Multiscale effect of paint pulverization orientation on appearance after painting

S. Mezghani¹, H. Zahouani², J. Piezanowski³

¹Arts & Metiers ParisTech, LMPF, rue St Dominique – BP 508, 51006 Châlons-en-Champagne – France;
²Ecole Centrale de Lyon, LTDS UMR CNRS 5513, 36 avenue Guy de Collongue, 69131 Ecully Cedex, France;
³Arcelor Ledeep Florange, 17 Avenue des Tilleuls, 57191 Florange, France;

E-mail: sabeur.mezghani@ensam.eu

Abstract. The perceived quality of a vehicle is strongly affected by paint appearance that shares major part of the outer car body panels. The painting process modifies the surface topography in a wide range of roughness and waviness scales, and consequently modifies the functionality of the surface in terms of appearance. Since painting process is a multistage process leading to stratified surfaces, a multiscale surface topography characterization approach is suited. In this paper, 2D multiscale signature of the painting process was introduced and applied to track the effect of the painting process working variable on painted surface topography in a wide range of wavelength. To this aim, experimental painting tests were performed using three painting orientation modes (horizontal, oblique and vertical) on random and deterministic metal sheet surface textures. Results show that the painting orientation mode affect only the wavelength band greater than 500 µm and optimal painting orientation depends strongly on the texture of the initial sheet surface.

1. Introduction

The exterior paint finish of a car plays an important part in how the customers perceive its quality. Unfortunately, the large number of different process parameters (paint thickness, substrate texture and orientation during paint application...) makes it complicated for the plant operator to maintain a high quality of production. Moreover, quality inspection and monitoring are carried out visually these days, by means of measurements by trained personal after the painting process [1]. This method is inadequate for various reasons: (1) undefined evaluation conditions; (2) judgment is dependent on the mood of the observer; and (3) different observers have different visual acuity [2, 3]. Therefore, improved quality inspections and objective quality criteria are necessary to meet rigorous quality requirements.

In this paper, the concept of multiscale process signature (MPS) is applied as a new experimental investigative approach for monitoring the dynamics of surface features modification after paint coating with different substrate orientations [3, 4]. To this aim, experimental painting tests were performed using three painting orientation modes (horizontal, oblique and vertical) on random and deterministic metal sheet surface textures. Rays-tracing simulations of light scattering from painted surfaces were performed to track the effect of substrate orientations during painting on surface appearance. As we...
will see in subsequent sections, MPS spectrum presents a good indicator of the light scattering behavior of the painted surface and hence of its appearance.

2. Experimental procedure
The paint finishing of automotive board is a multistage process [2, 3]. It consists of the deposition of three successive paint layers. The first coated layer called “Primer” is the thickest; its thickness varies between 37 µm and 43 µm. The second coat is the main layer of the paint, we call it “basecoat” and it has a thickness varying between 32 µm and 38 µm. Finally, the last top coat “Lacquer” is a finer film, ranging from 14 µm to 16 µm thicknesses.

In this study, three orientations of the substrate sheet surface during painting were considered: horizontal, oblique (45°), and vertical. In addition, two main different textures types of a steel sheet substrate were considered: stochastic and deterministic (see Figure 1). They were finished by a succession of the three paint coating layers. Fig. 2 shows the topography of the steel substrate of each texture categories at the final stage by three orientations of the substrate during painting.

![Figure 1. 3D metal sheet surface topography with two texture categories: (a1) random and (b1) deterministic and their height distribution histogram respectively (a2) and (b2).](image)

In each painting process configuration, the measurement of the initial and painted surface topography was carried out by interferometric instrument (Interferometer NT 2000 WYKO). This 3D microscope can be prided on a resolution of 2 µm and total amplitude of measurement bordering 2mm. The resolution in z-direction of interferometer is 10 nm. The surface was sampled in 512×512 points with a 26 µm step scale in the x-direction and 30 µm in the y-direction. In this study, the wavelength bandwidth range from 200 µm to 6 mm is considered.

3. Multiscale quantitative expression for the scale of painting appearance
To derive a quantitative expression for paint finishing, we consider a multiscale analysis of the surface texture before and after painting which involves the decomposition of its topographic profiles into different roughness scales. This decomposition uses continuous wavelet transform which can be considered as a mathematical microscope, where the resolutions are the basic functions obtained from a single wavelet or mother wavelet by $\psi(x)$ dilation (or compression) and translation [3, 4]. The "Morlet 1D" wavelet given by the following expression is used:
The result of the decomposition makes it possible to identify the various scales of the topographic signal after a 1D inverse wavelet transformation [4]. The methodology consists of the quantification of the arithmetic mean value for each scale.

\[
\psi(x) = \pi^{1/4} e^{i\omega x} e^{-x^2/2}
\]  

(1)

The objective is to determine a quantitative expression of the spectrum of arithmetic mean value from the scales of waviness to roughness, \( Ma \) [3, 4]:

\[
Ma(a) = \frac{1}{N} \sum_{x=1}^{N} \left| W^a_x(x) \right|
\]  

(2)

The multiscale characterization methodology was applied in order to quantify the effect of the painting orientation mode on the various scales of the substrate surface. The painting process can be expressed by the action of a weight function, which transforms all the scales of the initial surface (Fig. 1). The painted surface \( F(x, y) \) and the initial substrate topography \( I(x, y) \) can be related by the multiscale process signature \( MPS(a) \) of painting using Eq. (3) [3, 4].

\[
MPS(a) = \frac{[SMa^F(a)] - [SMa^I(a)]}{[SMa^I(a)]} . 100
\]  

(3)

where \( SMa^I(a) \) and \( SMa^F(a) \) are respectively the multiscale roughness spectrum of the surface before and after painting.

