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Evaluation of Duct Tape Physical Characteristics: Part I – Within-Roll Variability *

ABSTRACT

Fifty-five rolls of duct tape, including tape from the four major tape manufacturing companies in North America [Berry Plastic Corporation, Shurtape, 3M, and Intertape Polymer Group (IPG)], were sampled at ten equally-spaced distances down the length of each roll. The 550 samples were randomly numbered to remove examiner bias and the following physical characteristics were measured and/or recorded: backing color, backing texture, adhesive color, total tape thickness, backing-only thickness, tape width, scrim pattern, scrim count, warp yarn offsets, number of backing layers, and backing layer structure. The variation of physical characteristics within a single roll was evaluated and tolerance levels were determined using Microsoft's Excel Software. The following tolerances are recommended based on their ability to include at least 95% / 99% of within-roll samples, respectively: total thickness ± 8% / 11%, width ± 0.09mm / 0.13 mm, scrim count ± 1 / 1, backing-only thickness ± 15% / 23%, and warp yarn offset ± 0.49 mm / 0.57 mm. Caution should be taken when comparing warp yarn offset values in questioned and known samples, as a high within-roll variation was seen. R Statistical Software was used to determine if any relationships exist between quantitative and non-quantitative physical characteristics; however, most non-quantitative physical characteristics did not have enough representation to evaluate these relationships. A statistically significant relationship was found between backing texture and backing-only thickness variations. When considered separately, to include

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at least 95% / 99% of within-roll samples respectively, the tolerance for backing-only thickness is ± 18% / 26% for smooth backings and ± 7% / 11% for dimpled backings.

Keywords: forensic science, trace evidence, duct tape, within-roll variability, physical characteristics

INTRODUCTION

When comparing duct tape samples in the forensic laboratory, examiners perform a battery of tests to determine the physical and chemical characteristics of the tape samples. Assessing physical characteristics is the first step in the tape comparison process which includes both macroscopic and stereomicroscopic observations such as color, thickness, width, and fabric reinforcement (a.k.a. scrim) construction [1]. These physical characteristics are easily observed and require little sample manipulation.

Yet in 2012, seven out of 49 respondents (roughly 14%) falsely eliminated either one or two questioned tape samples from the known tape sample provided in Forensic Testing Services' annual tape proficiency test. This test included three duct tape samples torn from the same roll. False eliminations were based on reported differences in physical characteristics such as warp yarn offset, width, scrim count, and scrim pattern [2].

At that time, the Scientific Working Group for Materials Analysis (SWGMAT) *Guideline for Assessing Physical Characteristics in Forensic Tape Examinations* stated "the analyst must decide what is within an acceptable tolerance" when determining if physical characteristics are consistent between questioned and known duct tape samples [3]. No values were provided in terms of expected or acceptable within-roll variability.

The 2013 revision of that SWGMAT document provided further guidance adding "[w]hen available, within-roll variances are best derived from a known roll submitted." Two alternative options were supplied as well. One alternative suggested assessing similar products to "gain insight into expected variances." The other alternative was to rely on approximate tolerances provided by duct tape industry representatives [4]. As cited by Mehltretter and Bradley, industry tolerances were reported for thickness (± 10%), width (± 1.0 mm), and scrim count (± 1) [5]. These were the first numerical guidelines provided, however, there were no research studies or published data to support these values. These tolerances, while helpful, were provided for only three of the roughly five numerical physical characteristics typically examined. Furthermore, given that "physical characteristics of a tape may change after removal from the original roll" [3, 4], manufacturer provided tolerances may not be what is seen in casework samples.

The 2013 and 2014 tape proficiency tests did not include duct tape [6, 7], though three of the six respondents which incorrectly eliminated electrical tape samples in 2013 cited some physical characteristic differences [6]. In 2015, three out of 48 respondents (roughly 6%) falsely associated two tape samples which originated from the same manufacturer, but were actually different duct tape products [8]. Over half of those respondents who got the right answer used color and chemical composition of the adhesives to differentiate the two tapes, though other physical properties were cited in smaller percentages (e.g., tape thickness 25%, tape width 20.8%, physical scrim characteristics 10.4%, and warp yarn offset 4.2%) [8]. In the 2016 tape proficiency test, 53 out of 54 respondents reported a correct association of two compared duct tapes with only one respondent reporting an inconclusive result due to chemical heterogeneity [9].

Forensic duct tape examinations include both physical construction and chemical composition comparisons. Research has shown variation in physical and chemical properties between duct tape products, manufacturers, and batches [5, 10, 11]. Although research has shown there are no significant within-roll variations in chemical composition, data which evaluates the variation of physical characteristics within a single roll is limited [11]. Within-roll variability is expected in physical characteristics but no research is available which addresses the extent of variability looking across a large number of tape rolls. Therefore, within-roll variation of duct tape physical characteristics was the sole focus of this research. Variation was not expected in all of the physical characteristics described, however, they were noted to determine if any relationships exist between the measurement variations and non-quantitative characteristics.

The physical characteristics measured and observed included those which were used for exclusion in the 2012 proficiency, as well as others commonly used for the analysis of duct tapes [4]. These were examined down the length of a single roll to determine to what degree they vary. Relationships between quantitative and non-quantitative characteristics were investigated to determine if any tolerances were affected by non-quantitative characteristic groupings.

