INTER-RELATIONSHIP BETWEEN 3D AND 2D ROUGHNESS PARAMETERS AND THE STAMPABILITY/ PAINTABILITY OF COLD ROLLED STEEL SHEETS FOR THE AUTOMOTIVE INDUSTRY: A PRELIMINARY ANALYSIS[1]

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Abstract
The aim of this research work is to study the inter-relationship, under controlled industrial conditions, between surface topography (characterized by 2D and 3D) roughness parameters and painting surface finish quality for automotive steel sheet stampings. Different surface textures obtained from cold rolling finishing have been evaluated in terms of paintability tests (rating and spectral curve) and tentatively related to the roughness (2D and 3D) obtained from the cold finished sheets. Some relevant tendencies have been established amongst these parameters. The results here presented are in accordance with other recently published research show that there is a clear relationship between these parameters, and that further detailed studies are needed.
Keywords: Surface topography; Steel sheet metal; Paintability.

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1 INTRODUCTION

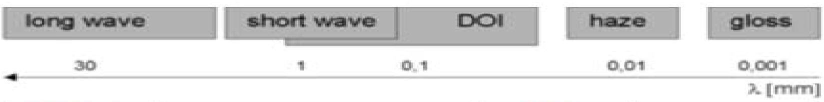
The visual appearance of the painted steel sheet surface has always been given close attention because it is often experienced as a first expression/evaluation of the quality of the product towards the end-user, especially in the automotive and consumer appliances industry. Protecting the steel sheet against environmental influences was also the main challenge for the steel manufacturer for many years. More recently however, sheet steel manufacturers (and mainly end users) have also been focusing their attention on the visual appearance of painted steel sheet as soon as it was clearly established that there was an influence of steel sheet topography on properties such as orange peel and image clarity. Interest increased still further when it became obvious that the requirements for formability and appearance after painting were difficult to reconcile. For a nondeterministic roughness, such as the traditional shot blast texture (SBT), one usually observes that the higher the roughness, the better the formability, however poorer will be the appearance after painting. Several studies were published in which the influence of the steel sheet surface on the final paint appearance has been described. From the literature it was found that the surface appearance after painting decreases with increasing waviness and all roughness parameters associated with height of profile. Painting appearance increases with increasing of peak and valley density roughness parameters.(1) On the other hand, the surface structure of steel sheets in metal forming is commonly applied by the skin pass rolls which are to be roughened by several methods.(2) The function of the generated surface is to influence the tribological properties in the forming process and to achieve an excellent paint appearance of the finished product. As the common stochastic structures like shot blast texturizing (SBT) do not meet all requirements of the production line on the way to the final product several new structures have been developed: EDT(electro discharge texturizing), LT(laser texturizing), EBT(electron beam texturizing), Pretex, etc.(2-5) Due to the deterministic feature of their structure, such topographies are totally different from those usually applied. This is of great consequence to their characterization by roughness parameters which are well known from ISO, DIN and others: common 2D parameters are not in a position for a clear characterization of the topography. Thus these surfaces require adequate new parameters to characterize them. This can only be done sufficiently by 3D surface parameters, which are able to describe the characteristics.(2) Furthermore, many metal forming operations involve liquid lubricants to reduce friction at the tool/part interface to improve the finished part surface quality. In most of these operations the mixed lubrication regime appears, leading to local asperity contact between the tool and part surfaces in between pockets functioning as micro-reservoirs for the lubricant. During processing the reservoirs are deformed and the entrapped lubricant is pressurized and eventually escaping by Micro Plasto Hydrodynamic Lubrication (MPHDL), leading to local, non-uniform deformation of the surface layer. It is of great importance to understand and control the lubrication phenomena in order to reduce friction and improve the resulting surface quality. As pointed out by Bay et al.(6) and Dubar et al.(7) the advantages of using structured sheet surfaces are due to the special lubrication mechanisms appearing when lubricant is entrapped in pockets in the surface, pressurized and subsequently extracted from the pockets. On the other hand, friction influences strain paths during stamping which plays the major influence on sheet metal roughness evolution. Further details on these subjects may be obtained from Nunes.(8)

The main aim of the present study was the assessment of a group of parameters (2D and 3D) which better correlate steel sheet metal roughness to painting appearance in order to optimize it for automotive panels. Therefore it is essential to comprehend how sheet metal surface topography evolves in each of the five painting layers as shown in Figure 1 (Phosphate, E coat, primer, base coat and clear coat) and how clear coat surface topography influences painting appearance.

