

A Multidimensional Scaling Analysis of Surface Perceptual Parameters on Scratch and Mar Visibility Resistance in Polymers

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ABSTRACT

Brightness, transparency, and color impact critically the aesthetics of polymeric surfaces. They can significantly change the perception of common damages such as scratch and mar. Particularly, subtle mar damage is more dependent on surface perceptual properties. In this study, we investigate the impact of these attributes on scratch and mar visibility resistance of commercialized polymeric model systems frequently used in automotive industry. Twenty subjects were involved in a psychophysical test based on pairwise comparison, and results were treated using multidimensional scaling (MDS) analysis. A tied ordinal weighted Euclidian MDS model was used to visualize the relational structures of mar perception space. Results show that scratch visibility resistance tends to decrease with dark, more transparent, and green surfaces. Mar perception was reasonably conceptualized by a two-dimensional MDS space. MDS results show that Brightness, transparency and color have a decreasing level of impact on mar perception. Mar visibility resistance decreased with dark, less transparent, and green stimuli. However, transparency effect is still dependent on the sample background. To the best of our knowledge, this is the first MDS study applied to the analysis of mar perception on polymeric surfaces, or any surface damage perception in general. The presented MDS-based model can be utilized to study the effect of other attributes on surface perception. This approach offers a new avenue for the assessment of scratch and mar perception and the development of polymeric materials with better visibility resistance.

KEYWORDS: Product design, aesthetic properties, multidimensional scaling, visibility resistance, scratch and mar

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I. INTRODUCTION

Surface appearance is the foremost and most impressive product message [1]. Extensive studies were performed to understand and quantify the assessment of surface visual appearance by the consumers [2, 3]. The aesthetic properties of the different materials and products are considerably affected in the presence of surface mechanical damages such as scratch [4, 5, 6, 7]. Particularly, scratch has a significant impact on the appearance of polymeric materials, extensively used in the industry [8]. This created an urgent need to quantify and improve their scratch visibility resistance. Using an optical imaging methodology, Rangarajan et al. determined scratch visibility resistance on polymeric systems by applying a constant load and measuring the contrast between the scratch damage and its surrounding area [9]. To better investigate the different transitions across the scratch path, Wong et al. applied a progressive load to study the scratch behavior of polypropylene [10]. This test was later considered as an ASTM/ISO standard [11, 12]. Based on this

standard, many other studies were conducted to investigate scratch visibility resistance in polymers. Jiang et al. used light scattering theories to establish a correlation between scratch perception and scratch features, namely the height and the depth of the scratch grooves [13]. However, the scanning angle and direction used in this study posed several challenges for samples with high gloss levels due to significant light reflections. Therefore, Hamdi et.al proposed a new experimental setup to overcome light reflection and better capture scratch damage on glossy surfaces [14]. Scratch resistance can be affected by several material properties and experimental parameters such as test rate and direction [15, 16], thermal history [17], molecular weight [17, 18], molecular orientation [19], surface roughness [20], additives [21], and laminate structure [22]. These parameters change scratch features, and thus affect the contrast between the scratch and its background.

Automatic Scratch Visualization (ASV) software was designed to better quantify scratch visibility resistance in polymers [13]. It was demonstrated in previous studies that 3% contrast, 90% scratch continuity, and 90 μm minimum feature size are consistent parameters for the approximation of human perception [23]. ASV uses these parameters to approximate the scratch visibility resistance obtained via human observation test, also known as *psychophysical test*. The combination of psychophysical and ASV results provides a better understanding of scratch visibility resistance. This software is designed and commercialized by Surface Machine Systems (SMS) Company [24]. It has been employed in our study to determine scratch visibility resistance and compare it to psychophysical test. The scratch pictures introduced to ASV were obtained using the same black box setup described previously [14].

Mar is another surface damage that can significantly affect the aesthetic properties of polymeric products and thus the visual assessments of the consumers. It is frequently encountered in automotive industry, such as the damage caused by automated car washing [25, 26]. But it can also be found in many other industrial fields like paint and label industries. Although its frequent occurrence in industry, little research has been conducted to study mar visibility resistance because of its challenging and complex properties. Up to recently, the terms “scratch” and “mar” have been exchanged carelessly in some studies as if they meant the same damage [27]. However, scratch consists in medium to severe damage, while mar refers to shallow and faint surface damage. A few experimental tests were employed previously to assess mar resistance such as Amtec laboratory car wash test [26]. Although these tests are realistic, they were unable to provide a quantitative description of mar behavior. A more standardized mar test can be performed based on the same scratch ASTM/ISO standard, but using a different tip, as was done in a previous study [28]. In the same study, a contrast-based analysis showed that mar visibility resistance, determined using mar onset, improves with textured and modified surfaces. However, for more consistent results, Hamdi et al. showed recently that, unlike scratch, the whole mar damage should be considered while studying mar visibility resistance and not just mar onset [14]. The quantification of mar is still an ongoing effort to better understand its behavior. Since this faint damage is more dependent on surface properties, it is believed that perceptual properties like brightness and transparency play a major role in its visibility resistance. Yet, to the best of our knowledge, no previous study was conducted to determine the impact of these properties on mar.

