (Overall and Film)

The results of thickness measurements on the individual rolls and pieces of tape are summarized in Table 2. Measurements of the mean overall thickness of individual tape pieces taken from the same roll showed maximum relative differences that ranged from 3.0%–19.3% depending upon the roll (Table 3). Similarly, measurements of the mean film thickness of individual tape pieces taken from the same roll showed maximum relative differences that ranged from 1.9% – 12.7% depending on the roll (Table 3). In general, the Two-Way Repeated Measures ANOVA analysis results revealed statistically significant effects on tape thickness (both film and overall) as a function of position along the length of the individual rolls. Likewise, Two-Way Repeated Measures ANOVA revealed statistically significant effects on tape thickness as a function of roll position (left, right or center of a jumbo roll).

Table 2 Mean (n=60 or 65) thickness by roll with the minimum and maximum mean (n=5) thicknesses for tape pieces taken from the same roll.

Roll	Overall Thickness (mils)				Film Thickness (mils)		
	Mean	Minimum	Maximum		Mean	Minimum	Maximum
B0A	8.42	8.24	8.52		5.07	5.00	5.13
B0B	8.60	8.40	8.91		5.26	5.20	5.33
B0C	8.36	8.22	8.47		5.21	5.16	5.26
C0A	7.00	6.76	7.14		2.07	1.99	2.20
C0B	6.91	6.63	7.23		2.08	1.99	2.23
C0C	7.33	6.98	7.99		2.13	2.06	2.25
I0A	8.70	8.55	8.91		3.08	2.99	3.16
I0B	8.96	8.69	9.12		3.11	3.01	3.21
I0C	8.68	8.53	8.80		3.19	3.12	3.32
M0A	8.66	8.52	9.03		2.56	2.44	2.66
M0B	8.53	8.29	8.82		2.61	2.45	2.76
M0C	8.41	8.23	8.77		2.58	2.48	2.68
S0A	8.31	7.84	8.79		3.98	3.92	4.03
S0B	8.41	7.76	9.26		3.97	3.89	4.06
S0C	8.25	7.75	8.69		3.97	3.92	4.02

Tukey's HSD test was used to conduct pairwise comparisons of the mean overall thickness (i.e., the average of all of the overall thickness measurements made on a given roll) amongst rolls from the same product. The comparisons demonstrated that these rolls often had statistically significant differences in this parameter. For example, the center roll of product B differs significantly in mean overall thickness from both the left and right rolls. However, the difference between the left and right rolls was not statistically significant (Figure 3). Of the tapes examined, only product S had no statistically significant difference in mean overall thickness between any of the pairs (left-center, left-right, center-right). The largest relative differences in mean overall thickness between rolls from the same product ranged from 1.9%-6.0% (Table 4).

Table 3 Maximum relative difference in mean thickness among tape pieces taken from the same roll

Roll	Overall Thickness	Statistically Significant at α=0.05?		Film Thickness	Statistically Significant at α=0.05?
B0A	3.4%	No		2.6%	No
B0B	6.1%	Yes		2.5%	No
B0C	3.0%	No		1.9%	No
C0A	5.6%	No		10.6%	Yes
C0B	9.0%	Yes		12.1%	Yes
C0C	14.5%	Yes		9.2%	Yes
I0A	4.2%	Yes		5.7%	No
I0B	4.9%	Yes		6.6%	Yes
I0C	3.2%	Yes		6.4%	Yes
M0A	6.0%	Yes		9.0%	Yes
M0B	6.4%	Yes		12.7%	Yes
M0C	6.6%	Yes		8.0%	Yes
S0A	12.1%	Yes		2.8%	No
S0B	19.3%	Yes		4.4%	No
S0C	12.1%	Yes		2.6%	No

Table 4 Maximum relative difference in mean thickness among individual rolls from the same jumbo roll/product

Product	Mean Overall Thickness	Statistically Significant at α=0.05?		Mean Film Thickness	Statistically Significant at α=0.05?
B	2.81%	Yes		3.63%	Yes
C	6.02%	Yes		2.98%	Yes
I	3.22%	Yes		3.52%	Yes
M	2.91%	Yes		1.86%	Yes
S	1.87%	No		0.21%	No

Similarly, the results of Tukey's HSD test determined that again only product S had no statistically significant difference in mean film thickness between any of the rolls. At least one pair of rolls from the other four products had a statistically significant difference in mean film thickness. It was also observed that all of the products contained at least one pair of rolls that did not differ significantly in mean film thickness. The largest relative differences in mean film thickness between two rolls from the same product ranged from 0.21% -3.63% (Table 4).

