



# A Critical Study On Scratch Resistance Test Methods

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## Scratch Resistance Test Methods

- How do we evaluate thin-film UV-curable coatings' abrasion resistance properties?
- Which ASTM wear or other International Standard Test provides quick, accurate and relevant results that correlate well with field use or experience?
- How do companies report test data with various scratch, abrasion wear methods?
- How do we rate and select thin-film coatings to use for our products?
- Does higher crosslinking density and higher functionality necessarily improve abrasion resistance?

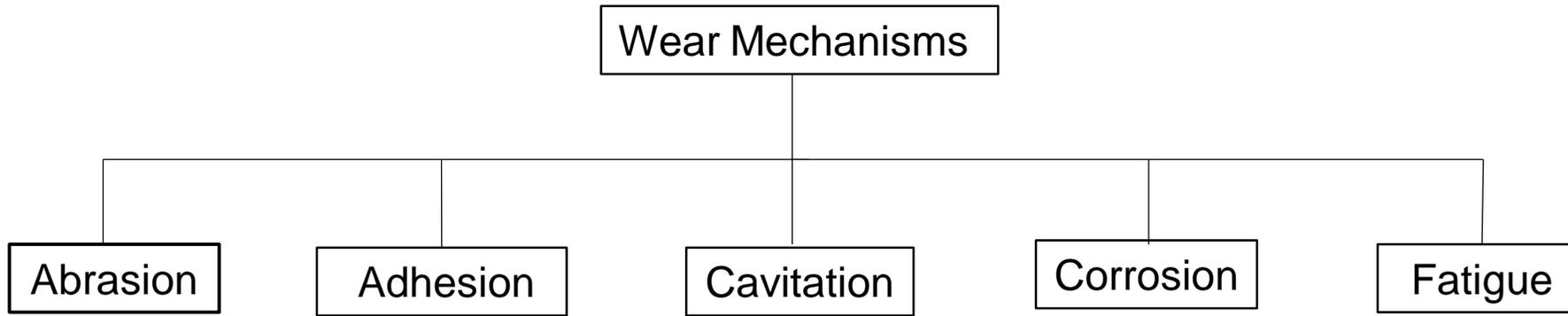


## Scratch Resistance Test Methods

- The identification and characterization of surface wear in plastics, is paramount in Product Performance, critical to Quality and invaluable for Manufacturing operations.
- Scratches in optical clear plastics used in electronic touchscreens, portable instruments, displays and many opto-electronic devices are created by different abrasion modes than mechanical components in constant contact, under cyclic load.
- Physical damage due to scratches changes the substrate's morphology, product appearance causing optical changes in gloss, color and reflected image's focused quality.
- All plastic displays, lenses, etc. will eventually wear; scratches affect durability and lead to premature failure.
- One of the critical features for a Good Laboratory Test (in R&D and QC) is that findings and conclusions correlate well with product's actual use in predicting real failure modes; which can only be verified by field testing!



## Scratch Resistant Test Methods



Wear is damage done to a surface (removal of material,) based on the movement of asperities between two bodies in relative motion, under load. Wear is a complex phenomenon and various wear mechanisms above cause “Industrial” wear.

The concepts of friction and impact are critical to understand and predict wear.



## Scratch Resistance Test Methods

- The frictional force resisting movement of objects in relative motion, does not depend on contact area but on the gravitational, normal force.
- Every smooth surface at the nano level is “rough”; thus, materials in contact only touch over small “peaks,” called asperities. These asperities in contact reach stability (equilibrium) by elastic and plastic deformation.
- The Archard wear equation is a simple model used to describe the sliding abrasion wear, based upon the theory of asperity contact:

$$Q = KWL/H$$

Where:

Q = total volume of wear material removed

W = normal load (gravitational force)

L = sliding distance

K = dimensionless constant, for severity of wear

H = hardness of the softest of the contacting surfaces



## Abrasion Wear

Scratch abrasion is a surface deformation process; is caused by indentation (on a surface) due to the displacement and removal of material , under load, over a period of time by another harder object.

Most thermoplastics due to their viscoelastic properties, do not follow the classical laws of friction (non-linear relationship between contact pressure, sliding speed and coefficient of friction) because of the large plastic deformation that occurs at the tips of the asperities.





# Scratch Resistant Test Methods

## Experimental Foundations

- Mechanical properties of UV-cured resins strongly depend on the effective chain length between cross-links.
- A high network density is thus necessary for superior mechanical properties and chemical resistance. However, higher flexibility is achieved with non highly cross-linked coatings.
- The functionality and concentration of reactive thinners and diluents have a significant influence on hardness and elasticity in the UV curable, thin film coatings.
- Two UV-curable, multi-functional acrylate coatings (one moderately hard and one extra hard) w/o nanoparticles were tested on PC and PMMA substrates, at dry film thickness of 7 $\mu$ m and 13  $\mu$ m.