The study of mar visibility resistance on samples with different perceptual properties is more consistent when, like scratch visibility resistance, supported by psychophysical test. This test is much more reliable if it is based on a recognized fundamental statistical technique, such as *Multidimensional scaling (MDS)*. MDS is an exploratory data analysis technique designed to unveil the “hidden dimensions” in the organization of data displaying the most important relationships and inferences in an economical, visual fashion [29]. It is frequently employed to represent measurements of dissimilarities among pairs of objects as distances between points in a low-dimensional space [30]. Instead of dissimilarities, the experimental measurements can be other various expressions of distances like similarities, probabilities, interaction rates between groups, correlation coefficients, or any other measure of proximity or dissociation [31]. MDS was utilized in a wide range of applications. Particularly, it was used to study the human assessment of surface perceptual attributes, such as color and brightness [32], gloss [33], as well as other properties like haptic perception [34]. A broad review of MDS technique and its utility in different psychological domains is provided by Jaworska et.al [35]. Also, the basic concepts of MDS technique are summarized in the [appendix](#) of our paper.

The aim of this work is to study the impact of brightness, transparency, and color on scratch and mar perception based on a series of model plastics. In mar analysis, a psychophysical test was performed based on pairwise comparison test and using MDS statistical approach. The usefulness of this study in quantifying and improving scratch and mar visibility resistance is discussed.

II. EXPERIMENTAL

1. Model Systems

The model material systems selected in this study consist of 13 commercialized polycarbonate (PC) stimuli frequently used in automotive and other industries. They were used to study the impact of three perception attributes, namely, brightness, transparency, and color. The polymeric composition and sample processing conditions were uniformly controlled for all samples, varying only slight additive formulation to control their aesthetics. Opaque samples have three colors, red (R), blue (B) and green (G), with three brightness levels, low (1), medium (2), and high (3) per color to study brightness effect. Color effect is mainly studied using medium-brightness samples where brightness level is moderate. Transparency samples (T) consist of four levels of transparency, low (T1), medium (T2), high (T3), and highest (T4). Red and transparency samples are shown in [Figure 1](#).

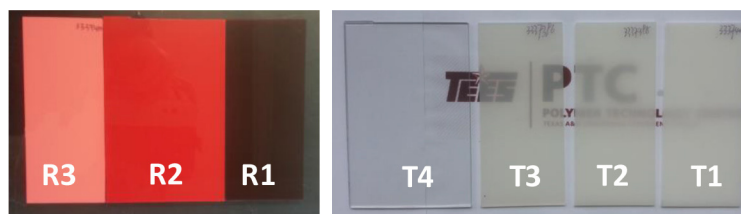


Figure 1. Red and transparency model systems used for the present study.

Also, to quantify their transparency level, the transmission UV-Vis spectra of the transparency samples were acquired using a UV-Vis-NIR spectrophotometer (Shimadzu, UV-3600). The wavelength range was set from 200 nm to 800 nm as shown in Figure 2. The transmittance of highest-transparency sample (T4) is higher than 80 % in almost all the visible light region (400 nm to 800 nm). Then, it decreases with decreasing transparency level as illustrated in the figure. It has a significantly low value for the sample T1 which has the lowest transparency. These results quantify and provide a better understanding of the transparency levels of transparency model systems.

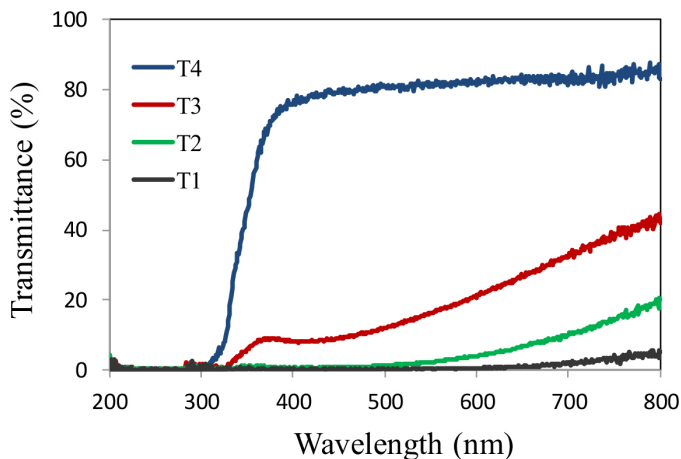


Figure 2. UV-Vis transmittance spectra of transparency samples.