MATERIALS AND METHODS

Duct Tape Collection

An attempt was made to acquire a wide variety of duct tape brands of varying qualities/grades from major retail stores including Home Depot, Lowe’s, and Walmart; however, only limited brands were available. Further samples were sought to encompass the four major tape manufacturing companies in North America—1) Berry Plastics Corporation, 2) Shurtape, 3) 3M, and 4) Intertape Polymer Group (IPG) [12]. Each of these manufacturing companies produces multiple brands of duct tape. For example, Berry Plastics Corporation manufactures Polyken and Nashua [2013 June 4 telephone conversation with Griffith K, Johnson of Berry Plastics Corporation] while Shurtape manufactures Shurtape, Ace, and Duck [12]. These brands are further divided into different qualities/grades such as utility, all-purpose, and industrial. As all of these manufacturers were not located in local retail stores, individual manufacturing companies were contacted and asked for assistance in acquiring products. All duct tape rolls acquired were new or had limited previous use. Furthermore, all duct tape rolls were of a nominal 48 mm width with a single-colored backing. Restricting the nominal width and backing color was expected to reduce the examiner bias during the analysis as it could not be determined which samples came from the same duct tape roll. A total of 55 rolls of duct tape were analyzed. The manufacturer, brand, and quality/grade of the 55 rolls of duct tape collected for this study are shown in Table 1.

Table 1: Duct tape roll manufacturer, brand, and quality/grade with corresponding roll number

Roll Number	Manufacturer	Brand	Quality/Grade
1	3M	Tartan	Utility- Bundling and Holding
2	3M	Scotch	Basic-Bundling, Patch, Protect & Repair
3	3M	Scotch	Repair, Decorate, Color Code
4	3M	3M	All-Purpose- Repairs In & Around the House
5	Berry	Gorilla	Incredibly Strong
6	3M	3M	TOUGH- Outdoor Tough
7	3M	3M	TOUGH- Contractor
8	3M	3M	TOUGH- No Residue
9	3M	Scotch	TOUGH- Extreme Hold
10	3M	Scotch	TOUGH- Pro Strength
11	3M	Scotch	TOUGH- Outdoor Painter's Clean Removal
12	Shurtape	Shurtape	All-Purpose
13	Shurtape	DUCT	-
14	IPG	IPG	#635 (AC 35)
15	Shurtape	T-REX	All Weather- Super Tough
16	Shurtape	Shurtape	#590
17	Shurtape	Shurtape	Color coding & repairs, #521
18	IPG	IPG	#620
19	Shurtape	Shurtape	Contractor, #575
20	IPG	IPG	#617
21	Shurtape	DUCK	Industrial, #721
22	Shurtape	DUCK	Ultimate- strongest, stickiest, most durable, #741
23	Shurtape	Shurtape	Industrial Grade, #618
24	Shurtape	Shurtape	-

25	Shurtape	MILSPEC	-
26	IPG	IPG	#629
27	Shurtape	DUCK	Standard
28	Berry	Tyco	-
29	IPG	IPG	#636 (J3020714)
30	IPG	IPG	#615 (AC 15)
31	IPG	IPG	#630
32	IPG	IPG	#615 (J3280632)
33	IPG	IPG	#607
34	-	DUCT TAPE	Tape-All (Made in USA)
35	3M	Tartan	Utility Duct Tape, #955
36	-	DUCT TAPE	(Made in China)
37	-	Seal-it	General Purpose (Made in China)
38	IPG	RUST-OLEUM	General Purpose (Automotive Ductape)
39	Shurtape	DUCK	Basic Strength (Made in China)
40	Shurtape	DUCK	Basic Strength (Made in U.S.A.)
41	Berry	Nashua	307 Utility Grade
42	Berry	Nashua	308 Utility Grade
43	Berry	Nashua	2280 Multi-Purpose
44	Berry	Nashua	300
45	Berry	Nashua	398
46	Berry	Polyken	203 Multi-Purpose
47	Berry	Polyken	223
48	-	Stanley	-
49	IPG	TALON	#606
50	IPG	IPG	Black
51	IPG	IPG	White
52	Shurtape	Shurtape	PE 609 Silver
53	Shurtape	Shurtape	PE 460 BULK
54	Shurtape	Duck	PE 595 Silver
55	Shurtape	Duck	PE 455 Silver

Berry = Berry Plastics Corporation; IPG = Intertape Polymer Group

Sample Preparation

The first 25 mm (~ 1 inch) of all new duct tape rolls was removed to simulate those that have been previously used. A total of ten samples were taken from the remaining length of each duct tape roll. The samples were 2.5 inches in length and evenly dispersed. In a few instances, circumstances prevented the collection of a sample at the appropriate distance, such as the tape folding onto itself during the unrolling process. In these instances, samples were collected as close as possible to the intended area.

Equation 1 shows the calculation performed to determine the spacing between samples. The first and last 25.4 mm (1 inch) as well as 10 times the length of each sample [63.5 mm (~2.5 inches)] were subtracted from the total length of the duct tape roll, which was taken from the manufacturer's label. This was then divided by 9 to determine the spacing between each of the 10 samples. Duct tape rolls that had been previously used only had the last 25.4 mm (1 inch) subtracted from the total length of the duct tape roll.

$$\text{Distance Between Samples} = \frac{\text{Length}-(2\text{x}25.4\text{ mm})-(10\text{x}63.5\text{ mm})}{9} \qquad \text{Equation 1.}$$

Previously used duct tape rolls or those that did not come with a manufacturer stated length were unrolled and measured to determine the overall length before sampling began. Samples were cut from the roll using a Bard-Parker® RIB-BACK® Carbon steel (no. 60) blade. Cut samples were placed onto a portion of a transparency film and numbered. Sample A was the first sample when unrolling a roll, whereas sample K was closest to the core. The letter "I" was not used to eliminate confusion with the number one. In addition, one edge of the duct tape sample was marked on the transparency film in relation to the machine direction for warp yarn offset orientation purposes. The 550 samples were re-assigned a random number by an impartial individual who removed the originally assigned number. The random numbers were generated using a number generating function in Microsoft Excel. This was done to avoid bias during measuring or recording of physical characteristics. The duct tape segments left behind were re-rolled onto a cardboard tube for storage.

