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Plastics — Quantitative evaluation of scratch-induced damage and scratch visibility

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National foreword

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A list of organizations represented on this committee can be obtained on request to its secretary.

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Plastics — Quantitative evaluation of scratch-induced damage and scratch visibility

Plastiques — Évaluation quantitative des dommages induits par rayure et visibilité des rayures

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical properties*.

Plastics — Quantitative evaluation of scratch-induced damage and scratch visibility

1 Scope

This International Standard deals with quantitative evaluation of scratch–induced damage and scratch visibility in polymers.

This International Standard specifies two methods to assess scratch damage and scratch visibility expressed by three colour coordinates of a 3-D colour model.

Method A uses a scratch tip capable of area-contact or line-contact with material surfaces under a constant load condition. It is represented by scratch damage index (SDI).

Method B uses a scratch tip capable of line-contact under a linearly increasing load condition. It is represented by scratch visibility index (SVI).

The methods are suitable for use with coated and uncoated thermoplastic and thermosetting moulding materials.

The methods specify the preferred dimensions of testing specimens and the preferred scratch-tip geometry.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 291, *Plastics — Standard atmospheres for conditioning and testing*

ISO 294-1, *Plastics — Injection moulding of test specimens of thermoplastic materials — Part 1: General principles, and moulding of multipurpose and bar test specimens*

ISO 294-2, *Plastics — Injection moulding of test specimens of thermoplastic materials — Part 2: Small tensile bars*

ISO 294-3, *Plastics — Injection moulding of test specimens of thermoplastic materials — Part 3: Small plates*

ISO 6508-1, *Metallic materials — Rockwell hardness test — Part 1: Test method*

ISO 19252, *Plastics — Determination of scratch properties*

ISO 20753, *Plastics — Test specimens*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
scratch
visual surface damage such as cutting and whitening, which is generated by sliding of the scratch tip over the surface of the test specimen under defined conditions

3.2
normal force
F_n
load applied by the scratch tip in a direction perpendicular to the material surface

Note 1 to entry: It is expressed in newtons.

3.3
tangential force
F_t
load applied by the scratch tip in a horizontal direction on the material surface

Note 1 to entry: It is expressed in newtons.

3.4
scratch path
connected line of scratch damage induced on the material surface by the scratch tip

3.5
whitening
visual damage which is generated on the material surface along the scratch path such as micro-cracking, crazing, voiding, and debonding

3.6
single-damage
SD
simple surface damage which is generated in a single direction on the material surface

3.7
multiple-damage
MD
latticed damages which are generated in two perpendicular, horizontal directions on the material surface

3.8
scratch force
F_s
resultant force applied to the material surface as the summation of the normal and tangential force vectors

Note 1 to entry: It is expressed in newtons.

3.9
scratch strength
S_s
scratch force per unit contact area of area-contact scratch tip

Note 1 to entry: It is expressed in newtons per square millimetre.

3.10
scratch resistance
R_s
scratch force per unit contact length of line-contact scratch tip

Note 1 to entry: It is expressed in newtons per millimetre.

3.11
degree of scratch damage
ΔD
euclidean distance between the color coordinates of the scratched and unscratched surfaces

3.12
percent difference in luminance
L_{norm}
percent difference between the luminance values of the scratched and unscratched surfaces

3.13
scratch damage index (SDI)
[ΔD, S_S (or R_S)] or [L_{norm}, S_S (or R_S)]
set of the relative severity of scratch damage and scratch strength (or scratch resistance) values, which are quantitative values obtained under a constant normal load

3.14
critical intensity value
I_C
threshold intensity value where the onset of scratch visibility occurs

3.15
critical saturation value
S_C
threshold saturation value where the onset of scratch visibility occurs

3.16
scratch visibility index (SVI)
[I_C, S_C, R_S]
set of the relative intensity, saturation, and scratch resistance values, which is the onset of scratch visibility obtained under a linearly increasing normal load

4 Principle

This test method provides a quantitative evaluation of scratch damage and visibility on polymer and coated surfaces. Scratching is generated by a scratch tip capable of area-contact or line-contact on the material surface and can be induced under a constant normal load or a linearly increasing load.

The scratch damage index (SDI), the severity of surface damage caused by scratching under a constant normal load condition, is determined by comparing the Euclidean distance or percent difference in the luminance between colour coordinates of the scratched surface and the ones of the unscratched surface. SDI is defined as a set of the degree of scratch damage (or percent difference in luminance) and scratch strength (or scratch resistance) values, as a quantitative determination.

The scratch visibility index (SVI), the onset point of scratch visibility where the surface damage can be perceived by the naked eye, is determined under a linearly increasing load condition and defined as a set of intensity, saturation, which are two of three coordinates in HSI colour model, and scratch resistance value.