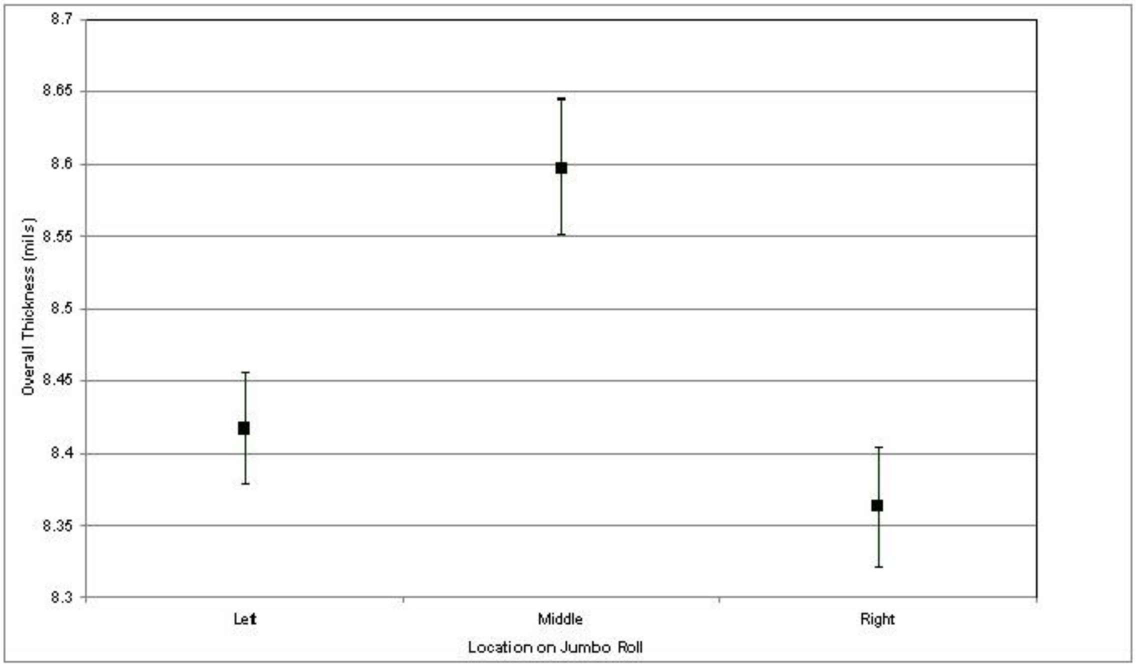

Figure 3 95% confidence intervals for mean overall thickness by roll location for product B. For this product, the left and right side rolls are statistically indistinguishable but both are significantly thinner than the center roll.

Pairwise comparisons performed with Tukey's HSD test on tape pieces taken from the same individual roll revealed statistically significant differences in overall thickness for at least one pair of samples in 12 of the 15 rolls examined. An example of this is shown in Figure 4. Under the assumption that the thickness of samples taken from a given roll is homogeneous, one might choose to conclude that two samples do not share a common origin if they differ significantly in overall thickness. However, for the 12 rolls for which significant differences are observed, the pairwise comparisons would lead to unwarranted exclusions between pairs of samples in as many as 78% of the comparisons under this scenario. The pairwise comparison data from all of the rolls are summarized in Table 5.

Similarly, pairwise comparisons performed with Tukey's HSD test of tape pieces taken from the same individual roll revealed statistically significant differences in mean film thickness for at least one pair of samples in seven of 15 rolls examined. Among these seven rolls, pairwise comparisons would lead to unwarranted exclusions from 1.3% to 18% of the time. No significant difference in film thickness was found in pairwise comparisons of tape pieces from the same roll for any of the rolls from products B and S. The pairwise comparison data from all of the rolls are summarized in Table 5.