Physical Characterization

The backing color, backing texture, and adhesive color were recorded for each sample. See Table 2 for the designations used. Subtle differences in backing sheen/luster or dimple arrangement were not accounted for. Early attempts were made to describe dimple shape due to claims that tape manufacturers could be recognized based on this feature [12], but those attempts were quickly abandoned due to the subjective nature, the tendency for inconsistencies, and the variability in shape within a sample. The adhesive color categories were based on the descriptors used in Smith 1998 [10] with some customizations. Other examiners may disagree with the color assignments used, however, consistency in application by a sole examiner was considered more important than color labels.

Next, the width of each sample was measured using a calibrated Mitutoyo Digital Caliper. Each sample was measured on the transparency film over a Shandon Scientific light box. The back lighting allowed for more accurate assessment of the caliper and tape edges. Three width measurements were taken per sample.

Table 2: Classification designations used for three characteristics

Physical Characteristic	Classifications
Backing Color	White, Gray, Dark Gray, or Black
Backing Texture	Smooth or Dimpled
Adhesive Color	Clear, Off-white, Light Gray, Gray, Dull Yellow, Brown, or Light Blue-green

The total tape thickness of each sample was also measured using the Mitutoyo Digital Caliper. The total tape thickness of duct tape is the combined thickness of the backing, scrim, and adhesive. A portion of the sample was pulled off of the transparency and three thickness measurements were taken per sample, from three adjacent sides. The total tape thickness was recorded after the width measurements to avoid distortion in the sample width caused by removal from the transparency. Furthermore, some samples required the total tape thickness be measured on the transparency, and the thickness of the transparency be subtracted to obtain the measurements, due to a large portion of the adhesive remaining on the transparency during sample removal.
The warp yarn offset was measured on both edges of the duct tape samples using the Mitutoyo Digital Caliper under an Olympus SZ-11 stereomicroscope (9x magnification). Warp yarn offset is the distance between the tape edge and the nearest scrim warp yarn (a.k.a. machine yarn or the nearest lengthwise yarn). Variation in this measurement may arise due to the scrim's flexible nature or if the scrim is at an angle during the manufacturing process. The entire length of each sample edge was viewed, and the measurement was taken from the region where the smallest warp yarn offset was observed. Some samples required limited adhesive removal with xylenes (Mallinckrodt, lot # 8671 KBMB) to visualize the scrim to obtain the measurement.

Based on literature recommendations, xylenes (xylene isomers plus ethylbenzene), toluene, and hexane were compared on extraneous duct tape pieces to see which was optimal for adhesive removal [3, 10]. The solvent requiring the least sample agitation and quick solvent removal was sought. Xylenes was selected because: (1) xylenes removed the adhesive as well as toluene, (2) unlike toluene, xylene was listed in SWGMAT's Guideline for Assessing Physical Characteristics document [3] , and (3) unlike hexane, xylenes did not require sonication [13].

Next, the scrim pattern and scrim count were recorded for each sample using an Olympus SZ-11 stereomicroscope (9x magnification). The scrim pattern describes how the scrim was constructed. The structure of the scrim pattern along with the composition of the fibers influences the effort necessary to hand-tear the tape [13]. Scrim count is the number of yarns per inch in each of the opposing directions [13]. Approximately three quarters of each sample was removed from the transparency with a Bard-Parker® RIB-BACK® Carbon steel (no. 60) blade. The majority of the samples required adhesive removal to view the scrim pattern. This was accomplished by dabbing with KimWipes® using xylenes. The overall scrim pattern was recorded as well as the appearance of the machine and fill fibers/yarns (textured, twist direction, filaments, etc.). The scrim count was determined by placing a VWR Scientific Products 6" ruler over each sample to measure the number of machine yarns in one inch and the number of fill yarns in one inch.

The sample portion cut from the transparency was then placed in a beaker of xylenes for full adhesive removal. The samples were removed from the beaker and allowed to fully dry. The thickness of the backing alone was measured with a Mitutoyo Digital Caliper. Three backing-only thickness measurements were taken per sample, from three adjacent sides. From the portion of backing where the adhesive was removed, cross-sections of the tape backing were cut manually using a no. 11 scalpel blade and aerosol duster propellant (Dust-Off®) to temporarily freeze the sample. Cross-sections were viewed using a Leica CFM2 compound microscope (100x and 200x) and the number of backing layers present and the relative layer structure (e.g., inclusion density, relative layer thicknesses, layer color) were described.

RESULTS AND DISCUSSION

Quality Check

A qualified tape examiner (i.e., examiner 1) was asked to record the backing color, backing texture, adhesive color, total tape thickness, tape width, and backing-only thickness of 20 randomly chosen samples. Comparing these values to the primary researcher's values served as a quality check. No inconsistencies were found between the researcher and the qualified tape examiner. The physical characteristics of scrim count, scrim pattern, and warp yarn offsets could not be recorded by the qualified tape examiner, as the remainder of the original sample was less than a one inch by one inch section.