5 Apparatus

5.1 General description

The instrumented scratch machine consists of a load device, position sensor, specimen stage, clamping devices, and scratch tip with a preferred geometry. An environmental chamber can also be added for testing at non-ambient condition. For evaluation after scratching, tools such as optical microscopes, flatbed scanners, profilometer, and colour analysis software are used.

5.2 Scratch tip

The scratch tip shall be made from stainless steel or tungsten carbide having a hardness greater than Rockwell HRC 64 value, as specified by ISO 6508-1, and a roughness less than 0,20 µm, in accordance with ISO 19252.

Two scratch tips with a preferred geometry are used in this method. Type 1 is used to induce an area-contact with the material surface (see Figure 1). Type 2 is used to induce a line-contact with the material surface (see Figure 2). It is permissible to use other sizes of the scratch tip but this shall be noted in the report.

Dimensions in millimetres

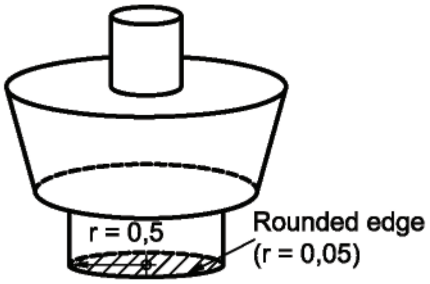


Figure 1 — Schematic of area-contact scratch tip, Type 1

Dimensions in millimetres

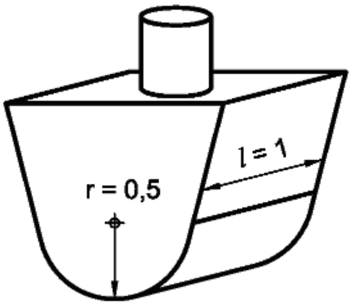


Figure 2 — Schematic of line-contact scratch tip, Type 2

5.3 Load and position sensors

The instrumented scratch machine shall be equipped with devices to monitor the normal force, tangential force, instantaneous scratch depth, and horizontal position. The forces acting on the scratch tip shall be measured with an accuracy of ±1 % of actual value. The data acquired for depth and horizontal position of the scratch tip shall have an accuracy of ±10 μm or better.

5.4 Test load

The instrumented scratch machine shall be capable of maintaining the test load within a tolerance of ±1 %, for any test load chosen as specified in 7.3 and 7.4, and shall be capable of applying the load perpendicular to the test specimen within a tolerance of ±1°.

5.5 Test speed

The instrumented scratch machine shall be capable of maintaining the test speed within a tolerance of ±1 %, except for the first stage and the end stage of 10 mm for the total scratch distance, for any test speed chosen as specified in 7.3 and 7.4, and shall be capable of reaching the test speed within 10 mm and stopping within 10 mm.

5.6 Specimen stage

The specimen stage shall be flat, smooth, and free of holes in the area where the test specimen will be placed.

6 Test specimens

6.1 General

Test specimens having homogeneous surface in texture, colour, and flatness shall be prepared and tested.

The specimen shall be cleaned to remove any contaminants or residues which can alter surface characteristics. The reagent used for cleaning shall not affect the inherent surface properties of the specimen.

6.2 Shape and dimensions

Bars, plaques, discs, or other specimen types of sufficient size for testing can be used.

For only single-damage tests, standard multipurpose test specimens as specified in ISO 20753 can be used. If the scratch length is taken to be 100 mm, the specimen shall be at least 150 mm in length to provide enough area for clamping.

For both multiple-damage and single-damage tests, injection-moulded test specimens shall be acceptable. It is recommended to use plaques having dimensions of at least 150 mm wide by at least 150 mm long.

6.3 Preparation

Prepare test specimens as required by the relevant moulding materials standard, or, if none exists, following the conditions in ISO 294-1, ISO 294-2, and ISO 294-3, as applicable, and the recommendations of the material supplier.

6.4 Conditioning

The specimens shall be conditioned in one of the standard atmospheres specified in ISO 291 or the appropriate material specification.

6.5 Number of test specimens

At least five specimens shall be tested to assess repeatability for each set of test conditions.

7 Procedure

7.1 Test atmosphere

The atmosphere used for testing shall be the same as that used for conditioning, as specified in accordance with ISO 291 or the appropriate material specification. If scratch tests are to be conducted at temperatures other than the room temperature, an environmental chamber shall be used to maintain the scratch tip and the specimen at the desired temperature. Prior to testing, the scratch tip and specimen shall be conditioned in the environmental chamber for not less than 30 min.

7.2 Scratch tip

Before testing, the scratch tip shall be inspected for damage, deformation, or contamination using a microscope, magnifying glass, or other suitable inspection device.

7.3 Method A (constant load condition)

Choose one of two scratch tips (i.e. area-contact tip, Type 1 or line-contact type tip, Type 2), as specified in 5.2.