All model systems were provided by SABIC. They were molded on a 260 ton on molding machine using a 15 cm x 20 cm variable thickness smooth mold (Society of Plastics Industry, SPI A-2 Finish). They were cut in half to make 10 cm x 15 cm plaques. They were then fixed in direct contact with the background of the setup, and tests were conducted on the smooth side of each sample. The background of the samples is black in scratch observation setup and white in mar observation setup. It is expected that this background plays a major role in determining scratch and mar visibility resistance of transparency samples.

2. Scratch and Mar Tests

After cleaning the samples with air brush, scratch and mar tests were conducted using ASTM D7027-05/ISO 19252:08 standards [11]. The applied load increased linearly from 1 N to 150 N for scratch and from 1 N to 120 N for mar, at a speed of 100 mm/s, over a distance of 100 mm. A 1 mm spherical tip was used for scratch tests, and a barrel tip with a diameter of 10 mm and a width of 12 mm was used for mar tests. For each stimulus, at least five scratch tests and three mar tests were conducted in the flow direction to avoid scratch variation [17]. Also, usually scratch resistance of polymeric systems is lower in the flow direction as was shown for PC samples [15]. Therefore, scratch test is conducted in this direction to consider the worst-case scenario.

3. Psychophysical Tests

The psychophysical test was conducted at least 24 hours after performing scratch and mar tests to account for the viscoelastic recovery of the samples. None of the authors was included in the psychophysical tests. For scratch analysis, the observation setup has a

black background and visibility onset was determined by five trained subjects. This number of subjects was sufficient because scratch perception is much clearer and more straightforward than subtle mar damage. For mar analysis, the pairwise test was conducted as follows:

a. Subjects

Since mar observation is trickier than scratch, 20 subjects were involved in this test for more statistically reliable results. They were from different backgrounds and they consist of 8 undergraduate students, 10 graduate students and 2 professionals with corrected to normal vision and aged between 19 and 35. They were unaware of the purpose of the experiment and the used MDS technique.

b. Test Condition

To achieve a better mar visualization, the psychophysical test was conducted in controlled conditions (Figure 3). The experimental setup was in a dark room to avoid unwanted light reflections. Illumination and observation angles were fixed to 0° and 45° consecutively relative to normal, with a fixed distance between subjects and the samples. In other words, the light direction is perpendicular to the plan of the samples and forms always a 45° angle with the observation direction.

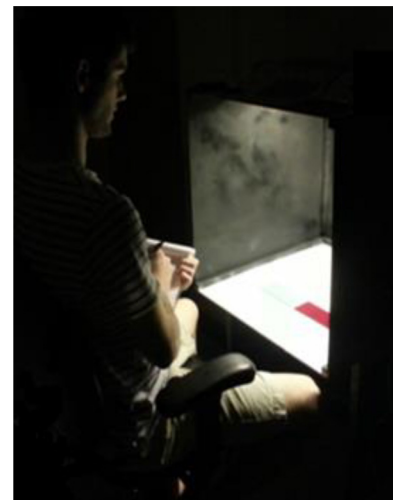


Figure 3. Experimental conditions for mar MDS psychophysical test.

A 940 lumens fluorescent light bulb was utilized on the top of the white surface with an area of almost 0.25 m². Therefore, the light intensity of the bulb is around 3700 lux, which is believed to be a reasonable intensity. In fact, it is reported that the luminance of an overcast day is about 1000 lux and that of a full daylight starts from 10000 lux [36]. Therefore, a luminance of 3700 lux is sufficient to mimic real-life scenarios as shown in Figure 3.

c. Pairwise Comparison Test

Subjects were first asked to look carefully at all the samples to familiarize themselves with mar damages. Then, they were given the following instructions of pairwise comparison test:

"Put two samples just below the indicated line in the middle [to maintain the required 45° observation angle], look at mar damages on both of them and record their ranking. Do not rate how visible the damages are, but rather how different they are from each other. The dissimilarity scale goes from 0 to 10, 0 means that mar damages look very similar between the two samples, and 10 means they are very different. Also, indicate which sample has more visible mar. Then, do the same process for each pair of all these samples."