# Scratch Resistant Test Methods

Coatings	Material	Dry-Film Thickness	Designated
Coating 1	PC	7 microns	C1,1,1
Coating 1	PC	13 microns	C1,1,2
Coating 1	PMMA	7 microns	C1,2,1
Coating 1	PMMA	13 microns	C1,2,2
Coating 2	PC	7 microns	C2,1,1
Coating 2	PC	13 microns	C2,1,2
Coating 2	PMMA	7 microns	C2,2,1
Coating 2	PMMA	13 microns	C2,2,2

Materials Tested:

Polycarbonate (PC) – Lexan 9034 from SABIC Innovative Plastics IP BV.

Acrylic (PMMA) – Optix from Plaskolite, Inc.

Material Properties			PC - Lexan 9034		PMMA -OPTIX	
Properties	Test Method	Unit	Mfg	PCI Labs	Mfg	PCI Labs
Initial Haze	ASTM D1003	%	<1	0.18	2	0.1
Taber @ 100 cycles	ASTM D1044	% haze	10	34.9 (500 g)	24.2	37.61 (500 g)
Pencil Hardness	ASTM D3363		NR	3B	NR	H
Sheet Thickness	Micrometer	mm	1.5	1.5	1.5	1.5



## Scratch Resistance Test Methods

### Process Conditions

- Spray System: Fully automatic w/ air pressure pod, HVLP gun (w/ 1mm tip) .
- Convection Oven (w/ air circulation): 3 minutes @ 30 °C
- UV: 460 mJ/cm<sup>2</sup> (1.36 W/cm<sup>2</sup>) @ 127 mm/s (25 fpm) – with UV Fusion H lamps
- QC: Cross-Cut Adhesion Check - ISO Class: 0 / ASTM Class: 5B - (ISO 2409, ASTM-D3002)
- Conditioned Samples: Prepared per ASTM – D618-95
- Samples Tested: 30 per test, with a 90% confidence interval ( $\alpha/2=0.05$ )



# Scratch Resistant Test Methods



Rotary Steel Wool Tester



## Scratch Resistant Test Methods

### Rotary Steel Wool Test Methods - Measurements

$$\text{Steel Wool Ratio} = \Delta\text{coat} / \Delta\text{sub}^{(1)}$$

$$\text{Steel Wool Ratio} = \Delta\text{coat} / \Delta\text{std}^{(2)}$$

$\Delta$  coat = final haze value of test sample – initial haze value of same

$\Delta$  sub = final haze value of uncoated substrate – initial haze value of substrate

$\Delta$  std = final haze value of standard coating – initial haze value of standard coating

The Rotary Steel wool test is applicable to:

- Rank optically clear coatings; same dry-film thickness on same substrate material
- Rank different optically clear materials; same coating (same dry-film thickness) on different substrates.
- Rank competitive coatings Vs. benchmark coating of same thickness



### Rotary Steel Wool Tester

- The Steel Wool Tester is one of the few abrasion tests that the test loads can be large >345 Kpa and can simulate “real-life” damage.
- It is a quick and easy method that provides both qualitative and quantitative QC data.
- The Rotary Steel Wool Tester with a constant angular velocity ( $\omega$ ), creates both varied tangential velocities ( $\omega r$ ) and centripetal acceleration ( $\omega^2 r$ ) components that impact thin film coatings, dramatically.
- If the most prevalent mode of failure is scratching, the use of steel wool as an abrasive medium is well suited to quickly generate scratches on the surface of a material in curvilinear motion.
- The preparation of the standardized steel wool pad (by the same manufacturer,) by folding and with proper fiber orientation is critical for measurement. Furthermore, conditioning of the pads for 250 cycles is necessary for consistent results.



## Scratch Resistant Test Methods



“RCA” Abrader – Norman Tool Tester  
(ASTM F-2357)



## Scratch Resistant Test Methods

### “RCA” Abrader – Norman Tool Test Method

- The RCA test is influenced by humidity and age of paper, required for testing. New paper from the same source without wax, must be used.
- For the RCA Test, temperature and humidity play an important role and must be reported; as well as, how the tested material and tape used were conditioned!
- RCA wear tests are significantly influenced by coating thickness and substrate material's hardness; PMMA performed better than PC.
- With both coatings tested it performed better @ higher dry film thickness.
- Higher functionality UV-cured coatings faired better than lower functionality.
- Temperature rise due to frictional heating with the corresponding change in the coefficient of friction, has an effect on the results of the test.