In order to quantitatively determine the scratch damage, it is recommended that one of the combinations of constant loads and test speeds specified in Table 1 is used over a scratch length of 100 mm. It is permissible to use scratch lengths other than 100 mm but this shall be noted in the report. However, the scratch length shall be at least 50 mm long.

Although the constant loads stated in this standard are 10N, 20N, 30N, 40N, and 50N, it is permissible to use loads other than thoses shown in the table but this shall be noted in the report.

7.4 Method B (linearly increasing load condition)

Use the line-contact tip, Type 2, as specified in 5.2.

In order to quantitatively determine the scratch visibility, it is recommended that one of the combinations of linearly increasing loads and test speeds specified in Table 2 is used over a scratch length of 100 mm. It is permissible to use scratch lengths other than 100 mm but this shall be noted in the report. However, the scratch length shall be at least 50 mm long.

Although the linearly increasing loads stated in this standard are 1-10N, 1-20N, 1-30N, 1-40N, and 1-50N, it is permissible to use loads other than those shown in Table 2 but this shall be noted in the report.

Table 1 — Type of constant load used and test conditions

Type of load	Test load	Test speed
constant load	10N, 20N, 30N, 40N, 50N	1 mm/s, 10 mm/s, 100 mm/s

Table 2 — Type of linearly increasing load used and test conditions

Method	Test load	Test speed
linearly increasing load	1–10N, 1–20N, 1–30N, 1–40N, 1–50N	1 mm/s, 10 mm/s, 100 mm/s

7.5 Scratch testing

7.5.1 Single-damage test

7.5.1.1 Securely mount a clean specimen on the specimen stage with lockable clamps.

7.5.1.2 Remove any dust and contaminant from the specimen surface.

7.5.1.3 Check that the scratch tip is not contaminated or damaged.

7.5.1.4 Define the start and end position of scratch path.

7.5.1.5 Setup the appropriate test method (A or B) and the necessary parameters (e.g. test speed and test load).

7.5.1.6 Apply pre-load of less than 1 N to the start position of the specimen surface.

7.5.1.7 Start the scratch process.

7.5.1.8 Record the normal load, tangential load, depth of scratch tip, and scratch length.

7.5.2 Multiple-damage test

7.5.2.1 Follow 7.5.1, using constant loads only, except for the following steps.

7.5.2.2 Make a set of scratches with a total of 15 lines at intervals of 2 mm.

7.5.2.3 Remove the specimen, rotate it 90°, and securely remount it.

7.5.2.4 Make additionally a set of scratches with 15 lines at intervals of 2 mm oriented 90° from the original set of scratches.

8 Interpretation of result

8.1 General

The types of surface damage measured in this International Standard include single-damage in which a scratch is generated in one direction under a constant or a linearly increasing load, and multiple-damage in which two sets of scratches, superimposed in a normal (90°) orientation, are generated under a constant load (see Figure 3).

8.2 Scratch strength and scratch resistance

During the scratch test, there exist two orthogonal vectors, the applied normal force and the resulting tangential force on a scratched surface. The scratch force, scratch strength, and scratch resistance are calculated using Formula (1) to Formula (3):

$$F_s = F_n + F_t \quad (1)$$

$$S_s = F_s / A \quad (2)$$

$$R_s = F_s / l \quad (3)$$

where

A is the contact area of area-contact scratch tip;

l is the length of line-contact scratch tip.

8.3 Single-damage (SD)

8.3.1 Digital image processing

A digitized image of the scratch-induced damage can be obtained using a flatbed scanner, with a resolution of 600 × 600 dpi or higher and 24-bit colour mode for the quantification of scratch damages. For colour calibration of flatbed scanner, a spectrophotometer shall be used with a calibration chart and software, and then the new scanner profile obtained shall be assigned to a scanning software prior to scanning.

The resulting digital image is analysed using a colour analysis software, capable of determining colour coordinates using three-dimensional colour space (e.g. HSI model).

Colour analysis software is used to quantify the scratch damage. In order to increase the reliability of experimental data and to exclude the unusual data on the edge region, a 3-tuple of colour coordinates within a 90 % region of a scratch width may be represented (see Figure 3).

Representative colour coordinates for each column of pixels along the scratch path are calculated as averages of the corresponding pixel values in that column. Overall average and standard deviation for each colour coordinate are calculated using all the average column values for all the tests after performing five scratch tests on a sample (see Figure 4).

8.3.2 Degree of scratch damage

Each pixel of the digitized image can be expressed as three colour coordinates using image analysis tools. For example, it is expressed in the case HSI colour model by Hue, Saturation, and Intensity values.

