

ANALYSIS OF COATINGS APPEARANCE AND DURABILITY-TESTING-INDUCED SURFACE DEFECTS USING IMAGE CAPTURE/PROCESSING/ANALYSIS

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ABSTRACT

This paper describes the applicability of optical imaging techniques to the analysis of the scratch resistance of automotive interior plastic materials. The evaluation of so-called "finger testing" has traditionally relied upon human vision for detection of the initial scratch position. Commonly performed under uniform and defined illumination conditions, the relative contrast difference signified by whitening on a surface as determined by unaided human vision is a highly variable subjective perception; thus individual inspectors may determine the "whitening" point differently. This paper compares test data obtained from both visual and instrumental evaluation methods and discusses the advantages of optical imaging techniques for surface defect analysis.

INTRODUCTION

The resistance of automotive interior plastics to permanent, visible damage by scratching is a significant concern during the manufacturing of such components as well as during the life of the product. Plastics manufacturers are constantly striving to develop formulations that provide enhanced scratch resistance as well as long-term durability under end-use conditions. To determine the performance of these polymeric materials, test methods have evolved for scratching a test sample surface in a repeatable manner with specialized apparatuses. Scratches so obtained are then visually evaluated to characterize the damage with respect to the test conditions. Formulations are then ranked according to their resistance to damage.

Test methods for producing simulated damage in molded or extruded plastic substrates involve the application of a scratching device (stylus, finger or indenter) to a specimen. The scratching device traverses the surface of the specimen to produce single or multiple

scratch channels. The test method applied to create the test samples used for this paper, SCRATCHO 155°F-3-finger, prescribes dynamic loading of the scratching device, wherein the load weight of the scratching head increases as the head travels across the sample surface [1]. This results in scratch channels that begin with a faint appearance (elastic-plastic deformation of the test surface) and then become easily visible as a whitened streak after fracture (micro cracking of the test surface) starts to occur. This starting point is referred to as the "first whitening." Since the portion of the scratch channel exhibiting fracture is neither self-healing over time nor reversible through restorative means, this damage is considered permanent and is used as the key qualitative factor in the evaluation of the specimen's scratch resistance.

Traditionally, the starting point of the whitened scratch channel has been determined by visually inspecting the test sample. Since the loading rate of the scratching device is linear, an accurate load value may be calculated by simply measuring the distance of the first whitening from the starting point at which the scratching fingers were applied. But the determination of these two points on the specimen is influenced by the subjective visual and perceptual biases of the person conducting the evaluation; thus introducing variability in test results between operators that cannot be controlled or factored out. It will be shown in this paper that the evaluation of scratch-tested specimens with an automated optical imaging and analysis system provides numerous, important advantages over traditional visual evaluation techniques. These include consistently repeatable test results that derive from reproducible diffuse lighting conditions, image magnification, image enhancement for optimal scratch detection and automated functions such as: image capture/enhancement, determination of finger load values and digital data recording. Scratch test evaluation results generated by the VIEEW™ Digital Image Analyzer are presented here and

are compared to visual evaluation results to substantiate the claim of these advantages. VIEEW™ is a relatively new technology with capabilities for evaluating automotive exterior coatings defects such as chipping, marring, corrosion, and appearance that also can be applied to the evaluation of the scratch resistance of molded and extruded plastics [2-7].

GENERAL ASSESSMENT OF THE APPLICABILITY OF OPTICAL IMAGING TO SURFACE DEFECT EVALUATION

The human eye is an unparalleled organ that allows us, in one moment, to count the stars in the sky and in the next, the spots on a ladybug clinging to our fingertip. Yet the eye is not without serious limitations in its perception of the physical world. Despite these limitations, we have grown to depend on its capabilities in the evaluation of surface defects in a wide variety of manufactured materials.