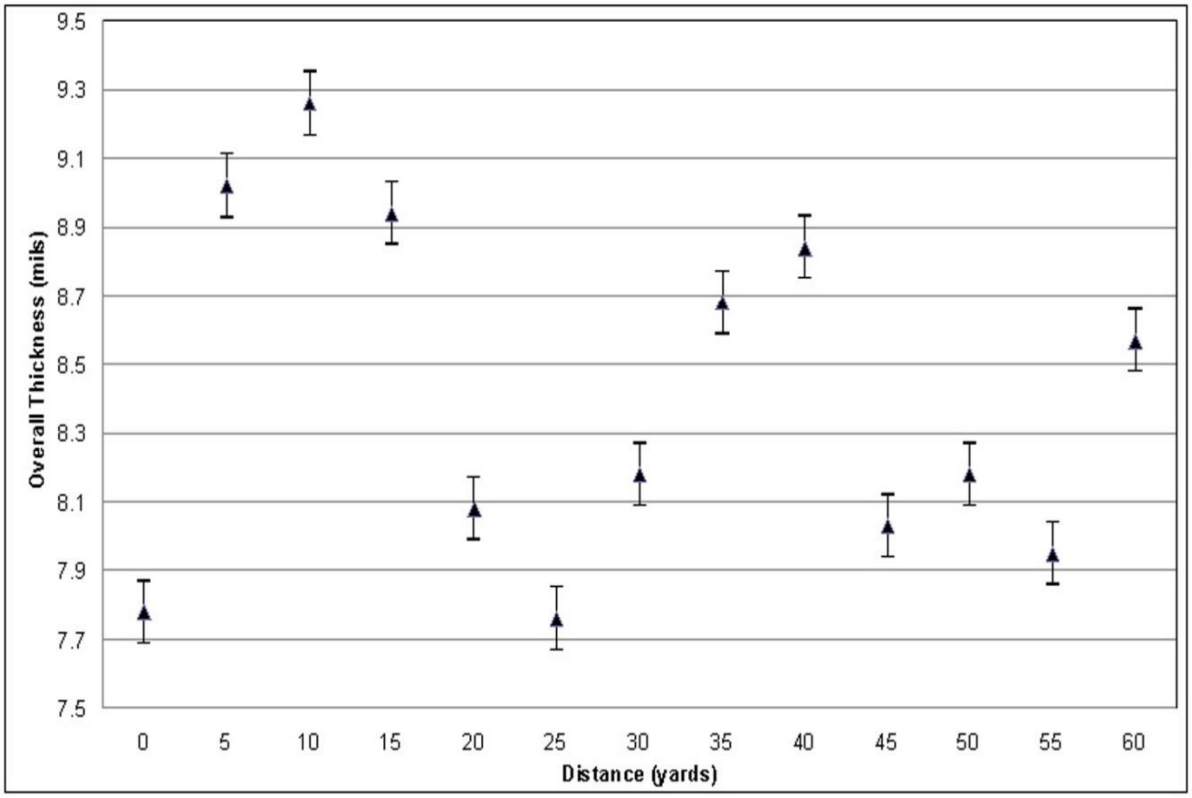

Figure 4 Individual 95% confidence intervals for mean overall thickness as a function of location on a single roll of tape from product S. Many of the pieces are statistically distinguishable in thickness.

In general, the results of the Two-Way Repeated Measures ANOVA and the One-Way ANOVA tests reported were found to yield comparable conclusions. Interaction effects between the length and the roll position factors also tended to be statistically significant but no clear trend was evident that would permit the interaction to be straightforwardly interpreted.

FTIR

The average first derivative FTIR spectra are plotted in Figure 5 as a heat map. Visual inspection of the roll homogeneity shows that differences between rolls (both along the length of a single roll and across the width of a jumbo roll) are much smaller than differences between products. However, potential differences along the length of the individual rolls and across the width of the jumbo rolls may be present even if not

Table 5: Tukey HSD pairwise comparisons results for tape pieces from the same roll