The changes of colour components in the colour spaces correspond to the changes of scratch damages. Thus, the degree of scratch damage is calculated from Formula (4):

$$\Delta\mathrm{D}(x, y) = \|x - y\| = \sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}} (x_{\mathrm{i}} - y_{\mathrm{i}})^2} \ (\mathrm{n} = 3) \quad (4)$$

where

$\Delta\mathrm{D}$ is the Euclidean distance between the colour coordinates;

x is the colour coordinate of the scratched surface;

y is the colour coordinate of the unscratched surface.

8.3.3 Determination of scratch damage index

The scratched surface damages under a constant normal load can be quantified and expressed by the term “scratch damage index (SDI)”:

$$\mathrm{SDI} = \left[\Delta\mathrm{D}, S_s \left(\mathrm{or}\, R_s\right)\right] \quad (5)$$

8.3.4 Determination of scratch visibility index

The onset of scratch visibility under an increasing normal load can be quantified and expressed by the term “scratch visibility index (SVI)”. The onset of scratch visibility is derived from the second colour transition point (see B.3):

$$\mathrm{SVI} = \left[I_{\mathrm{c}}, S_{\mathrm{c}}, R_{\mathrm{s}}\right] \quad (6)$$

8.4 Multiple-damage (MD)

8.4.1 Measurement condition

The severity of scratch damage can be directly expressed, in the case of L*a*b* colour model, by the percent difference in luminance (L_{norm}) between the scratched and unscratched zones using a spectrophotometer. For scratch evaluation, in general, the L_{norm} value is simply employed instead of the difference in colour (ΔE). The colour analysis using a spectrocolourimeter shall be performed under preferred standard conditions, such as D65 standard illuminant, and specular component excluded (SCE) mode for reasonable measurement.

8.4.2 Percent difference in luminance

The percent difference in luminance for evaluating scratch damages is defined as:

$$L_{\text{norm}} = \frac{L_{\text{s}} - L_{\text{u}}}{L_{\text{u}}} \times 100\,(\%) \tag{7}$$

where

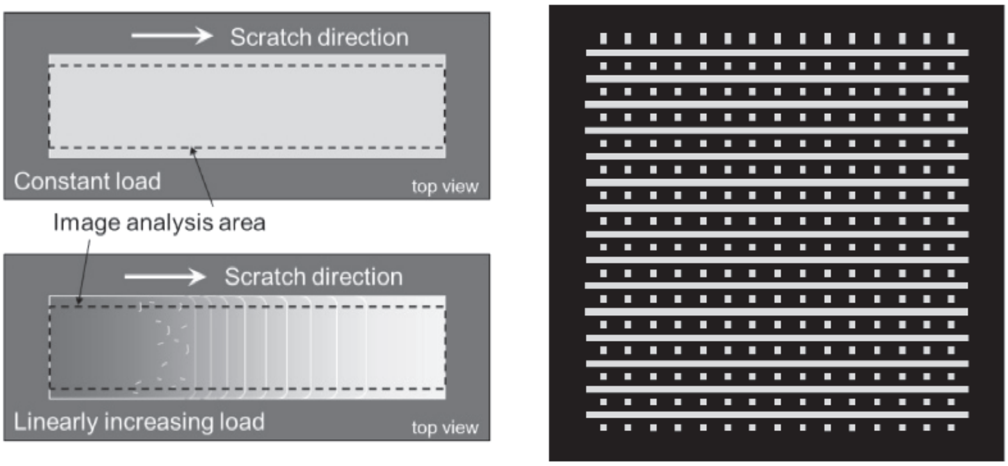
L_{s} is the luminance value of the scratched surface;

L_{u} is the luminance value of the unscratched surface.

8.4.3 Determination of scratch damage index

In case of multiple-damage, the SDI is expressed as follows:

$$\text{SDI} = \left[L_{\text{norm}}, S_s \left(\text{or}\, R_s\right) \right] \tag{8}$$



a) Single-damage

b) Multiple-damage

- Resolution higher than 600 × 600 dpi
- 24-bit colour mode
- D65 standard illuminant
- Specular Component Excluded (SCE)