The human eye, coupled with the subjective judgment of a material inspector, determine the surface quality levels that are acceptable in raw materials and finished goods. Where visual perception is lacking in acuity, or conscious judgment is incapable of quantifying a large number of physical surface defects, pictorial references are employed for general comparison to allow a classification of the severity of a sample's defects. This technique has admirably compensated for our visual limitations, but has come at the cost of questionable repeatability and, with its inherent subjectivity, includes the perceptual and psychological biases of the observer.

While this methodology has sufficed throughout the history of industrialization, revolutionary advances in photographic, video imaging and computer technology have originated precision tools for minimizing subjective, human influences and for automating inspection procedures; the repetitiveness and laboriousness of which can also diminish human performance through fatigue. The VIEEW™ digital image analyzer, developed by Atlas Electric Devices Company, is an integration of these modern technologies. It is capable of capturing digital images of samples under various lighting schemes optimized for the sample surface, of digitally processing the images to highlight and enhance surface defects, and of measuring and counting defects such that each sample is defined by a comprehensive statistical profile. This process may also be applied to graded reference samples and stored on disk, ultimately allowing a classification of test samples by automatic, statistical comparison to the reference data. Thus the basic, historical evaluation method is preserved, but is automatically performed by precision optics and software analysis algorithms at the press of a button.

VIEEW™ OPTICAL IMAGING SYSTEM – SPECIMEN ILLUMINATION – The technique used to illuminate a sample is of critical importance in optical

imaging since it is the reflected light that is detected by an imaging sensor. Light source spectrum and angle of incidence on the sample surface are key factors in determining what can be optically detected and captured. In the VIEEW™ system, distinctly differing illumination geometries are applied to achieve optimal illumination under two schemes: diffuse, chromatic (color) lighting for the detection of variations in tonal and chromatic contrast; and direct lighting to measure variations in geometric reflection (specular reflection) and its textural characteristics.

Diffuse illumination – To accurately measure surface abnormalities resulting from chromaticity, or color difference, the sample should be illuminated by a diffuse chromatic source where each color component (Red, Green and Blue, or RGB) may be independently adjusted to maximize contrast on the sample surface. Optimal light diffusion is obtained by mounting the light source(s) inside an integrating sphere (a spherical cavity); the interior walls of which are treated with a high-reflectance coating to maximize reflection and scattering, as shown in Figure 1. Light emitting diodes (LEDs) are suitable light sources for use inside the sphere for their output stability, reliability and compact size. As used for the investigation of scratch resistance of plastics described in this paper, an optimally adjusted, diffuse illumination can enhance surface characteristics that are created by differences in chromaticity, as in the “first whitening” effects.

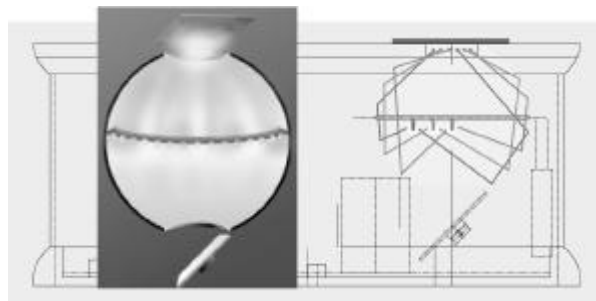


Figure 1. VIEEW™ Diffuse Illumination

Direct illumination – The most accurate measurement of the reflectance, or gloss, of a surface (which also reveals surface irregularities such as scratches, chips, orange peel, etc.) is made when light strikes the sample normal to its plane at an incident angle of 0°. Light striking an optically smooth surface under these conditions will be reflected back at 0°, but light striking an uneven or textured surface (surface with defects) will be reflected at angles other than zero; and, in effect, will be lost to the detector of the camera which is viewing the sample at a 0° angle. See Figure 2. This results in very smooth surfaces appearing as a uniform light gray and the irregularities being revealed as significantly darker areas; or in the case of scratches, as distinctly dark lines. An example of this beneficial phenomenon is shown in Figure 3. It is important to note

that the unaided human eye is incapable of perceiving an object or surface with an illumination incident angle of θ as it would require a light source emanating from the center of the ocular pupil.