In the interest of time, a second qualified tape examiner (i.e., examiner 2) assisted the primary researcher with tape backing cross-sectioning. Forty samples were cut by both the researcher and examiner to serve as quality checks. Once again, in order to minimize bias, a qualified tape examiner (i.e., examiner 1) unfamiliar with the samples cut cross-sections of 20 samples. Discrepancies were anticipated due to the inexperience of the primary researcher in both cutting of difficult flexible tape backings as well as recognizing layers microscopically. Two discrepancies were found in the quality check samples. Discrepancies were re-checked by both the researcher and a qualified tape examiner (i.e., examiner 2) together and resolved by reaching a consensus which was consistent with the expected result.

Preliminary Data Review

Following all data collection and revelation of sample/roll identities, inconsistencies were found, for example, where one or two samples within a roll had a large deviation from the other roll's samples. It was unknown whether these inconsistencies were true variation or merely typographical errors. Therefore, for each roll, the mean and standard deviation of all measured characteristics were calculated. For example, with 10 samples per roll and three measurement repetitions per sample, there would be 30 measurements for one roll for a single characteristic from which the mean was calculated. All individual sample measurements falling outside of the mean ± 2 times the standard deviation (2σ) were flagged. Therefore, from the previous example, if any of the 30 measurements fell outside of the mean +/- 2σ, it was flagged. The number of measurements falling outside of the mean ± 3σ was also determined, however, this led to a substantial decrease in the amount of samples flagged. Therefore, a more conservative approach using ± 2σ was utilized.

A total of 126 samples out of 550 were flagged when checking total tape thickness, backing-only thickness, and tape width. All three physical characteristics were re-measured to prevent the primary researcher, in the absence of the previous data, from knowing which characteristic was flagged. The sample remaining on the transparency sheet and the backing sample with adhesive removed were used to re-check measurements. The re-measured values were compared to the original measurements. If one of the three original replicate values was determined to be a typographical error, it was deleted. If all three of the replicate values were determined to be typographical errors, all three of the values were replaced with the re-measured values. Preference was given to the originally collected data when possible. A total of nine samples, 17 measurements, were found to have extreme typographical errors (see Table 3). All of these extreme typographical errors occurred in the first or second decimal places. The percent of samples with extreme typographical error for thickness, width, and backing-only thickness was calculated to be 0.34% [(17 measurements with typographical errors/4950 total measurements)*100%]. No typographical errors were found in backing-only thickness measurements.

A total of nine samples were flagged when checking warp yarn offsets. Using the sample that remained on the transparency sheet, both edges (top and bottom) warp yarn offset values were re-checked to prevent bias as to which measurement was of concern. If the original and re-checked values were inconsistent, the original value was deleted. Variation could not be properly rechecked because the majority of the original sample had since had the scrim removed. Deletion, rather than replacement, was chosen as the recourse for warp yarn offset typographical errors due to the inability to recheck with the original sample and to be consistent with the treatment of single-value inconsistencies found in the width and thicknesses. A total of five samples or measurements were found to have extreme typographical errors (see Table 4). The deletion of these measurements left nine values along the length of these five duct tape rolls for variation analysis. The percent of samples with extreme typographical error for warp yarn offsets was calculated to be 0.45% [(5 measurements with typographical errors/1100 total warp yarn offset measurements)*100%].

Table 3: Samples with extreme typographical errors for width and total tape thickness. Values in red are original recorded measurements found to be extreme typographical errors, and were deleted.

Assigned Random Number	Roll/Sample Number	Physical Characteristic	Measurement Number (inches)		
			1	2	3
293	55K	Width	1.9220	1.9220	1.2300
327	09A	Width	1.8845 (1.8750)	1.8840 (1.8760)	1.8835 (1.8760)
385	39A	Width	1.8525	1.8630	1.8625
386	25J	Total tape thickness	0.0120 (0.0025)	0.0130 (0.0030)	0.0125 (0.0030)
392	29J	Total tape thickness	0.0095 (0.0010)	0.0095 (0.0010)	0.0095 (0.0010)
471	11C	Total tape thickness	0.0090	0.0085	0.0950
501	08J	Total tape thickness	0.0011	0.0105	0.0105
567	22G	Total tape thickness	0.0155 (0.0055)	0.0155 (0.0055)	0.0155 (0.0055)
592	04D	Total tape thickness	0.0077*	0.0070	0.0075

*typographical error known as caliper measurements only end in a 0 or 5

Table 4: Samples with extreme typographical errors for top and bottom warp yarn offsets

Assigned Random Number	Roll/Sample Number	Physical Characteristic	Initial Measurement (inches)	Re-Measurement (inches)
18	17A	Warp Yarn Offset-Bottom	0.1450	0.0130
115	19H	Warp Yarn Offset-Bottom	0.0365	0
116	12H	Warp Yarn Offset-Top	0.0370	0
327	09A	Warp Yarn Offset-Bottom	0.0045	0
458	55B	Warp Yarn Offset-Top	0.0435	0

Inconsistencies were anticipated in the number of backing layers within a roll, and therefore, were handled a little differently. All discrepancies found in the number of backing layers, 33 in total, were flagged and rechecked by both the researcher and a qualified tape examiner together.