Figure 3 — Two different scratch damages proposed

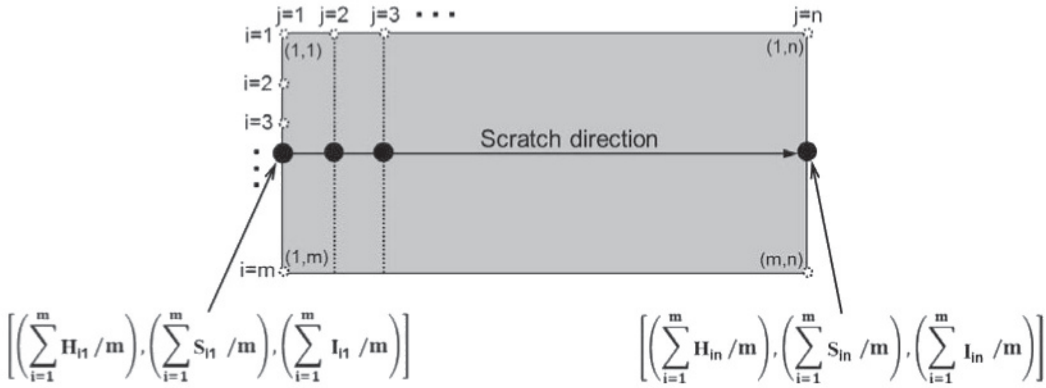


Figure 4 — Schematic diagram showing how to calculate the colour coordinate values using image analysis software

9 Test report

The test report shall include the following information:

a) a reference to this International Standard, i.e. ISO 17541;

b) the type, geometry, thickness, and width of test specimens;

c) the method used to prepare the test specimens;

d) the standard atmosphere used for conditioning and testing and the temperature measured during the test;

e) the test load and the speed chosen;

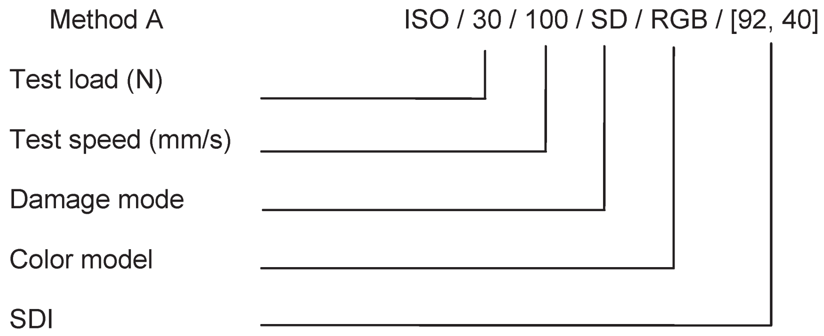
f) the type and size of the scratch tip used;

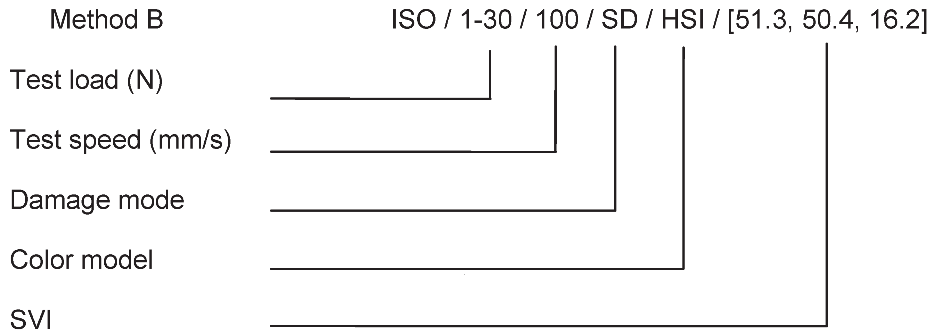
g) scratch damage mode (single-damage or multiple-damage);

h) the scratch damage index: [ΔD, S_S (or R_S)] or [L_{norm}, S_S (or R_S)], or the scratch visibility index: [I_c, S_c, R_S];

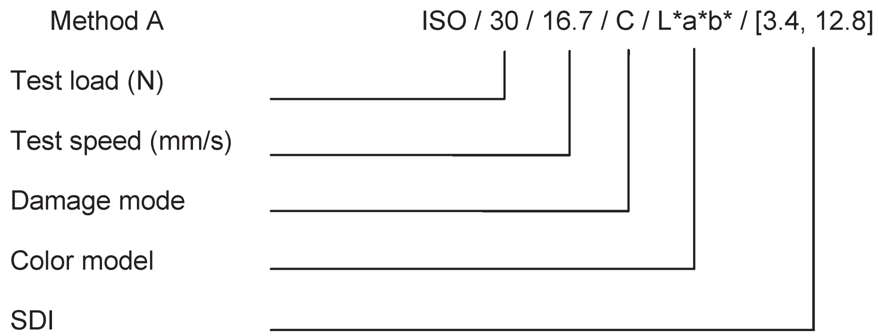
i) the test result of each specimen, as specified for instance in the following way.