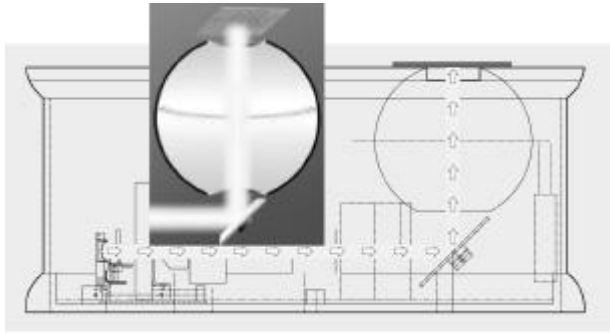


Figure 2. VIEEW™ Direct Illumination

Direct illumination further reveals its advantages with coated samples where defects are limited primarily to a clear topcoat layer. In this sample topology, light is reflected only from the surface of the clear coating and not from the deeper pigmentation layer, which is of no interest when the defects are produced by physical testing such as chipping, marring, or chemical and environmental exposure of the exterior layer.

The VIEEW™ system incorporates both of these illumination schemes, independently or in combination, to allow a comprehensive detection of surface defects. It is not uncommon for samples to be photographed under both lighting techniques to allow evaluation of more than one type of degradation mechanism exhibited by the sample. Illumination conditions are computer controlled and precisely repeatable since the final control-setting scheme may be named and saved as a setup file. This feature ensures reproducible evaluation conditions and repeatable results.

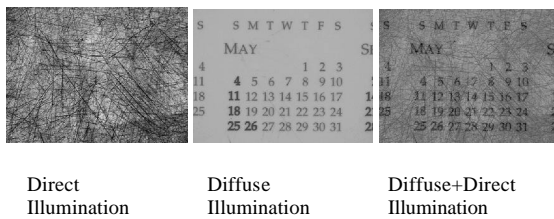


Figure 3. Selective Viewing of Laminated Surface Structure using VIEEW™ Direct/Diffuse Illumination

SOFTWARE ANALYSIS OF A DIGITAL IMAGE - BINARY AND GRAYSCALE IMAGES - In the computerized analysis of surface defects, two categories predominate: defect characterization and surface texture properties. The former category includes defect size, shape and distribution while the latter entails a determination of

the change in surface appearance (texture). Analysis software exploits two different image types to perform these characterizations and determinations: binary (or 2-bit black and white) images and grayscale images.

Binary Image Analysis - Binary images are created by processing the original 256-shade grayscale image with a thresholding filter that reduces the image to black and white pixels. A variety of different thresholding techniques, either in spatial domain or in frequency domain, are used to determine the proper settings that allow the image to retain optimal defect information while eliminating those pixels of the unaffected areas. Additional processing steps may be employed to further refine the area of interest before or after the thresholding procedure. The analysis program then applies special measurement and analysis algorithms to the black-on-white defects of each sample and records defect quantities and their geometric parameters in an associated statistical file. Typical parameters used in this type of analysis are defect count, size, shape, area, orientation, boundary analysis, gravity center analysis, Fourier shape analysis, etc.

The spatial formations (distribution over the sample surface) of the defects are also of importance in some applications since spatial characteristics can be related to physical and mechanical properties of the sample as well as to material processing. Parameters used for spatial analysis are spatial distribution by quadrant, nearest neighbor statistics, spatial variance and spatial density based on random points.

Typical examples of binary image analysis in coatings applications are: corrosion (rust) analysis, delamination analysis, pitting or popping analysis, crack analysis, chipping analysis - impact resistance, etc. See Figure 4 for various surface defects for binary image analysis.