With the large number of recorded measurements, data was recorded directly into a Microsoft Excel worksheet. This electronic-only approach is not recommended for future research purposes, as there is a risk for typographical errors. Electronic-only entry may be a concern for laboratories with paperless Laboratory Information Management Systems (LIMS), however, typical casework does not include such an extensive amount of samples. To minimize typographical errors, numbers should be double-checked if entered electronically.

Non-Quantitative Physical Characteristic Within-Roll Variation

As anticipated, the backing color and backing texture did not show variation along the length of each duct tape roll. Similarly, no variation was found in the number of backing layers or backing layer structure along the length of a roll. Though the number of backing layers is quantitative in nature, no tolerances are appropriate given the lack of variation.

Differences in adhesive color, however, were seen along the length of five rolls. Roll numbers 12, 16, 19, 23, and 24 were found to have one or more samples which varied in adhesive color (see Figure 1). Roll 16's adhesive varied from light gray to off-white, whereas rolls 12, 19, 23, and 24 varied between light gray and dull yellow. For four of the five rolls, a side-by-side comparison of the roll's 10 samples confirmed slight differences between adhesive colors. In the remaining roll, number 16, the side-by-side comparison of the roll's 10 samples revealed the adhesive color did not vary, but the color assignment did. This may have been caused by a lack of safeguards to prevent examiner eye fatigue which can alter the examiner's color perception when viewing a high number of samples consecutively [14]. Examiner eye fatigue is usually not a concern in forensic casework due to a lower number of samples needing assessment. As slight adhesive color differences were verified in four rolls, differences found in casework samples may be caused by contact with materials, exposure to environmental conditions, or due to within-roll adhesive color variation. Therefore, caution should be exercised when disassociating duct tape samples due to slight adhesive color differences.

Common scrim patterns of plain weave and weft insertion were observed along with two scrim patterns that were previously unfamiliar. One pattern, present in three IPG tape rolls, exhibited chain-stitched machine yarns which would intermittently crisscross with neighboring yarns (see Figure 2). The other pattern, found in two IPG tape rolls, exhibited neighboring textured fill filaments which appeared unequally sized and out of place (see Figure 3). Upon contacting IPG, they identified Milliken as the scrim manufacturer for each of the unfamiliar scrim patterns. A Milliken representative identified the scrim patterns in language the tape industry uses. The crisscross pattern occurs when a series of chain stitches are followed by a tricot stich, where yarns shift over at a preset pattern. The tricot scrim pattern, as of 2014, was manufactured in only one configuration. The other new scrim pattern is known to the industry as paired picks. The Milliken representative reported paired picks as being unintentional and due to tension. It is a "common phenomenon [referred] to as 'railroading', meaning the weft ends pull together so that the fabric actually appears to have railroad tracks in it" [2013 July 30 email conversation with David Martin, Milliken Representative].

(a)

(b)

(c)