<Single-damage test result>





<Multiple-damage test result>



Annex A
(informative)

3-D colour model

A.1 General description

Three-dimensional (3-D) colour model can be used to quantify both the observed scratch damages and scratch visibility. A change in scratch damage is accompanied by the variation of colour perceived due to additional light absorption and reflection on the scratched surface; therefore, the severity of surface damage can be captured by colour coordinates of 3-D colour models (i.e. a 3-tuple of HSI components) along the scratch path. As a result, scratch damage and scratch visibility can be exactly quantified by means of the corresponding colour values. The most common colour space generally uses the 24-bit implementation, with 256 discrete (8 bits) values of colour per channel. Any 24-bit-based colour space is thus limited to a gamut of 256 × 256 × 256. The HSI colour model is an attractive colour model for image processing applications since it represents colours similarly to how the human eyes perceive colours. In the HSI model, each colour is represented by three components of hue (H), saturation (S), and intensity (I). The hue component describes the colour itself, the saturation part signals how much the colour is polluted with white colour, and the intensity value illustrates the brightness of the colour. The values of HSI are assumed to be in the range of [0-255].

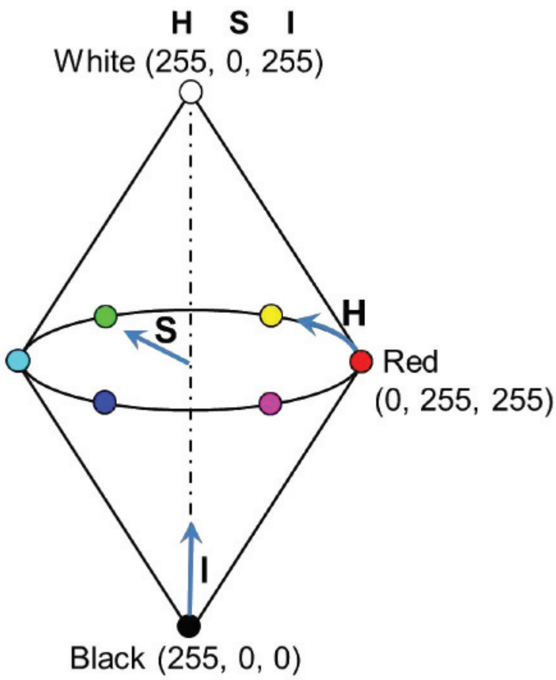


Figure A.1 — Schematic diagram of HSI colour model and its colour coordinates

Annex B
(informative)

Example for quantitative determination of scratch damageand scratch visibility

B.1 Testing condition

A polypropylene (PP) composite, containing 15 wt% of talc, 25 wt% of ethylene-octene rubber (EOR) and ~1 wt% of carbon black pigment, was prepared. The specimens having dimensions of 345 mm × 150 mm × 3 mm were injection-moulded.

Scratch tests were carried out at room temperature using a commercial scratch machine. The testing conditions involved a constant normal load of 30 N at a constant scratch velocity of 1 mm/s over a scratch length of 50 mm.

Two stainless steel stylus tips were used. One has a column (diameter of 1 mm) with rounded edge (radius of 0,05 mm) that can produce an area-contact with the polymer surfaces (see Figure 1). The other is a cylinder shape with a diameter of 1 mm and a length of 1 mm, for which a line-contact can be generated (see Figure 2).

Scanned images of the scratch-tested surfaces were prepared using an Epson Perfection V700 Photo flatbed scanner, a resolution of 600 × 600 dpi, and 24-bit colour mode for the quantification of scratch damages.

A GretagMacbeth Eye-One spectrophotometer was used for colour calibration of flatbed scanner and the new scanner profile after calibration was assigned to a scanning software.

A commercial surface analysis software, QWin, using HSI colour model, was also used to quantify the scratch damage and scratch visibility.

B.2 Example of scratch damage index

Figure B.1 showed optically scanned images of scratched polypropylene (PP) composite surfaces with constant normal loads: (a) no scratch damage zone, (b) 30 N with an area-contact tip, and (c) 30 N with a line-contact tip.

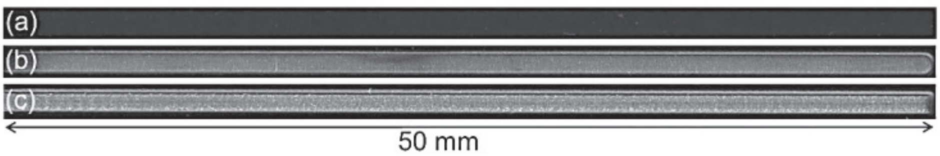


Figure B.1 — Optically scanned images of scratch-induced polypropylene (PP) composite surfaces with different test conditions: (a) no scratch damage zone (control), (b) 30 N with an area-contact tip, and (c) 30 N with a line-contact tip

Table B.1 — Colour image analysis results and scratch damage index for scratched-induced PP composite using the area-cotact tip (r = 0,5 mm)

Load	(S_n, I_n) (%)	ΔD (%)	S_s (N/mm^2)	Scratch damage index
Control	(25 ± 1,2, 15 ± 0,7)	—		
30 N	(10 ± 0,7, 41 ± 2,5)	30,0	40,0	[30,0, 40,0]

Table B.2 — Colour image analysis results and scratch damage index for scratched-induced PP composite using the line-cotact tip (*l* = 1 mm)

Load	(S_n, I_n) (%)	ΔD (%)	R_s (N/mm)	Scratch damage index
Control	(25 ± 1,2, 15 ± 0,7)	—		
30 N	(7 ± 0,7, 54 ± 2,3)	43,0	34,1	[43,0, 34,1]

NOTE Each S_n, and I_n value is normalized by dividing the maximum colour value of 255 and expressed as a percentage. For comparison purpose, the plot of non-scratched sample (referred to Control) processed with the same manner was also represented.