Roll	Unwarranted Exclusions (Overall Thickness)	Unwarranted Exclusions (Film Thickness)
B0A	0 of 66	0 of 66
B0B	16 of 66	0 of 66
B0C	0 of 66	0 of 66
C0A	0 of 78	1 of 78
C0B	1 of 78	5 of 78
C0C	2 of 78	12 of 78
I0A	3 of 78	0 of 78
I0B	12 of 78	2 of 78
I0C	7 of 78	4 of 78
M0A	12 of 78	14 of 78
M0B	10 of 78	11 of 78
M0C	8 of 78	0 of 78
S0A	48 of 78	0 of 78
S0B	61 of 78	0 of 78
S0C	49 of 78	0 of 78

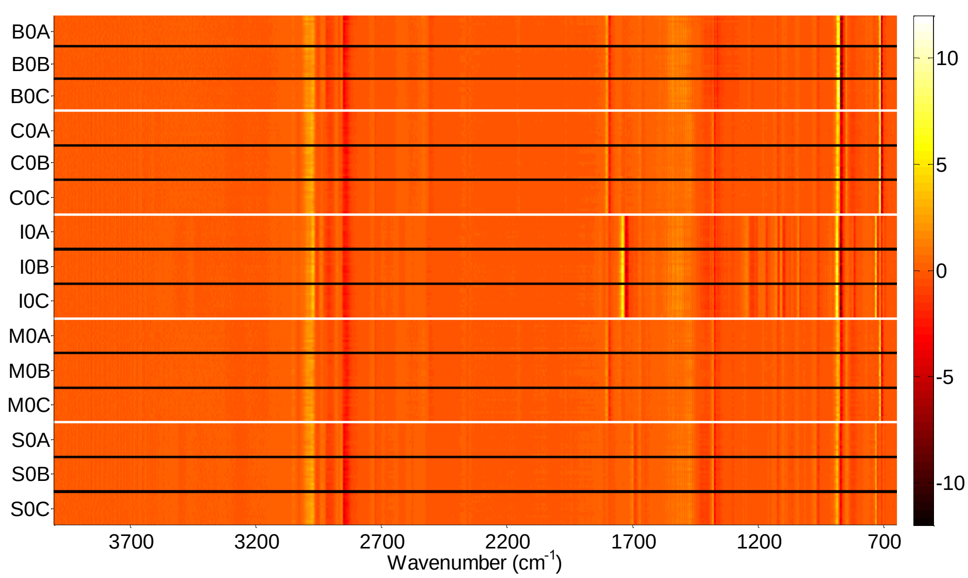

Figure 5 Heat map of average first derivative FTIR spectra. The color of each pixel corresponds to the intensity of the spectrum from each individual roll at each position along the roll length (stacked on the y axis) at the noted wavenumber (x axis) with a color scale given. Very close inspection will reveal minor differences for tape sections taken from the same roll.

visually apparent in the heat map. Therefore, the spectra were also compared statistically to identify potentially outlying samples for visual comparison.

To investigate potential differences along the length of each individual roll, the five to seven spectra from each piece of tape were used as replicate analyses and a separate PCA was performed for each individual roll. Initially, plots of the values of the first two PCs were used to identify potential outliers for visual comparison. None of the samples with the largest differences in PC1 by PC2 plots were distinguishable by spectral overlay when replicate analyses were taken into account. The values of the first 4 PCs were also used to conduct MANOVA analyses for each roll to determine if there were any statistically significant spectral differences along the length of any individual rolls. Statistically significant differences ($p \leq 0.05$) were detected within two rolls (one roll each of two different products): the left roll from product I and the center roll from product C (Table 6). Figure 6 shows the average spectra for the samples with the largest difference in replicate averaged PC values (the center roll from product C at 35 yards and at 60 yards). Although a possible difference in the average spectra occurs around 3600 cm^{-1}, this difference is not repeatable when the individual spectra are examined. Another possible explanation for the differences detected by the MANOVA tests for the samples in Figure 6 is prepared sample thickness, as the spectrum for one piece of tape indicates thicker samples than the spectrum of the other piece of tape. Other possible factors include spectral noise and unrepeatable peaks/ratios.

Because no differences were detected which would lead to an exclusion, the five to seven sample spectra from each piece of tape were averaged. The averaged spectra from each of the 12 or 13 locations along the length of each individual roll were then used as replicate analyses to compare differences across the width of each jumbo roll. A separate PCA was performed for each jumbo roll. The values of the first 4 PCs from each individual roll were compared to the values from the two other rolls arising from the same jumbo roll using a MANOVA test.