The MPS spectrum of the painting process between the final stage (Top coat) and the initial surface topography for three different position modes (horizontal, oblique (45°), and vertical) were computed. Figures 3-a and 3-b show the influence of the sheet substrate orientation during painting on the generated surface topography, respectively, for stochastic and deterministic texture of the initial sheet.

Figure 2. 3D topography respectively of random (a) and deterministic (b) substrate surface texture obtained by three orientation modes during painting process: (x1) horizontal, (x2) oblique 45°, and (x3) vertical.
We can remark from these figures that structured surfaces with small size patterns (0.35 mm) permit to discard generation of waviness scales greater than 3 mm. Moreover, The MAF spectrum shows that substrate orientation working variable affects the waviness scales. In fact, independently of the initial surface texture, horizontal painting mode leads to more waviness attenuation than by oblique (45°) and vertical mode.

![Figure 3. MPS spectrums after the top-coat painting stage respectively for (a) stochastic and (b) deterministic surface texture of steel sheet substrate. Three substrate orientations (Horizontal, oblique and vertical) during the paint process are considered for the two kinds of initial surface texture.](image)

4. Identification of the multiscale single-point diamond turning process signature

In this section, we are interested to investigate the light scattering from surfaces after painting process with different substrate orientation during painting. The objective is demonstrating the pertinence of the MPS as multiscale indicator of surface appearance in relation to the process working variables.

4.1. Ray-tracing simulation tests

The simulation is based upon geometrical optics approximation of the exact numerical integration methods available from electromagnetic wave theory. The approximation is ray-tracing approach, where energy bundles are traced throughout their interactions with the surface until they leave it [5-7]. The geometrical optics approximation (GOA) is valid for $\sigma \cos(\theta)/\lambda > 0.17$ and for $\sigma/\tau < 2.0$, where $\sigma$ is the root mean square roughness height, $\tau$ is the correlation length, $\theta$ is the angle of incidence and $\lambda$ is the light wavelength [5].

In this work, 500 rays were considered in each simulation allowing a tradeoff between execution time and statistical significance of the simulation results. Assuming that the whole surface is illuminated, the beam radius is equal to the surface length. A typical human eye will respond to wavelengths from about 390 nm to 750 nm. A light-adapted eye generally has its maximum sensitivity at around 555 nm. At this wavelength, the refractive index of the basecoat is considered equal to 1.5.

We assume here that the top-coat layer is opaque. Hence, it is where all the light is reflected. The root mean square of height and correlation length in the x and y direction of each painted surface are used as input in the simulation test. These parameters are computed from the acquired surface topography of each surface.

4.2. Effect of painting process orientation on light

Figure 4 show the influence of the sheet substrate orientation during painting on the bidirectional reflectance distribution function (BRDF) for an incidence angle of 20°. The BRDF spectrums represented in figure 4 show that horizontal painting mode leads to a surface topography characterized by the most important light scattering in the specular direction (fig. 4). Then, the best paint appearance is obtained when the sheet substrate is oriented horizontally during the painting process. From the MPS spectrum given in figure 3, we can see that this painting mode (horizontal orientation mode) leads also to the greater waviness attenuation in particular for wavelength greater than 2 mm (fig.3)
and independently to the initial substrate texture. Therefore, the better surface appearance results from the greatest waviness reduction.

![Figure 4](image)

**Figure 4.** BRDF of the different operating conditions respectively for: (a) stochastic and (b) deterministic substrate surface texture.

5. Conclusion

In this work, the concept of multiscale process signature (MPS) is applied as a new experimental investigative approach for monitoring the effect of substrate orientation during the paint coating process. Rays tracing simulations of light scattering from painted surfaces were performed to track the effect of substrate orientations during painting on surface appearance. Results demonstrate that the appearance quality of painted surface is closely related the waviness amplitude particularly for wavelength greater than 2 mm. Therefore, MPS spectrum ensures the link between the operating parameters of the painting process and the appearance quality of the generated surface.

References

[1] Talbert Roger, Paint technology handbook (ISBN 978-1-57444-703-3), p.172.
[2] H. Zahouani, S. E. Pokossi, S. Mezghani, R. Vargiolu, H. Jacobs, J. Piezanowski, "Characterization of the Painted Surfaces Appearance by Continuous Wavelet Transform", 9th International Conference on Metrology and Properties of Engineering Surfaces, 10 – 11 Septembre, Halmstad University, Sweden, pp.56-66, 2003.
[3] Mezghani, S., Zahouani, H., Piezanowski, J.-J., Multiscale characterizations of painted surface appearance by continuous wavelet transform, Journal of Materials Processing Technology 211 (2), 2011, pp. 205-211.
[4] H. Zahouani, S. Mezghani, R. Vargiolu, M. Dursapt, "Multi-scale study of abrasion signature by 2D wavelet decomposition", Wear, Vol. 264 (5-6), 2008, pp. 480-485.
[5] Tang, K.; Dimenna, R.; Buckius, R.: "Regions of validity of the geometric optics approximation for angular scattering from very rough surfaces”, International Journal of Heat and Mass Transfer, Volume 40, Issue 1, pp. 49-59 (1997).
[6] Bergström, D.; Powell, J.; Kaplan, A.: "A ray-tracing analysis of the absorption of light by smooth and rough metal surfaces”, Journal of Applied Physics, Volume 101, Issue 11, pp. 113504/1-11 (2007).
[7] Bergström, D.; Powell, J.; Kaplan, A.: "The absorption of light by rough metal surfaces - A three-dimensional ray-tracing analysis", Journal of Applied Physics, Volume 103, Issue 10, pp. 103515/1-12 (2008).