B.3 Example of scratch visibility index

Figure B.2 showed optically scanned images of scratch-induced polypropylene (PP) composite surface with increasing normal load range of 1-30 N. Scratch direction is from left to right.

NOTE The bracket and arrow indicated the corresponding mar zones and onset of scratch visibility, respectively.

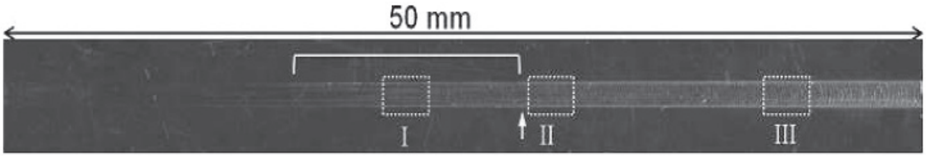


Figure B.2 — Optically scanned image of scratch-induced PP composite surfaces with increasing normal load range of a 1–30 N

Three zones were distinguished without any post-processing using image analysis tools: non-damage, mar, and scratch-induced damage zones. An increase in applied normal load led to an increase in scratch damage and in scratch visibility. In general, the damage features could be detected by significant light scattering from the scratched surface damage features.

The surface analysis result of PP composite using the HSI colour space are shown in Figure B.3.

The hue value remained constant along the scratch path, while there was a gradual increase in intensity and a decrease in saturation numbers. The amount of light scattering (i.e. whitening) along the scratch path increased with increasing applied normal load, with no change in hue value.

In other words, the appearance of whitening directly caused intensity value to increase and a moderate decrease in saturation value. An analytical evaluation indicated that the both intensity and saturation value profiles were distinctively marked by the changes of their slopes that are obviously derived from the variation of scratched damage, as scratching progresses.

The first colour transition region exhibited an increase in intensity number and afterward, the slope became flatter, followed by the repetition of the same trends along the scratch path. This implies that whenever the variation of the slope takes place, the change of surface damage features also occurs.

Optical microscopy observations were further employed to correlate the observed damage morphologies with the corresponding colour transitions in intensity and saturation values. Several regions of interest for scratch-induced PP composite were observed. Close-up views of regions that were marked with numbering in Figure B.2 were presented in Figure B.4. Figure B.4a-c showed in sequence the damage features at the 1st, 2nd, and 3rd colour transition points for PP composite surface scratched with a load range of 1 to 30 N.

In Region I, mild damages by plastic ironing were observed at the beginning and then small cracks or fragments were initiated at the end of the stage. This feature was termed as “mar”.

A rough and wave-like sheared pattern was observed in Region II. The wave-like patterns appeared to be closely spaced. This indicated that the surface damage mode was changed due to the increase of applied scratch force. These damages could be measured using an analytical method, because of the changes in colour values from the scratched path. Thus, the second colour transition point was defined as the “onset of scratch visibility”. In addition, the onset of scratch visibility was quantified and expressed by the term “Scratch Visibility Index (SVI)”.

Region III represented the corresponding damage feature around the third colour transition. The wave-like fragments were broadened, signifying the increase of surface damage.

Table B.3 — Colour image analysis results and scratch visibility index for scratched-induced PP composite

Load	I_c	S_c	R_s (N/mm)	Scratch visibility index
1 to 30 N	51,3 ± 0,8	50,4 ± 0,9	16,2 ± 0,3	[51,3, 50,4, 16,2]

NOTE The critical intensity (I_c) and critical saturation (S_c) value indicates that the onset of scratch visibility occurs.