Table 6 p-values for a MANOVA test for comparison of FTIR spectra along the length of an individual roll

		Individual roll		
		A	B	C
Product	B	0.5307	0.0828	0.3827
	C	0.6152	0.0101	0.2232
	I	0.0338	0.2353	0.1154
	M	0.0537	0.8611	0.2217
	S	0.3734	0.0806	0.4622

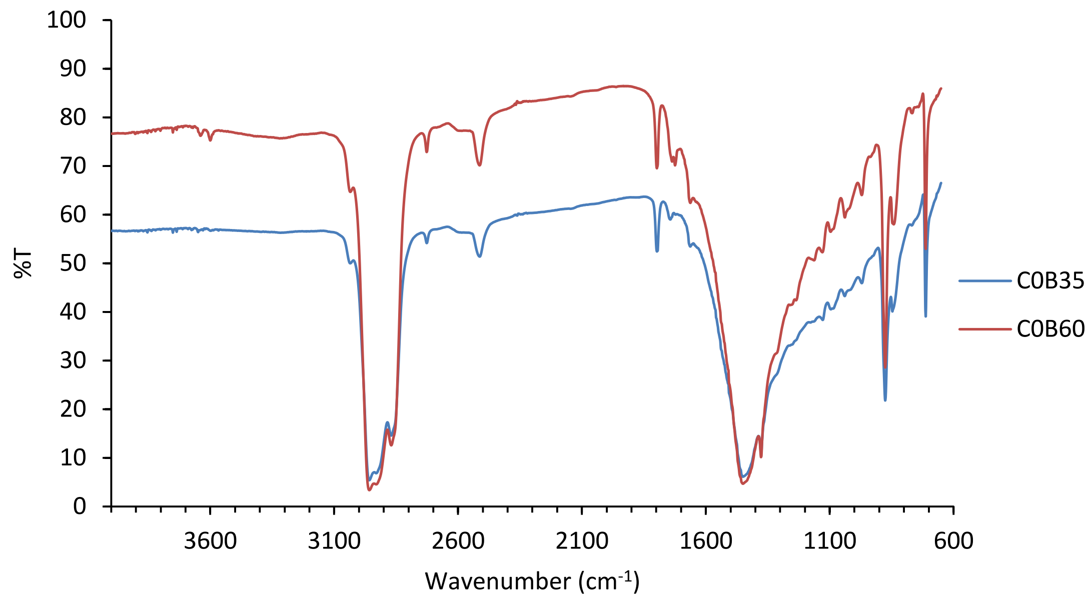

Figure 6 Product C FTIR spectra (average of six samples each) from the center roll at 35 yards (C0B35, blue trace, bottom spectrum) and at 60 yards (C0B60, red trace, top spectrum). These two average spectra had the largest difference between average PC scores for the two rolls (C0B and I0A) that showed a statistically significant difference along the roll length. The spectra are displayed on a common scale, in which the y-axis values are applicable to both spectra. The difference observed between these two spectra appears to be due primarily to the thickness of the samples analyzed. A doublet is observed at 3600 cm.$^{-1}$ However, these peaks had a low intensity relative to background and were not sufficiently reproducible to call the spectra different when observing individual spectra (note: mean spectra are displayed for clarity).

Differences at $\alpha=0.05$ between individual rolls produced from the same jumbo roll were detected for four of the five jumbo rolls tested (Table 7). However, when the spectra with the largest difference between their PC values (the left roll at 20 yards and the right roll at 15 yards from product I) were compared visually no differences were detected (Figure 7). The difference between these two spectra could be due to the thickness of the samples analyzed (I0A20 appears to have been thicker than I0C15).

DISCUSSION

The scrim count measurements usually did not vary along the length of an individual roll or between rolls taken from the same jumbo roll. In rolls that did vary, additional observations (e.g., curved fill yarns) were made that should be considered when assessing whether two scrim counts are significantly different. In general, a tolerance of ± 1 yarn in either direction appears acceptable; however, analysis of a greater variety of tapes would be of benefit to establishing a specific criterion. Caution is advised in casework samples when there is possible damage to the scrim (e.g., film deformation or a severely degraded adhesive).