Figure 4. Various Surface Defects for Binary Image Analysis

Grayscale image analysis - Grayscale images are used in their original grayscale form as acquired by the system. In some cases, image preprocessing may be applied, equally to all the samples, to highlight defect information. Sample images are then analyzed for surface texture and variations in shade that do not submit to geometrical

definition. Since the original grayscale (or equally preprocessed) images are analyzed, this method provides objective results comparable to visual perception techniques. Sample illumination is the only variable, but the system allows it to be applied under precisely the same conditions to all samples; whether direct, diffuse or both illumination techniques are used. This ensures absolute results within sample groupings, and in applications where reference samples and their analysis data are used for comparative classification, ensures the most objective accuracy in relative comparisons.

Typical parameters used in grayscale image analysis are: histogram, surface fractal dimensioning, flow field measurement, gray level run length, surface texture uniformity, roughness, and numerous others. Grayscale image analysis is applicable in mar analysis, scratch analysis, discoloration, micro texture analysis, pattern analysis, surface structure analysis, etc. See Figure 5 for various surface defects for gray image analysis.

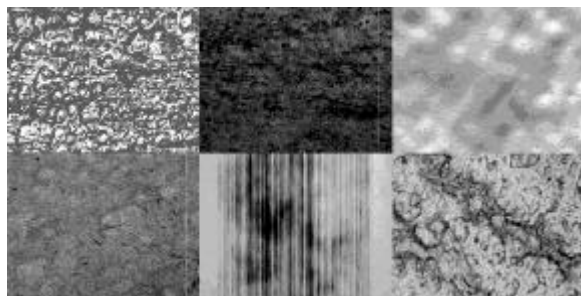


Figure 5. Various Surface Defects for Gray Image Analysis

TEST METHODOLOGY

SCRATCH RESISTANCE TESTING METHOD -

The SCRATCHO 155°F – 3-finger test method was conducted with a SLIDO apparatus [1]. It includes a scratching head comprised of a machined, stainless steel helix. Each protrusion (scratching finger) spiraling around the helix rod is 0.8 mm in diameter and separated from the next protrusion by a gap of 2 mm. The test sample was placed onto an insulated TPO base support and heated to 155°F by radiant quartz heaters. The scratch head was then loaded onto the sample at a ramped load rate of 10 to 300 pounds over a distance of 15.24 cm. Various scratch head velocities were used, ranging from 0.5 to 6 in./sec., at acceleration rates ranging from 0.5 to 40 in./sec².

Visual Evaluation Method – Visual inspection of the resulting scratch deformations was conducted under a McBeth white light with the sample held at a 45° angle. The distance of the first sign of fracture from the scratch starting point was measured with a steel scale and equated with the applicable finger loading for that distance. The result was then reported as a load (e.g., pounds or Newtons to first fracture).

VIEEW™ Evaluation Method – Application of the optical imaging system for the scratch resistance testing requires four functional steps to “train” the system for the specific specimen topology: 1) selection of optimal illumination setting, 2) selection of region of interest setting, 3) selection of image processing routine and 4) creation of a macro routine for automatic execution of the previous settings. Once the steps are programmed into a macro function, the test can be performed with a click of the macro button. So initiated, the instrument recreates the programmed conditions (illumination, region scanning, image processing and detection) as a recurring process.

1) Selection of illumination setting: To detect the “whitening” point on the plastics sample, monochromatic diffuse illumination was selected to bring out the chromatic differences of the whitening region from the background. It is the contrast difference that establishes the region of interest from the background. Typically, chromaticity of light that is opposite in color space to the background color of the sample is suitable for enhancing the region of interest. This is because the opposite chromaticity restricts the reflection from the background while enhancing reflection from the defects. Once the optimal setting is chosen, it is saved as an illumination setting file.

2) Selection of region of interest setting: Often, only a part of the sample surface is used for testing and thus it is of no use to scan the entire sample surface. The X-Y automatic scanning stage can be programmed to scan only the region of interest. Since most mechanical testing is performed in a geometrically consistent manner, the automatic scanning mechanism is useful for multi-sample testing in the case of the scratch test. The automatic stage is indexed to successive X-Y coordinates and the exact sample location is reproduced as long as loading of the sample into the stage sample holder is performed in a consistent manner by users. For the scratch test, 1 x 5 frames (approx. 1.5” x 7.5”) were captured and combined to form a single-frame digital image. See Figure 6 for photos of the sample stage.