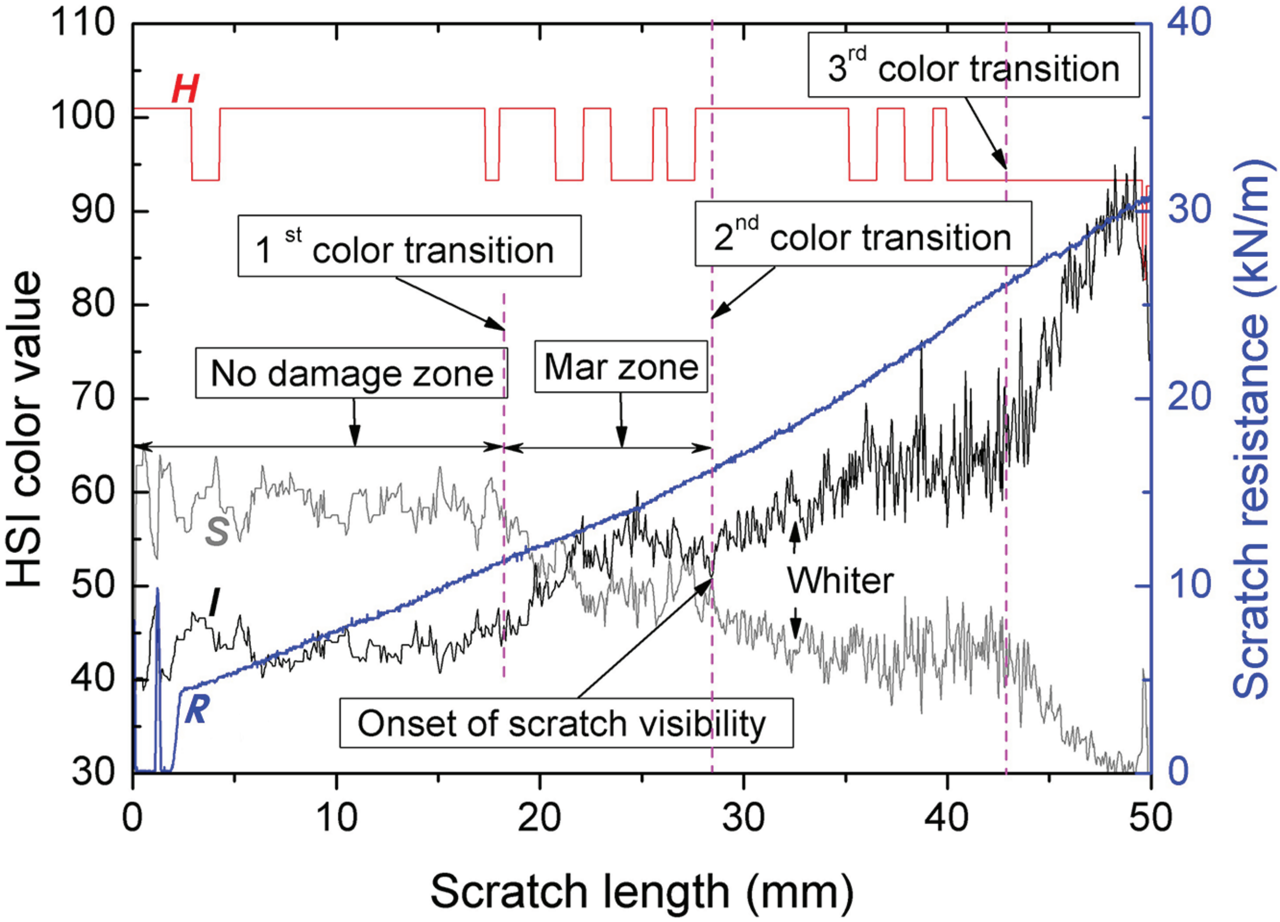
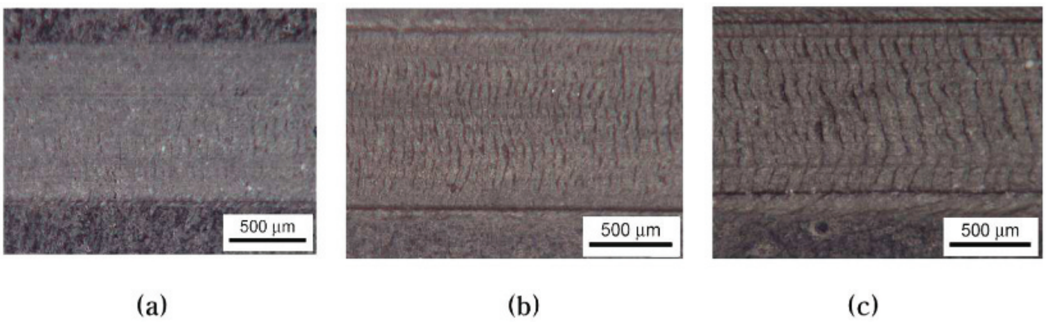


Figure B.3 — HSI colour image analysis result and the corresponding scratch visibility of PP composite surfaces with normal load ranges of 1-30 N (*H*: hue value, *S*: saturation value, *I*: intensity value, *R*: scratch resistance)



NOTE Subfigures (a) to (c) magnified micrographs taken from the areas as indicated in Figure B.2 I to III, respectively.

Figure B.4 — Optical microscopy micrographs of scratch-induced PP composite surfaces with various damage regions of interest

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