Table 7 p-values for a MANOVA test for the comparison of individual rolls from within the same jumbo roll using the first 4 PCs from a separate PCA generated for each product using the 12 to 13 averaged spectra as replicate analyses

Product	p-value
B	0.0012
C	0.0015
I	<0.0001
M	0.6670
S	0.0012

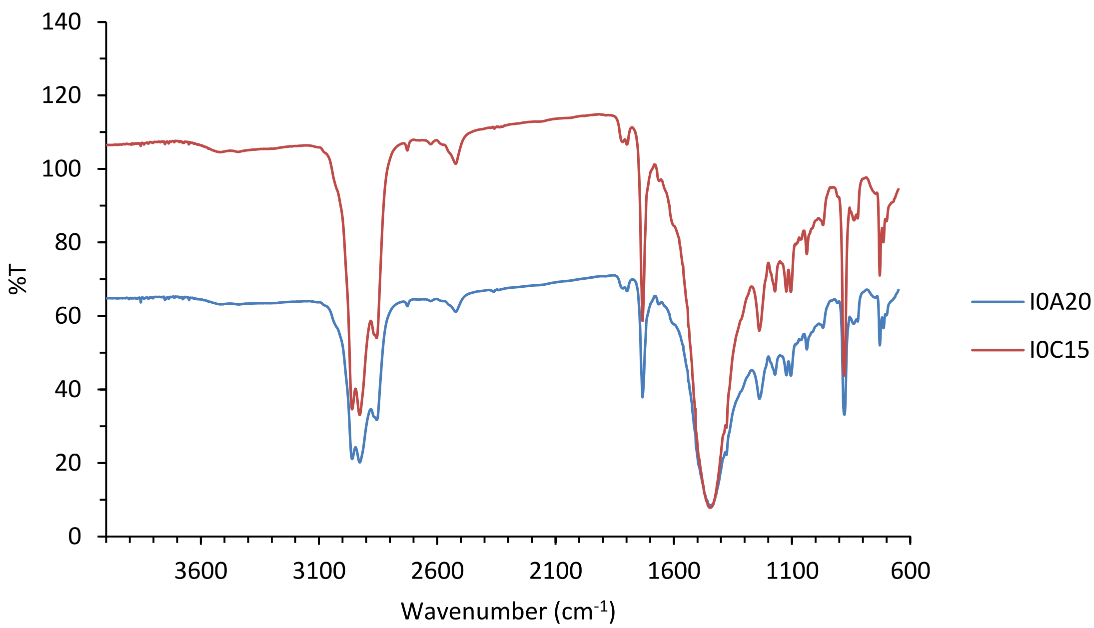

Figure 7. Product I FTIR spectra (average of six samples each) from the left roll at 20 yards (I0A20, blue trace, bottom spectrum) and the right roll at 15 yards (I0C15, red trace, top spectrum). These two average spectra had the largest difference between PC scores for product I (which had the most significant difference across a jumbo roll). The spectra are displayed on a common scale, in which the y-axis values are applicable to both spectra. The difference observed between these two spectra appears to be due to the thickness of the samples analyzed.

Since the warp yarn offset was observed to vary along the length of the individual rolls of tape, this examination should not be routinely conducted. A possible use of the

technique might be for end matching of tape pieces, since the fabric (and individual yarns) should be aligned when assessing whether an end match is possible.
In general, the widths of the examined tapes did not change or changed by only 0.5 mm within a single roll. Larger differences resulted between different rolls cut from the same jumbo roll. Since the sample set included only 15 rolls, a larger set of tapes should be analyzed before any broad statements are made regarding what criteria would result in an "exclusion". Additionally, the rolls examined were pristine and therefore not subjected to the effects of tearing or stretching. Any possible deformation should, therefore, be taken into account when assessing whether two widths are significantly different.