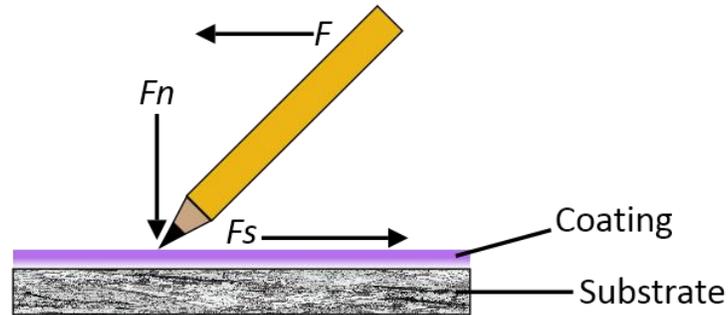
# Scratch Resistant Test Methods



Pencil Hardness Tester  
Wolf-Wilburn Method  
(ASTM-D-3363)

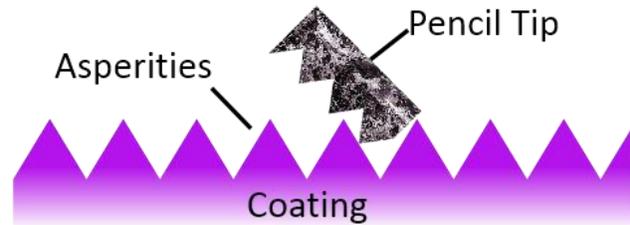


## Scratch Resistant Test Methods



$$F_s = \mu \times F_n \text{ (gravitational force)}$$

$\mu$  = coefficient of friction



Ordinary friction is arising from surface roughness

- Friction due to the movement of asperities on a material's surface in contact with another harder material, causes wear.
- Plastics in particular, with their wide range of plastic deformation have a coefficient of friction that is generally lower than other harder materials, under the same load conditions.



# Scratch Resistant Test Methods

## Test Results

Pencil Hardness Evaluation (*)										
Manufacturers	PC	PMMA	<u>C1,1,1</u>	<u>C1,1,2</u>	<u>C1,2,1</u>	<u>C1,2,2</u>	<u>C2,1,1</u>	<u>C2,1,2</u>	<u>C2,2,1</u>	<u>C2,2,2</u>
ASTM D3363	3B	H	HB	HB	2H	4H	H	HB	>6H	>6H
Mfg 1	2B	3H	F	H	5H	5H	F	F	7H	8H
Mfg 2	2B	3H	F	F	6H	5H	HB	HB	8H	8H
Mfg 3	2B	2H	2H	3H	8H	9H	2H	2H	9H	9H
Mfg 4	3B	2H	2H	2H	7H	7H	2H	2H	8H	8H
Mfg 5	2B	3H	F	H	6H	6H	F	F	8H	9H
Mfg 6	2B	H	HB	F	6H	6H	H	H	6H	7H
Manufacturer 1	Staedtler Mars - Lumograph 100, Staedtler Mars, GmbH & Co., Germany									
Manufacturer 2	Faber-Castel - Graphite Sketch Set, Faber-Castell, Germany									
Manufacturer 3	Derwent - Graphic Arts, Acco Ltd, UK									
Manufacturer 4	Sanford - Prismacolor Premier - Sanford, LP., USA									
Manufacturer 5	Artist's Loft - Sketching Pencils (ASTM D-4236) - Thailand									
Manufacturer 6	Mitsu-Bishi - Hi Uni , Mitsu-Bishi, Japan									



### On Pencil Hardness

- There is variation between pencil manufactures in graphite, clay and binder composition.
- There is variation in pencil hardness on the same coating and material, by different pencil manufactures.
- There is inconsistency within pencils (fail at 2H while passing 3H @ 5H).
- The substrate materials Rockwell hardness (M-scale) significantly influences a coatings pencil hardness measurement.
- Must report test load, pencil manufacturer, speed of slide and coating thickness, for relevant comparisons on same substrate material between thin film coatings.
- Proper conditioning of pencil lead is important, as per ASTM.



# Scratch Resistant Test Methods



Taber Wear Tester  
(ASTM D-1044)



## Scratch Resistant Test Methods

### Taber Abrader Test Method

- Can't use the Wear Index ( weight loss method ASTM - 4060) in thin film coatings.
- Measure the percent change in haze value (final – initial haze.)  
Haze of a specimen is defined as the percentage of transmitted light, which in passing through the specimen deviates more than  $2.5^{\circ}$  from the incident beam by forward scattering.
- Taber Abrader test instrument requires regular calibration to ensure accurate results.
- There is variability of Lab results based on test process; running continuously long cycles vs. stopping at regular intervals, cleaning abraser media from the substrate surface and continuing with the test .
- Temperature rise due to frictional heating with the corresponding change in the coefficient of friction, has an effect on the results of the test.