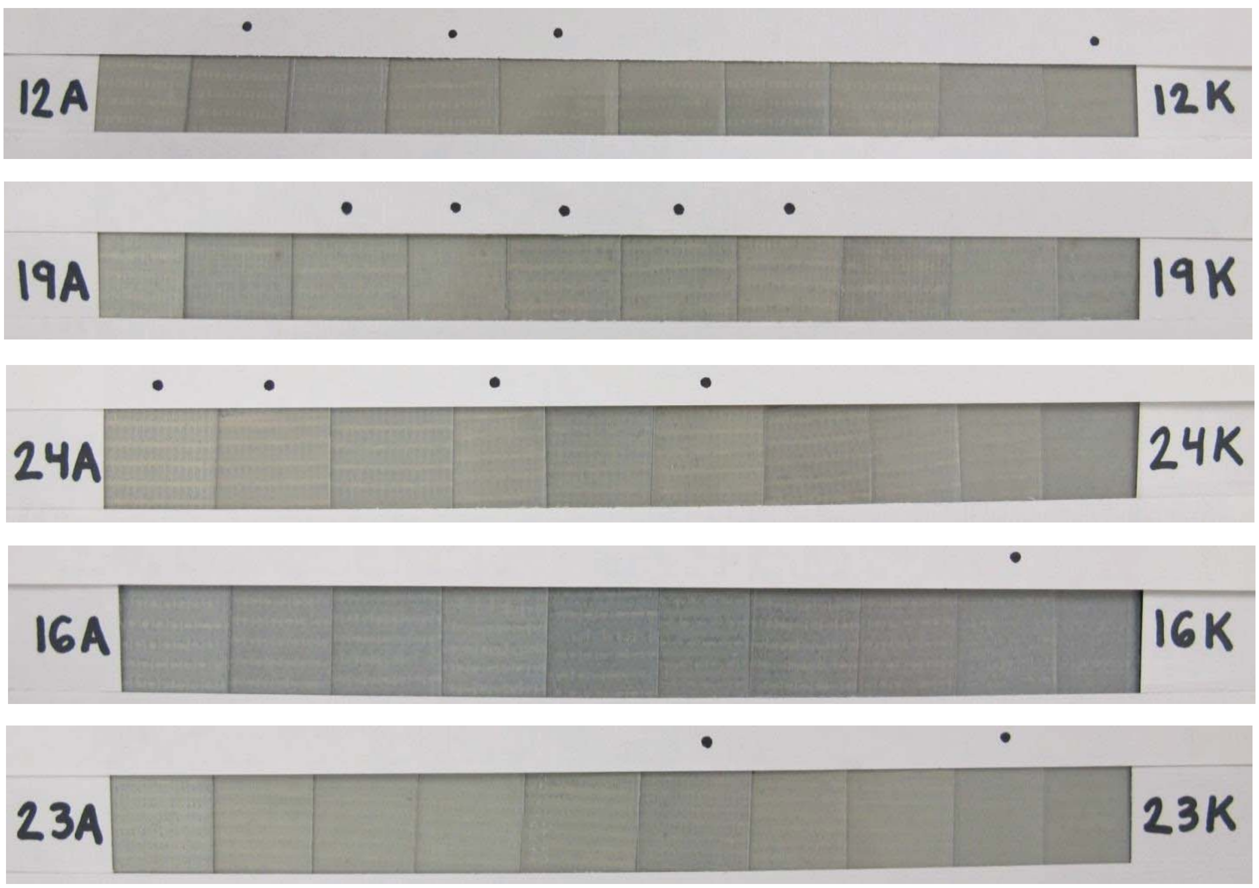

Figure 1: Side-by-side adhesive color comparison of within-roll samples recorded as having differences in adhesive color. (a) For Rolls 12, 19, and 24, marked samples were classified as having dull yellow adhesive while all others were classified as light gray. (b) For Roll 16, the marked sample was classified as having light gray adhesive while all others were classified as off-white. The difference in adhesive color classification for Roll 16 was not confirmed when the samples were viewed side-by-side. (c) For Roll 23, marked samples were classified as having light gray adhesive while all others were classified as dull yellow.

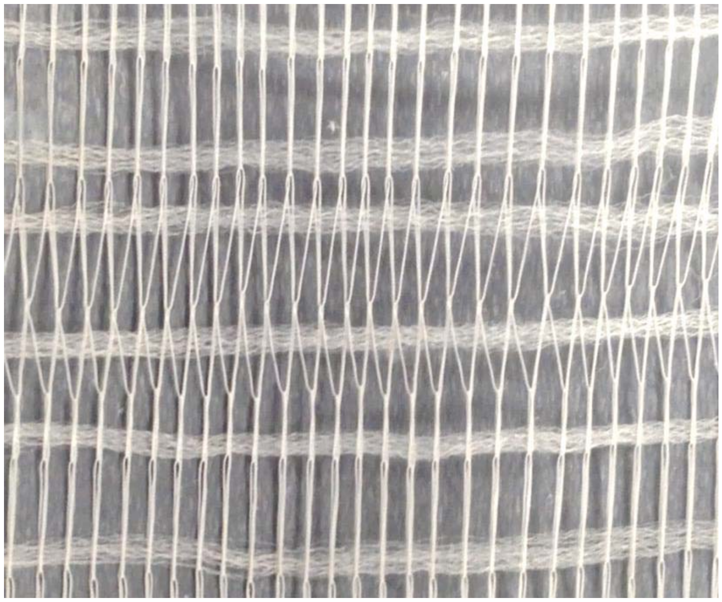

Figure 2: Tricot scrim pattern in IPG duct tape rolls 32, 33, & 38. (machine = ⇃↾, fill = ⇆).

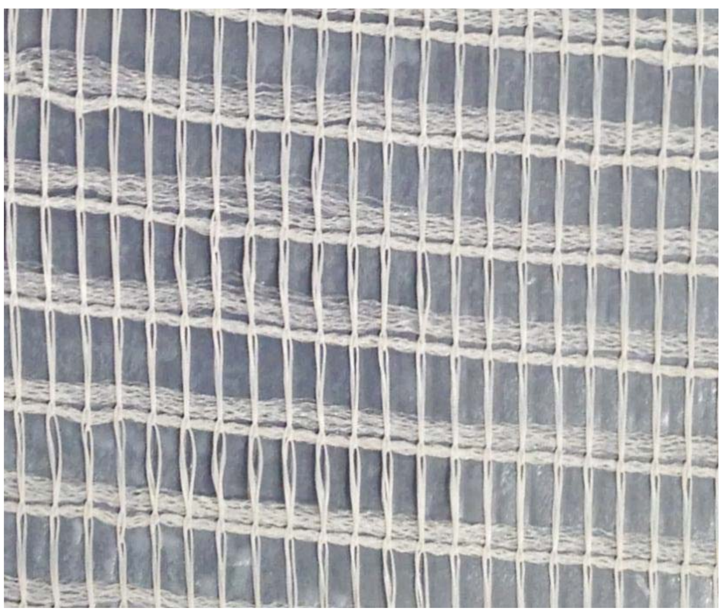

Figure 3: Paired picks scrim pattern IPG duct tape rolls 29 and 31. (machine = ⇃↾, fill = ⇆).

Within-roll variation in the scrim pattern was not expected, but was recorded for one duct tape roll, number 38. Upon further examination, this roll did not have a change in scrim pattern along the length of the roll, but rather the scrim pattern was not recognized. Roll number 38 exhibited the crisscrossed scrim pattern (chain and tricot stitches), however, some of the samples were misidentified as weft insertion scrim pattern (solely chain stitched machine yarns). This was most likely due to the distance between tricot stitches. The length of the tricot stitch was measured to be approximately 11 mm or ½ inch. The end of one tricot stitch to the beginning of the next tricot stitch was measured to be approximately 30 mm or 1.18 inches. Therefore, it was possible to clear adhesive from a one inch by one inch area on the sample and only observe chain stitches.