Figure 1: The layers: from substrate to clear coat.[8]

One of the main goals of the painting process is to minimize the transference of sheet metal surface topography to the clear coat surface which is evaluated with focus on the quality of the surface and the reflected image. Surface structures with dimensions above 0.1 mm can be seen directly by the unaided eye, smaller structures become manifest by their effect on the directional distribution of the reflected light. Structures at and below 0.1 mm reduce the distinctness of image (DOI), structures in the range of 0.01 mm induce haze and even smaller structures affect the gloss of the surface.[9] Table 1 summarizes the size of the surface structure / topography with the wavelength of the reflected light.

Table 1: Top: The size of the surface structure / topography and its correlation with the wavelength of the reflected light. Bottom: The equipment and standards used to evaluate its painting appearance characteristic[8]



Painting appearance	Equipment	Physical principle	Standard
Long wave Short wave	 Wave scan dual https://www.byk.com/en/instruments/products/appearance-measurement.html	Reflected light intensity	ASTM E 430 ASTM E 284-91
Gloss	 Gloss meter https://www.byk.com/en/instruments/products/appearance-measurement.html	Reflected light intensity	JIS Z 8741 DIN67530 DIN EN ISO 2813 ASTM D 523 ASTM D 2457

The most used equipment in automotive industry to evaluate painting appearance with focus on the size of the surface structure is the wave scan which works with a range of wavelengths based on the ones that are visible to the human eye at a distance of 40 cm (Short wave - SH) and 3 m (Long wave – LH), as shown in Figure 2, left side. Evaluation method consist on the analysis of the wavelengths, short (SW) and long (LW), that are created by the interaction of an incident laser beam at 60° to the painted surface and collected at the same angle on the opposite side, as shown in Figure 2, right side. Painting appearance is better as less SW and LW are created which means that for a perfect specular surface SW and LG should tend to zero.

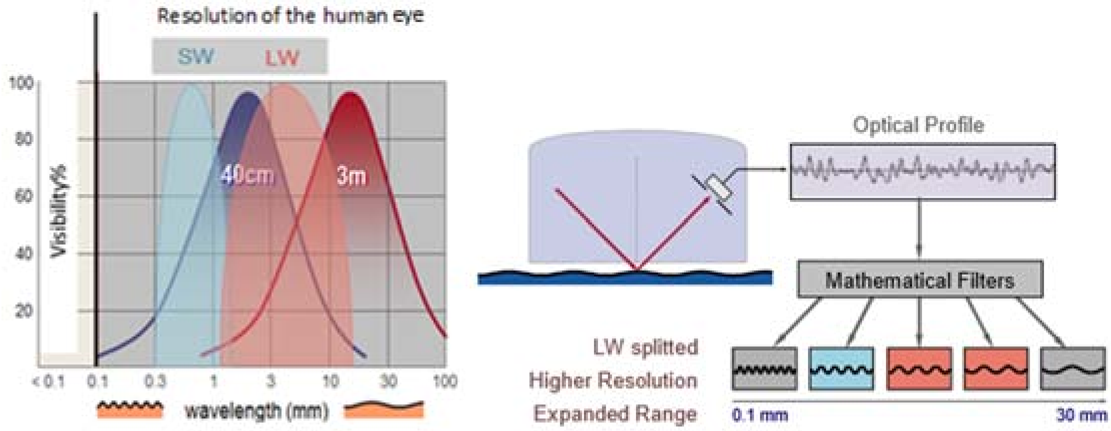
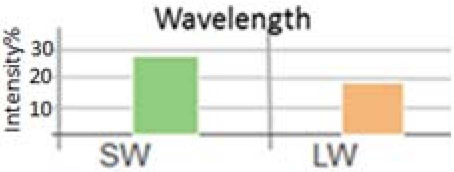