Figure 6. VIEEW™ Auto-indexing Sample Stage

3) Selection of image processing routine: For the detection of the whitening point, digitized gray images were divided into two gray regions: the whitening (scratched) region and the background, through the use of a gray thresholding technique. During this step, the thresholding point (gray value) was recorded. As the

subsequent samples were imaged with identical illumination geometry and intensity, the thresholding point allowed automatic determination of the region of interest. It is also at this step that the original image was digitally overlaid with a pseudo-color to more clearly identify the scratched whitening region. Once the region of interest was automatically detected, an inspector then recorded the dimensional coordinates of the initial whitening point, which can be converted to a breaking load. Refer to Figures 7 and 8.

4) Creation of macro routine: The preceding settings were recorded as a macro. Once finished, automatic testing was performed for the remaining samples executing the following steps as defined.

- 1) The X-Y stage positions the sample at the predefined region.
- 2) The preset diffuse light illuminates the sample.
- 3) The region of interest is scanned.
- 4) Complete region image constructed by stitching individual frames.
- 5) Initiates image processing - Applies thresholding filter to convert image to binary mode
- 6) Apply pseudo-color fill to white region of scratch deformations.
- 7) Identifies first whitening point of center scratch.
- 8) Saves specimen image and data in the image database.

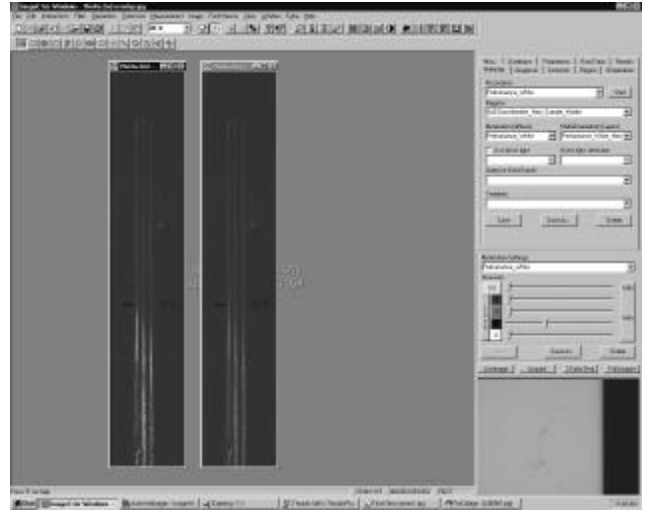


Figure 7. VIEEW™ Software Interface

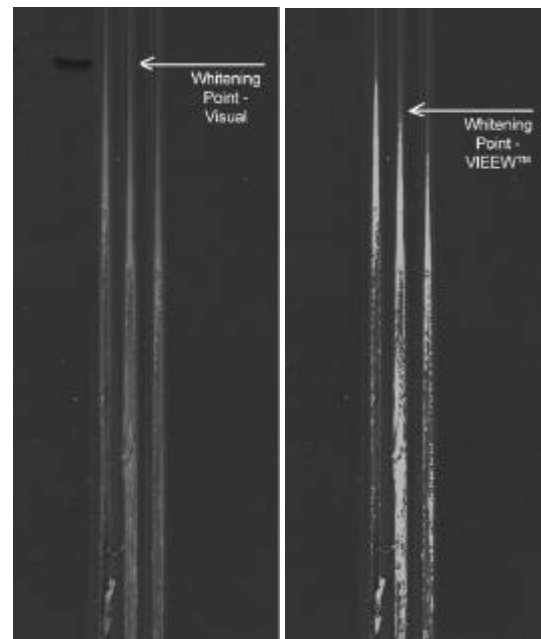


Figure 8. Comparison of Visually and VIEEW™ Detected Whitening Point

TEST DATA AND A DISCUSSION OF RESULTS

Due to the numerous finger velocity and acceleration rates used, it is important to view the test data on an inter-sample basis and to scrutinize the Difference values only within each pair of samples that have undergone identical scratch testing conditions. The data have been so grouped to facilitate this.