Each subject takes randomly two samples to compare, and keeps repeating the process until all possible pairs of samples are compared. The average test duration is about 90 minutes per subject.

4. Software

ASV software, described in the introduction, was used to determine the scratch visibility resistance of the studied model systems. As for the MDS analysis of mar visibility resistance, we utilized the widely used software package, *IBM SPSS Statistics* [37]. Particularly, Individual Differences Scaling (INDSCAL) algorithm implemented in SPSS is commonly used to conduct weighted Euclidean MDS [30, 38]. Individual proximity matrices of all the 20 subjects were uploaded to SPSS software. Tied ordinal weighted Euclidean MDS model based on monotone regression approach was conducted. Also, positive weights restriction was imposed and Kruskal stress (or Stress-1) was employed. To determine the optimal MDS space, Minkowski exponent r was changed from 1 to 4, and space dimension went from 2 to 6. Moreover, it is of computational significance to determine the most convenient number of iterations for each stress measurement. In ordinal MDS, the sufficient number of iterations is determined when Shepard diagrams of all the subjects show monotonic relationships [39]. This criterion will be considered in our analysis. Initially, a maximum of 30 iterations is considered. More details about the basic concepts of MDS tools used by IBM SPSS software can be found in the [appendix](#) of this paper.

III. RESULTS AND DISCUSSION

1. Scratch Visibility Resistance

Scratch visibility resistance is defined as the applied load at which scratch becomes visible. Therefore, a higher load corresponds to a better scratch visibility resistance. For each set of samples, experimental results obtained using ASV are compared to the psychophysical tests.

a. Brightness Effect

Brightness is a characteristic color feature which can be described by an existing amount of gray or black [40]. A distinction was made previously between the terms brightness and lightness. In some studies, lightness refers to the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting [41]. In other references, brightness refers to self-luminous objects while lightness to nonself-luminous ones [40, 42]. In our study, brightness simply refers to the amount of grey/black in the colors of the samples and it is standardized to a grey scale where white and black are assigned to the values of 1 and 0, consecutively [40, 42].

Brightness effect on scratch visibility resistance of green, red, and blue samples is shown in [Figure 4](#). The terms "low", "medium", and "high" in the figure refer to brightness level. For each color, psychophysical and ASV results are in a good agreement. They show that scratch visibility resistance improves with higher-brightness stimuli. This is explained by the behavior of scratch damage. In fact, during the scratch test, severe surface deformation leads to *stress-whitening* damage responsible for scratch perception [1]. Therefore, when brightness increases, i.e. when the amount of grey/black in the color decreases, whitening damage becomes more hidden, and scratch visibility resistance is improved.

To check this hypothesis, scratch damages on the transparent sample T4 ([Figure 1](#)) were observed on black (significantly low brightness) and beige (significantly high brightness) backgrounds. Results are shown in [Figure 5](#). Scratch visibility resistance is much lower (i.e. scratch-background contrast is much higher) when the brightness level is significantly low in the case of black background. This comparison shows better the brightness effect on scratch visibility resistance.

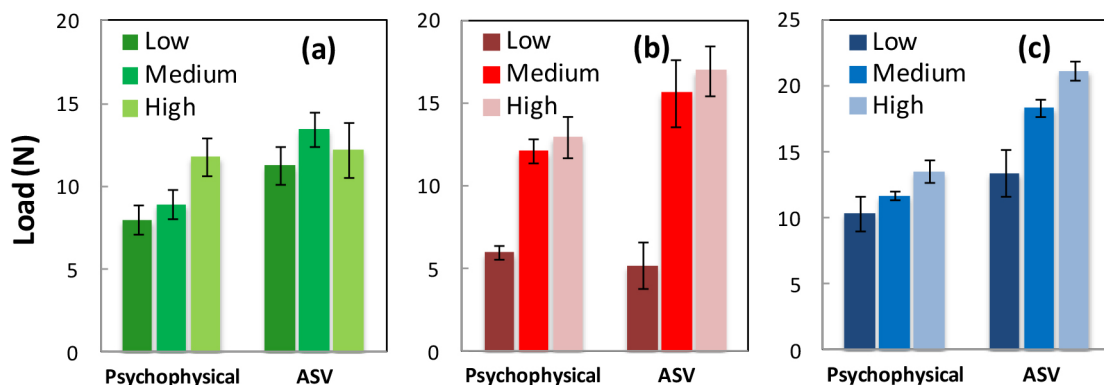


Figure 4. Brightness effect on scratch visibility resistance of (a) green, (b) red, and (c) blue samples.