Figure 2: Left: Visibility of structures is dependent on the observing distance. The curves blue and red show the wavelengths visible to the human eye at a distance of 40 cm and 3 m, respectively. Right: Wave scan evaluation method is based on the wavelength range (SW - 0.3 to 1.2mm and LW – 1.0 to 12 mm) similar to the ones visible to human eye at the distances of 40cm and 3 m.(11)

Although several companies use the same equipment, each one of them has their own way to evaluate its painting appearance. GM, for instance, uses a scale called rating (R), that usually varies from 3 (worst) to 10 (best) and its value is calculated from eq. 1, figure 3, which inputs are the intensity (0 to 100%) of the SW and LW created by the interaction of an incident laser beam with the painted surface. In general, from an automotive panel measured at the clear coat layer, intensity in percentage of LW should vary from 5 to 25 and SW from 10 to 50. As rating values are much more sensitive to LW, some car companies correlated its value to orange peel (LW).(11)



$$R = 10{,}5 - 4\log_{10}(a - 0{,}02^{*}|b - 20|) \qquad \text{Eq. 1}$$

$$a = 20\left(10^{(LW/67)} - 1\right) \qquad b = 20\left(10^{(SW/67)} - 1\right)$$

Figure 3: Rating is based on a range of wavelengths visible to the human eye at a distance of 40 cm (Short wave - SW) and 3 m (Long wave – LW).

In order to improve the quality of the painting appearance analysis Byk Gardner upgraded the wave scan analysis replacing the classical SW and LW scales by five sub-scales Wa, Wb, Wc, Wd and We which results in turn are represented by the spectral curve, as shown in Figure 4.

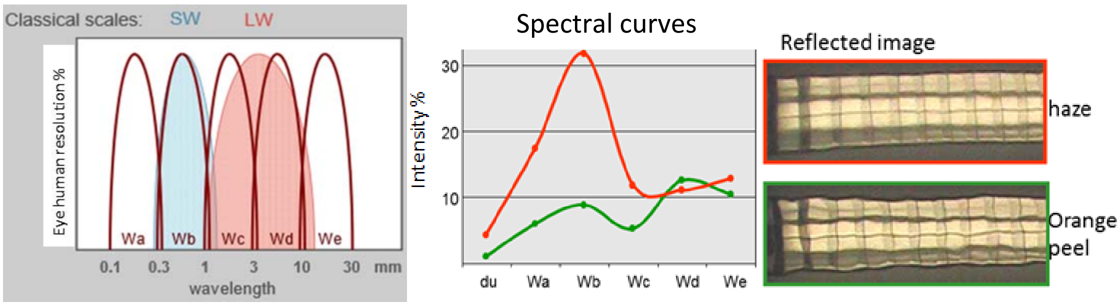


Figure 4: Left: The wave scan with five wavelength scales, Wa, Wb, Wc, Wd and We, instead of two, SW and LW from the current wave scan. Right: Two typical spectral curves. The red one where short waves are predominant and its associated reflected image with haze effect and the green one with predominant long waves and correspondent reflected image with orange peel effect.[11]

2 MATERIALS AND METHODS

The present study was divided into two steps (Figure 5).
First step: Rating was analyzed on 22 samples with different sheet metal roughness (Table 2) at the E- coated layer.
Second step: The best and worst rating (sorted out from the first step) sheet metal samples were fully painted, separating one sample at each stage, namely: Sheet metal, Sheet metal + phosphate, Sheet metal + phosphate + E coat, Sheet metal + phosphate + E coat + base coat and Sheet metal + phosphate + E coat + base coat + clear coat and then evaluated (for each stage).Their surface topography in 2D and 3D, rating and spectral curves from E coat to the clear coat and gloss on the clear coat were evaluated. The equipments utilized for the evaluation are listed in Table 3.