Although the paired picks scrim pattern is created unintentionally, it is important to note that this pattern stayed consistent for the length of the three IPG duct tape rolls. The tricot scrim pattern was also consistent along the roll; however, it is more likely for the tricot stitch to be missed. One way to prevent misidentification is to clear adhesive from an area larger than one inch by one inch to ensure the exposure of a tricot stitch. If this type of scrim pattern is unrecognized by the examiner, it may lead to a false elimination between questioned and known duct tape samples.

Quantitative Physical Characteristic Tolerance Levels

Microsoft® Excel was used to evaluate tolerance levels for the expected within-roll variation in duct tape rolls. Trial tolerance values were added to and subtracted from the quantitative physical characteristic measurements, for each of the 10 samples within a roll. The sample values from within a single roll would then be evaluated for range overlap. The trial tolerance level would be decreased or increased accordingly until a tolerance level was found that would include at least 95% of within-roll samples. Tolerances were also calculated for inclusion of at least 99% of within-roll samples[3]. The variation of each quantitative physical characteristic within a single roll was evaluated and tolerance levels were determined. A percentage tolerance for total tape thickness and backing-only thickness was determined while a whole number value tolerance was determined for width, scrim count, and warp yarn offset. This format was consistent with the format of the industry representative values for comparison purposes. See Table 5 for comparison between the recommended tolerances supported by this research versus the industry tolerances.

The minimum and maximum tolerances possible were also determined for the quantitative physical characteristics. Table 6 shows the minimum and maximum tolerance levels that correspond to the duct tape rolls with the least and most amount of within-roll variation, respectively. Duct tape rolls requiring the maximum tolerance

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[3] With 55 rolls and 10 samples per roll, there were 2475 within-roll comparisons. The number of comparison pairs per roll $= \frac{n(n-1)}{2}$, where n = the number of samples [15]. Therefore, per roll there were 10x9/2 = 45 comparison pairs x 55 rolls = 2475 total comparison pairs. The number of comparison pairs would be less if values were deleted due to typographical errors. Tolerance levels were sought that included at least 95% or 99% of the total number of comparison pairs.

levels to encompass 95% and 99% of within-roll samples for the physical characteristics included a mixture of lower and higher quality tapes and were not specific to a particular manufacturer. For the rolls which exhibited the least amount of variation, the same tolerance which would include 95% of samples within-roll would also include 99% of samples. Additionally, large variation in one physical characteristic did not equate to that roll having large variations in other physical characteristics.

Table 5: Tolerances recommended to include an average of 95% or 99% of within-roll samples supported by this research versus industry tolerances

Physical Characteristic	**This Research**		**Industry Tolerances [4]**
	95%	**99%**	
Total thickness	± 8%	± 11%	± 10%
Width	± 0.09 mm	± 0.13 mm	± 1.0 mm
Scrim count	± 1	± 1	± 1
Backing-only thickness	± 15%	± 23%	-
Warp yarn offset	± 0.49 mm	± 0.57 mm	-

Table 6: Rolls which exhibited the most and least variation and the respective tolerance level necessary to encompass 95% and/or 99% of within-roll samples for the physical characteristics

Physical Characteristic	**Minimum**		**Maximum**	
	Roll Number(s)	**Tolerance Level (±) (including at least 95% and 99%)**	**Roll Number**	**Tolerance Level (±) (including at least 95% / 99%)**
Total tape thickness	52	2%	2	16% / 24%
Width	46	0.03 mm	36	0.20 mm / 0.23 mm
Scrim count	in 27 of 55 rolls	0	15	2 / 2
Backing-only thickness	22	1%	38	31% / 39%
Warp yarn offset	8, 22, and 25	0.23 mm	28	0.63 mm* / 0.64 mm
			37	0.59 mm / 0.69 mm*

** Roll 28 required a higher tolerance to include at least 95% of within-roll samples, while roll 37 required a higher tolerance to include at least 99% of within-roll samples. Therefore, the maximum tolerance for warp yarn offset to include at least 95% of within-roll samples is ± 0.63 mm (roll 28), and the maximum tolerance for warp yarn offset to include at least 99% of within-roll samples is ± 0.69 mm (roll 37).*

Due to the wide variation seen in the warp yarn offsets, it is suspected that this is not a valuable characteristic to compare between questioned and known tape samples with regard to eliminations. The nearest scrim yarn crossed the tape edge in 54 out of 55 rolls. The data seems to support little value to warp yarn offset tolerances, though it is acknowledged that this characteristic will certainly be of greater value during physical fit examinations.

In casework, measuring the width of duct tape pieces using calipers over a light box is generally not feasible without extensive manipulation. Measuring width of flexible tape pieces using calipers alone is also impractical in most cases. Therefore, a tolerance for width was sought using simulated ruler measurements. Using Microsoft® Excel, each measured width value was rounded to the nearest ½ mm. If the decimal value was greater than or equal to half of 0.5 mm (i.e., 0.2500 mm), the number was rounded up. For example, 47.2567 mm was rounded to 47.5 mm. Using the simulated ruler measurements, a ± 0.05 mm tolerance was calculated and found to include 100% of the samples.

Cited by Mehltretter and Bradley, they list approximate guidelines for expected within-roll variability for thickness (± 10%), width (± 1.0 mm), and scrim count (± 1) [5]. In comparison, this research has provided data that distinguishes total tape thickness and backing-only thickness as needing separate tolerance levels, supports a lower tolerance level for width (± 1.0 mm vs. ± 0.09 mm for 95% inclusion, ± 0.13 mm for 99% inclusion or ± 0.5 mm for ruler measurements), and agrees only with regards to the scrim count tolerance.