It can be observed from the data in Table 1 that the visual method, for all samples, indicates first whitening occurring at an earlier displacement from the scratching finger contact point than the does the VIEEW™ method. Since the VIEEW™ methodology allows a more accurate technique for identifying and measuring the first whitening point, via gray level distribution (thresholding) and a magnified view of the sample surface image; it is probable that the visual method has historically determined a shorter distance to the first whitening and thus assigned a lower scratch resistance capability to such materials. While this has little bearing on the relative accuracy of historical visual evaluations, one-to-another, this significant and consistent offset between results does indicate that the visual technique is inclined to an absolute error that underestimates the scratch resistance of such materials. For these results, the average value of this offset is 9.5 mm and 22.98 Newtons. Excluding the three sample pairs exhibiting offsets in excess of 9.5 mm, the average offset then declines to 6.77 mm and 16.43 Newtons.

A comparison of the difference between the first whitening points detected by each method for each sample pair is presented in Table 2.

Since all the test samples were of the same material, this data indicates a positive agreement between the two evaluation methods with respect to the differing finger velocity and acceleration rates to which each pair of samples was subjected. This data is a logical result of the consistency observed in the offset or Difference values of Table 1.

The visual data presented in this paper was acquired from an evaluation performed by a single inspector in a single session. Therefore, the consistency of the measurement data can be assumed to be relatively high; however, data similarly obtained from multiple inspectors during multiple sessions would likely suffer a high degree of subjectivity between measurements. The VIEEW™ system is not subject to conditions that influence human visual and psychological responses and therefore provides more reliable and repeatable evaluation results.

Table 1 – Evaluation Results

Sample I.D.	Panel Number	Number Of Fingers	SCRATCHO 155°F (1 st Whitening: 3 finger – middle finger)				Difference Visual Vs. Atlas VIEEW™ Method		
			Conditions	Visual 1 st Whitening		Atlas VIEEW™ 1 st Whitening		mm	Newtons
				mm	Newtons	mm	Newtons		
1-HE4A	53	3	V = 6 in/s	84.07	217.74	90.48	234.31	6.41	16.57
1-HE4A-2	13	3	A = 40 in/s ²	79.25	206.10	87.56	226.33	8.31	20.23
2-HEA4	57	3	V = 0.5 in/s	76.20	198.73	94.29	242.28	18.09	43.55
2-HE4A-2	11	3	A = 0.5 in/s ²	47.50	129.47	63.28	167.47	15.78	38.00
3-HEA4	51	3	V = 3 in/s	51.56	139.28	57.23	152.76	5.67	13.48
3-HE4A-2	12	3	A = 10 in/s ²	66.29	174.85	75.30	196.29	9.01	21.44
4-HEA4	55	3	V = 2 in/s	81.03	210.41	89.92	231.86	8.89	21.45
4-HE4A-2	14	3	A = 4.4 in/s ²	77.98	203.04	86.77	224.26	8.79	21.22
5-HEA4	59	3	V = 4 in/s	81.03	210.41	86.47	223.27	5.44	12.86
5-HE4A-2	16	3	A = 17.8 in/s ²	60.20	160.11	65.71	173.60	5.51	13.49
6-HEA4	50	3	V = 5 in/s	79.25	206.10	80.25	208.55	1.00	2.45
6-HE4A-2	18	3	A = 27.8 in/s ²	66.55	175.42	74.37	194.45	7.82	19.03
7-HEA4	48	3	V = 3 in/s	83.31	215.92	91.43	235.53	8.12	19.61
7-HE4A-2	20	3	A = 18 in/s ²	77.72	202.42	84.04	217.75	6.32	15.33
8-HEA4	49	3	V = 2 in/s	74.68	195.05	82.61	214.07	7.93	19.02
8-HE4A-2	29	3	A = 8 in/s ²	64.26	169.92	74.62	195.06	10.36	25.14
9-HEA4	21	3	V = 4 in/s	55.63	149.10	71.34	187.09	15.71	37.99
9-HE4A-2	27	3	A = 32 in/s ²	57.15	152.74	78.99	205.49	21.84	52.75