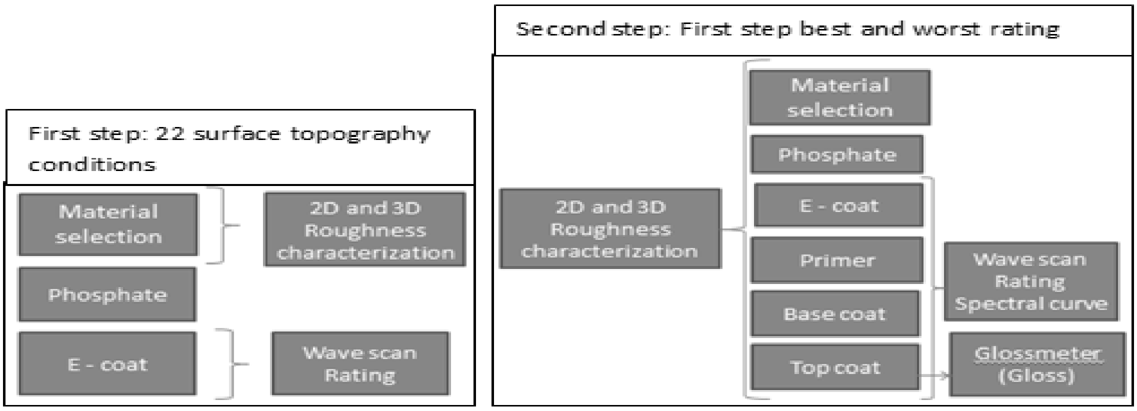


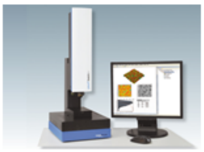
Figure 5: Methodology employed in the present work.[8]

Table 2: Materials with different roughness(8)

TEST	Cylinder Texture	Coil Position	reduction %	Material specification: Grade	Coating	Mill
1	Shot Blast	Initial	0.3	CR4	UNCOATED	A
2			0.5			
3			0.8			
4			1.0			
5		End	0.3			
6			0.5			
7			0.8			
8			1.0			
9	EDT	Initial	0.3			
10			0.5			
11			0.8			
12			1.0			
13		End	0.3			
14			0.5			
15			0.8			
16			1.0			
17	EDT			CR4	HD60G60G	B
18				CR2	UNCOATED	C
19				CR4	HD60G60G	D
20				CR2	UNCOATED	B
21				CR4	HD60G60G	C
22				CR4	HD60G60G	D

Note: HD60G60G = Zinc hot dip galvanized coating on both sides of the sheet metal. Thickness is 60 g / m^2. ISO 1460:92

Table 3: Equipment used in the present work(8)

Equipment					
Supplier	Taylor Hobson	Zygo	Nanofocus	Byk Gardner	Byk Gardner
Site	www.taylorhobson.com	www.zygo.com	www.nanofocus.com	https://www.byk.com	https://www.byk.com
Model	Form Talysurf Intra	New view 7300	µsurf basic	Wave scan dual	Glossmeter
Application	Roughness, waviness and form	Surface topography	Surface topography	Painting appearance: Short and long wave	Painting appearance: Gloss

3 RESULTS AND DISCUSSION

First step: Several 3D and 2D Roughness parameters on the 22 samples have been analyzed and correlated with its rating at the E- coat stage. Parameters with a correlation factor higher than 6 are listed in table 4. Following, the tendency line for these roughness parameters X ratings has been accessed. They were 14 3D parameters and 4 2D parameters (Figure 6). It may be observed one group of parameters for which the tendency line increases with rating. These were related to peak and valley density. Conversely, where the tendency line decreases with increasing rating, it may be related to profile height (Figure 6). Second step: The sheet metal surface topography for the best and worst rating (Figure 7) has been analyzed indicating a clear evidence of the behavior of the two groups of parameters.