# Scratch Resistant Test Methods

## Test Results

Abrasion Resistance Wear Tests									
Test	Units	Coatings (1)							
		C1,1,1	C1,1,2	C1,2,1	C1,2,2	C2,1,1	C2,1,2	C2,2,1	C2,2,2
		PC 7µm	PC 13 µm	PMMA 7µm	PMMA 13µm	PC 7µm	PC 13µm	PMMA 7µm	PMMA 13µm
Taber (2)	% Δ Haze	8.4	6.68	9.2	8.2	8.15	5.4	7.7	5.5
"RCA" (3)	Cycles	400	450	500	600	600	700	700	800
Pencil (4)	#	F	F	6H	6H	H	H	6H	6H
Steel Wool (5)	kPa (psi)	207 (30)	207 (30)	276 (40)	262 (38)	345 (50)	345 (50)	>345 (50)	>345 (50)
Steel Wool (6)		0.22	0.21	0.24	0.22	0.11	0.12	0.12	0.13

- (1) See Designation under Materials.
- (2) ASTM 1044-99, Taber Calibrase CF-10F @ 500g and 100 cycles
- (3) ASTM F 2357-04, Norman Tool Paper
- (4) Mitsu-Bishi, Hi-Uni Pencils
- (5) Rhodes American, Super Fine #0000 steel wool, 25 rotations (1 rps) @ load (4 cm<sup>2</sup>)
- (6) Steel Wool Ratio – Formula (2)
- (7) Temperature 21.5 °C +/- 1 °C (70.7 °F) & Relative Humidity of 52% +/- 3%

(\*\*) The number of coated samples tested were 30, per test, with a 90% confidence interval ( $\alpha/2=0.05$ ).



## Scratch Resistance Test Methods

### Conclusions

The RCA wear test is significantly influenced by coating thickness and substrate material's hardness. PMMA performed better than PC and both coatings performed better at higher dry film thickness.

In the Taber wear test the higher cross-linked coating performed better and the coating thickness had a positive effect. PC at the higher dry film thickness performed better.

There is a minor difference in pencil hardness with increased coating thickness in thin films. However, there was a substantial difference based upon the substrate's material hardness itself. PMMA performed much better.

The Steel Wool test verified better performance vs. higher crosslinking density. The best performer was PC at the smaller dry-film thickness.



# Scratch Resistant Test Methods

Scratch Test Methods Evaluation				
Scratch Test	Substrate Hardness (Rockwell)	Film Thickness	Crosslink Density	Coating Differentiator
Taber Wear	↓	↑	↑	Average
RCA Abrader	↑	↑	↑	Average
Pencil	↑	↔	↑	Average
Rotary Steel Wool	↔	↔	↑	Better



## Scratch Resistance Test Methods

### Conclusions

- The same coating with the same dry film thickness, will behave different on different substrate materials and that includes topcoats on different basecoats, used in a multi-layer systems.
- The overall scratch resistance is improved by the increased functionality of the acrylate based resins in thin film UV-curable coatings.
- The wear tests performed provide insight into how inconsistent test results can be within the anti-scratch coatings industry, when test methods and conditions vary.
- A number of different conclusions can be drawn from the data reported above, comparing different abrasion resistance test methods.
- Coatings evaluations must be performed on the same material, at the same dry film thickness with the same abrasive media, properly conditioned, to demonstrate clear statistical differences for thin film UV-curable coatings and provide reliable acceptance criteria.



## Scratch Resistance Test Methods

### Conclusions

- Scratch abrasion is complex mechanical damage process; test method dependent.
- Slip additives, fluorocarbons, solid lubricants (PTFE, etc.) with their extreme low coefficient of friction, have a positive effect on scratch wear tests.
- The type of abrasion wear (in movement and force) must be carefully analyzed regarding cycling, repeatability, randomness, constancy, etc. For example, most (coated) displays fail due to scratches caused by sharp objects and moderate load, rather than repetitive or constant loading.
- The rotary steel wool test is a quick test that provides better correlation with abrasion wear when the load is not cycling or repetitive, such as those experienced by portable mobile device users.
- It is unwise to make inferences about characterization of a coating's ability to withstand wear by a single value and test. The most effective way is to perform multiple abrasion resistance tests - under very precise and controlled environmental conditions - to evaluate a coating's ability to withstand real life, scratch abrasion conditions.



**THANK YOU**

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