Relationships Between Physical Characteristics

R Statistical Software was used for statistical computing to determine if any relationships exist between the quantitative and non-quantitative physical characteristics. Backing texture was the only non-quantitative physical characteristic with enough representation in each category to thoroughly evaluate for relationships (see Table 7). A single factor Analysis of Variance (ANOVA) was performed for smooth and dimpled backing textures against the quantitative physical characteristic measurement variations. A statistically significant relationship was found between backing texture and backing-only thickness (p-value = 0.001955), as seen in Table 8. Smooth backing duct tapes have a greater within-roll variation of backing thickness than that of dimpled backing duct tapes. If considered separately, to include at least 95% of within-roll samples, the tolerance for backing-only thickness was found to be ± 18% for smooth backings and ± 7% for dimpled backings. To include at least 99% of within-roll samples, the tolerance for backing-only thickness was found to be ± 26% for smooth backings and ± 11% for dimpled backings. No statistically significant relationships (those with a p-value ≤ 0.01) were found between backing texture and any of the other six quantitative measurement variations.

Table 7: Non-quantitative physical characteristic representation

Physical Characteristic	Categories	Number of Rolls in Category
Backing color	Black	5
	Dark gray	4
	Gray	44
	White	2
Adhesive color	Clear	7
	Off-white	7
	Light gray	14
	Gray	4
	Dull yellow	14
	Brown	8
	Light blue-green	1
Backing texture	Smooth	30
	Dimpled	25
Scrim pattern	Plain weave	38
	Weft insertion	12
	Tricot	3
	Paired Picks	2
Number of Backing Layers	1	10
	2	18
	3	27

Table 8: P-values yielded from the ANOVA performed to determine if differences in physical characteristic measurement variations existed between smooth and dimpled backing textures. Those with a p-value of less than 0.01 are considered to have a statistically significant relationship.

Physical Characteristic	P-value
Total tape thickness	0.5854
Width	0.1067
Scrim Count-Machine	0.05473
Scrim Count-Fill	0.1019
Backing-only thickness	0.001955
Warp Yarn Offset-Top	0.4259
Warp Yarn Offset-Bottom	0.3010

The number of rolls with a single backing layer may not be considered sufficient to thoroughly evaluate the number of backing layers for relationships with the quantitative characteristics, but it was attempted nonetheless. A single factor ANOVA was performed to determine if differences in measurement variations existed between 1-, 2-, and 3-layered backings. No significant relationships were present, as no p-values were less than 0.01 (see Table 9).

Table 9: P-values yielded from the ANOVA performed to determine if differences in physical characteristic measurement variations existed between 1-, 2-, and 3-layered backings. Those with a p-value of less than 0.01 are considered to have a statistically significant relationship.

Physical Characteristic	**P-value**
Total tape thickness	0.5043
Width	0.3679
Scrim Count-Machine	0.8559
Scrim Count-Fill	0.9477
Backing-only thickness	0.9401
Warp Yarn Offset-Top	0.3740
Warp Yarn Offset-Bottom	0.5533

CONCLUSION

Eleven physical characteristics were measured and/or recorded for 550 duct tape samples from 55 duct tape rolls. No within-roll variability was found for backing color, backing texture, scrim pattern, number of backing layers, or backing layer structure. Care should be taken when evaluating scrim pattern. It is advised that an area slightly greater than one square-inch be uncovered to ensure the observation of tricot stitches, if present. Caution is also emphasized when comparing duct tape adhesive colors as within-roll variation was found and visually confirmed. Furthermore, the early failed attempts to record dimple shape/arrangement suggest that this characteristic should not be used in the comparison of question and known duct tape samples unless more extensive research is performed.

The results suggest that warp yarn offset should not be used during tape comparisons due to the high within-roll variability seen. Warp yarn offset is a property worth noting during physical fit examinations only. A statistically significant relationship was found between backing texture and backing thickness where smooth tape backings were found to have a greater backing thickness within-roll variation than that of dimpled tape backings. The following tolerances provide a reference for examiners as to the expected variability down the length of a tape roll:

Average % of within-roll samples included:	95%	99%
Width	± 0.09 mm	± 0.13 mm
* width, if using a ruler	± 0.5 mm	± 0.5 mm
Total thickness	± 8%	± 11%
Backing-only thickness	± 15%	± 23%
* backing-only thickness, smooth backed	± 18%	± 26%
* backing-only thickness, dimple backed	± 7%	± 11%
Scrim count	± 1	± 1

These tolerances will assist in evaluating the significance of physical property differences found within duct tape samples. When applied to casework, if the questioned and known measurements overlap when adding/subtracting these tolerances, physical characteristics cannot differentiate the items and chemical composition comparison should be completed. However, condition of casework samples should be considered before applying the above tolerances. The intention is that the consideration of these tolerances may prevent false eliminations or associations during the evaluation of duct tape samples both in proficiency tests and casework. The possibility of variation in excess of the provided tolerances, however, supports that within-roll variances are best derived from a known submitted roll, when available. Further statistical analysis with this dataset will allow for the determination of the discrimination ability of each physical characteristic and for duct tape physical characterization cumulatively. This work revealed the additional need for within-roll variability assessments for other types of tape commonly encountered in forensic casework such as electrical tape.

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