It is evident from the statistical evaluations performed that many of the individual rolls examined are neither statistically homogeneous in overall thickness nor in film thickness. Moreover, an overall evaluation of the tapes taken from the same jumbo roll shows that a particular tape piece will often be closer in thickness to pieces taken from another individual roll of the same jumbo roll than to some pieces taken from its parent individual roll (Figures 8 and 9). It is then obvious that pairwise comparisons of tape thickness using standard statistical methods will often lead to unacceptably high false exclusion rates due to inherent inhomogeneities within a given roll. Based on the limited number of rolls examined, the overall thickness appears to be of the greatest concern in this regard.

For these tape sets, empirically setting a maximum permissible difference in overall thickness of 15% would result in an overall false rejection rate of 0.5% for pairwise comparisons of tape pieces known to be from the same roll. Similarly, allowing a maximum difference of 15% for film thickness would result in no false rejections in pairwise comparisons of tape pieces known to be from the same roll. However, given the small sample of rolls examined and their pristine state, it is not obvious that a 15% maximum difference rule could be expected to perform well in all circumstances.

Two of 15 individual rolls of duct tape showed statistically significant variation in their FTIR spectra along the roll length. Visual inspection by spectral overlay of the statistically identified outlier samples showed differences that would not lead to an exclusion in a forensic examination. Similarly, the statistical differences detected across four of the five jumbo rolls would not lead to an exclusion by visual comparison of the spectra with the highest and lowest PC values.

In conclusion, this research indicates that scrim count does not vary to a great extent along the length of an individual pristine roll of tape nor between different rolls cut from the same jumbo roll. Width also does not vary to a great extent along the length of an individual roll of tape, but it may differ between different rolls cut from the same jumbo roll. Warp yarn offset, however, should not be used to discriminate samples due to large variations in this feature along the length of a roll. Statistical analysis of the thickness and adhesive composition indicate that some statistically significant differences can be detected. However, these differences are not meaningful in the context of the forensic examination of mass-produced products. Notably, the thickness variation evident within a given roll means that relying on statistically significant thickness differences as a decision criterion can have a high probability of incorrectly excluding tape pieces that actually come from the same roll. As such, the finding of a relatively small but statistically significant difference in thickness cannot be used with high confidence to conclude that two tape pieces are from different rolls. Further, while there appear to be some statistically significant changes in chemical composition detected by FTIR along the length of an individual duct tape roll and more commonly across a jumbo roll for these samples, the changes are not large enough to cause an exclusion and are clearly much smaller than the changes in chemical composition between products.