V = Velocity A = Acceleration

Table 2

Difference in 1 st Whitening Point (by sample pairs)		
Sample Pair	Visual Method (mm)	VIEEW™ Method (mm)
1-HE4A	4.82	2.92
2-HE4A	28.7	31.01
3-HE4A	14.73	18.07
4-HE4A	3.05	3.15
5-HE4A	20.83	20.76
6-HE4A	12.7	5.88
7-HE4A	5.59	7.39
8-HE4A	10.42	7.99
9-HE4A	1.52	7.65

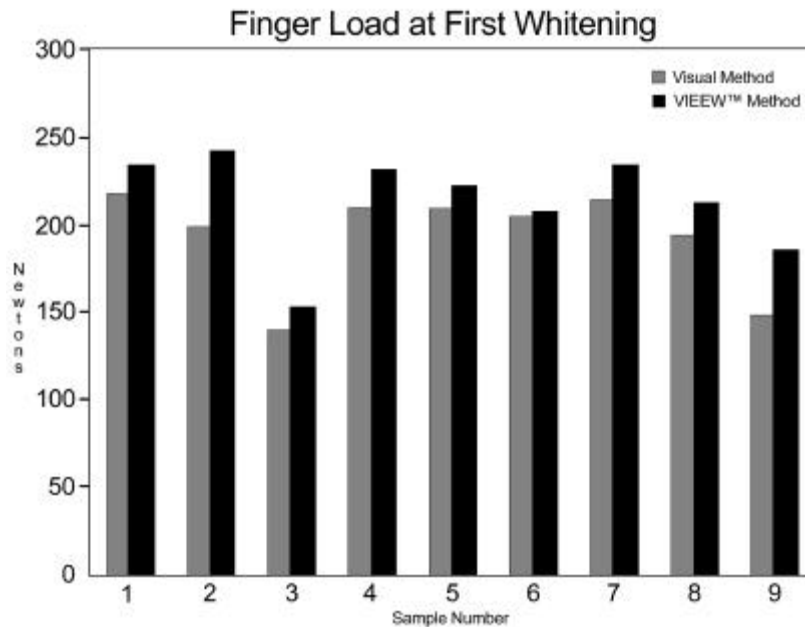


Figure 9. Comparison of Finger Loads at First Whitening

CONCLUSIONS

The perceptual biases and limitations inherent in evaluations conducted by the unaided human eye may be overcome through the use of optical imaging and software analysis technologies that are available today. The application of such technologies can provide improved accuracy and objectivity in evaluation results across the entire field of visual evaluation, especially in the analysis of coatings and plastics. The accuracy of the data obtained implies that smaller sample populations may be analyzed to achieve a sufficient level of confidence in the characterization of the material performance.

The use of the VIEEW™ optical imaging and analysis system allowed rapid capturing of the sample images with precisely the same region of interest on each being digitally recorded. Adjustable RGB diffuse lighting, generated within the integrating sphere of the instrument, allowed an initial high-contrast capture of the sample surface. Software-based image processing features provided further contrast enhancement of the grayscale image for improved visibility of the whitened portion of the scratches over that detectable in the visual evaluation method. The use of a gray level histogram and on-screen zoom magnification facilitated precise selection of the first whitening point of the center scratch.

The test data reveal that the VIEEW™ evaluation results correlate consistently with the visual evaluation results within a repeatable and quantifiable offset range.

This offset may, in part, be due to the improved measurement accuracy inherent in the VIEEW™ system and is likely the foundation for establishing new benchmarks in the evaluation of material scratch resistance.

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