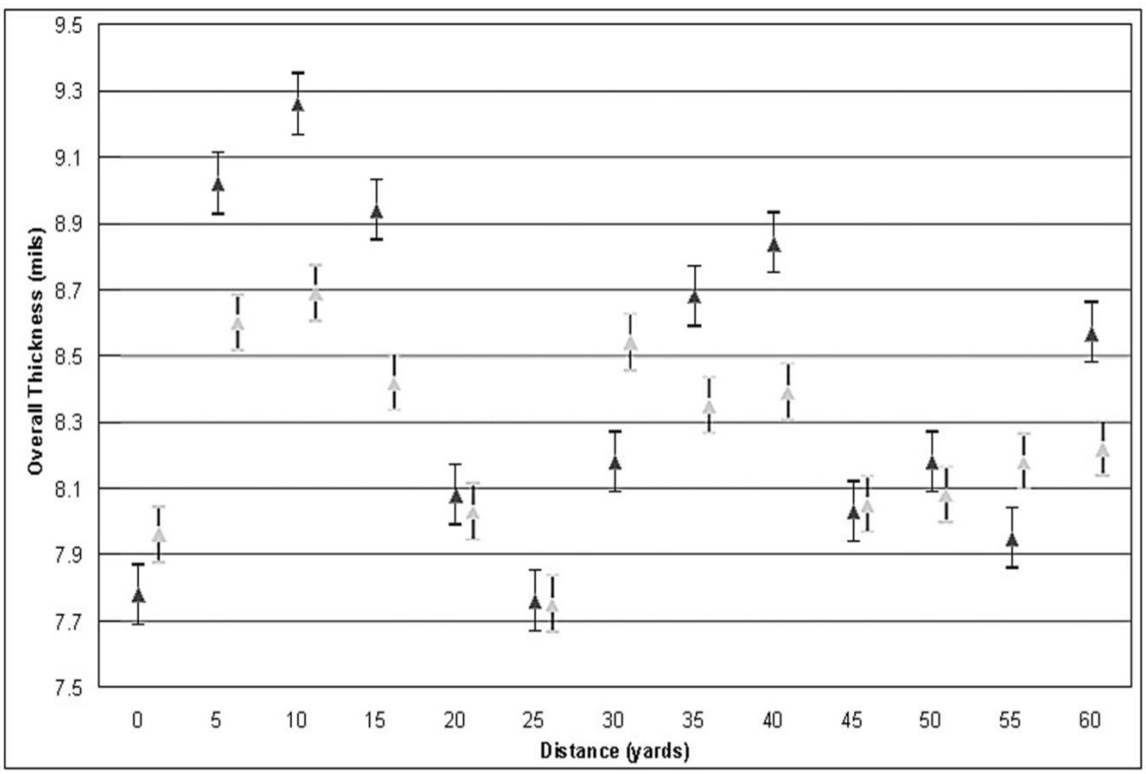

Figure 8 Individual 95% confidence intervals for mean overall thickness as a function of location for two different individual rolls of tape from product S. Often, a particular tape piece is closer in thickness to pieces taken from another roll from the same jumbo roll than to some pieces taken from its individual parent roll.

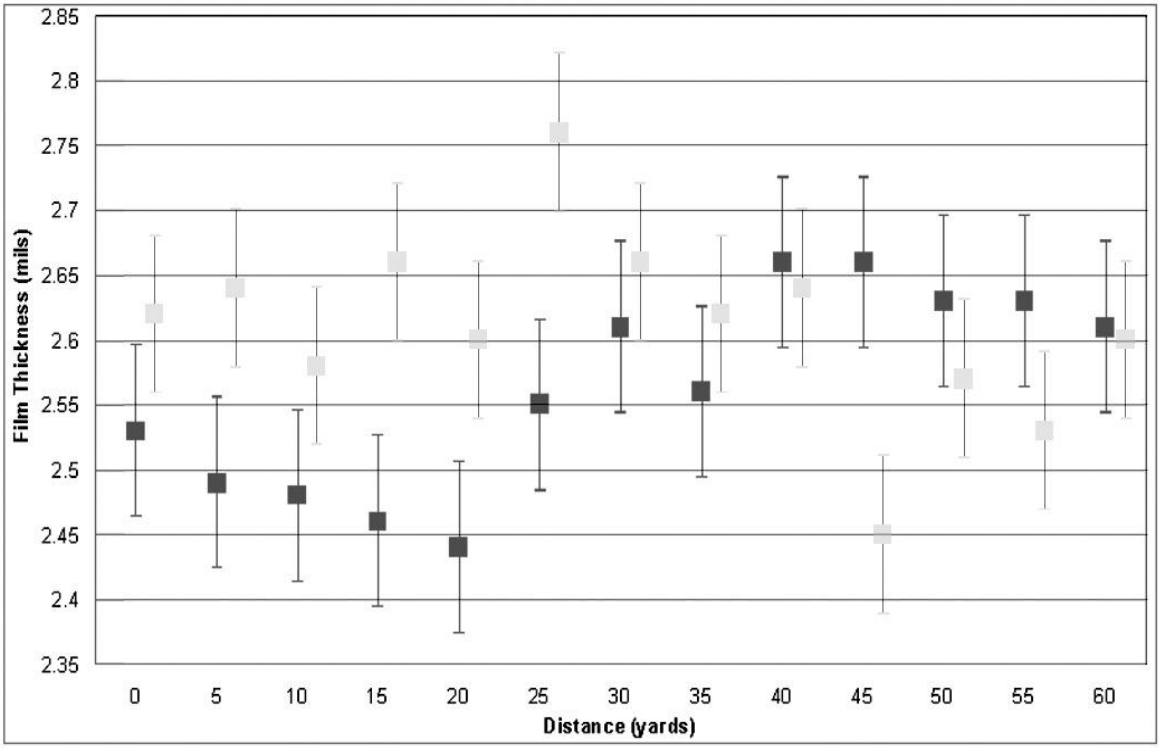

Figure 9 Individual 95% confidence intervals for mean film thickness as a function of location for two different individual rolls of tape from product M.

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