Table 4: Top: 3D and Bottom: 2D Main Roughness parameters of interested for the present work[8]

3D PARAMETERS		Standard / Reference
Sa	Arithmetical mean height of the scale limited surface	ISO 25178-2:2012
Sp	Maximum peak height of the scale limited surface	
Sz	Maximum height of the scale-limited surface	
Sq	Root mean square height of the scale-limited surface	
Sk	Core height	
Smr2	Dales material ratio	
Vv	Void volume	
Vvc	Core void volume of the scale-limited surface	
Vmc	Core material volume of the scale limited-surface	
Vmp	Peak material volume of the scale limited-surface	
Sha	Mean hill area	
Spd	Density of peaks	
Cclm	Distance of heighest peak to αclm	Pfestorf [2]
αclm	Maximum closed void area ratio	
2D PARAMETERS		**Standard**
Ra	Arithmetical mean height of profile	ISO 4287 - 2000 SEP 1940 - 1997
Rq	Root mean square height of profile	
Rz	Maximum height of profile	
Pc	Peak count	ASME B46.1 - 1995 SEP1940 - 1997

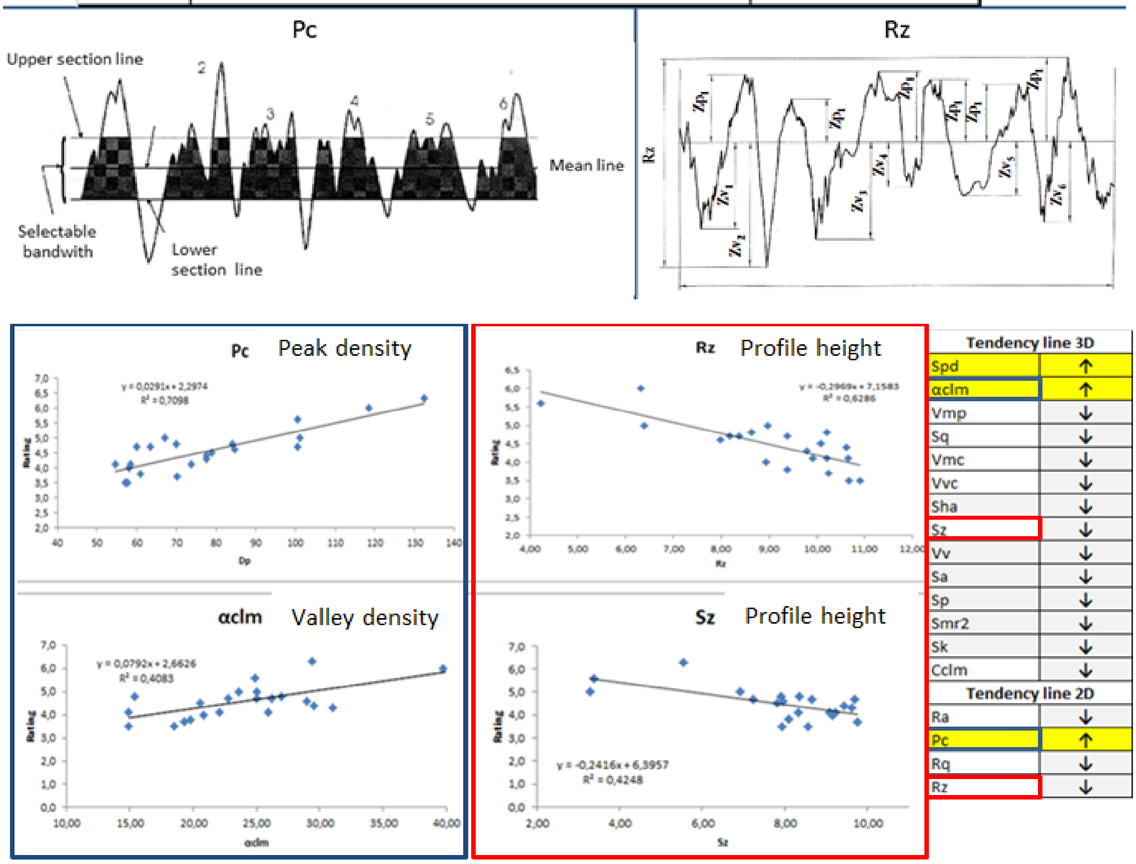


Figure 6: The two groups of roughness parameters: First one related to peak and valley density (Pc and αclm) for which the tendency line increases with increasing rating and the second one related to peak and valley height (profile height) for which the tendency line decreases with increasing rating.[8]

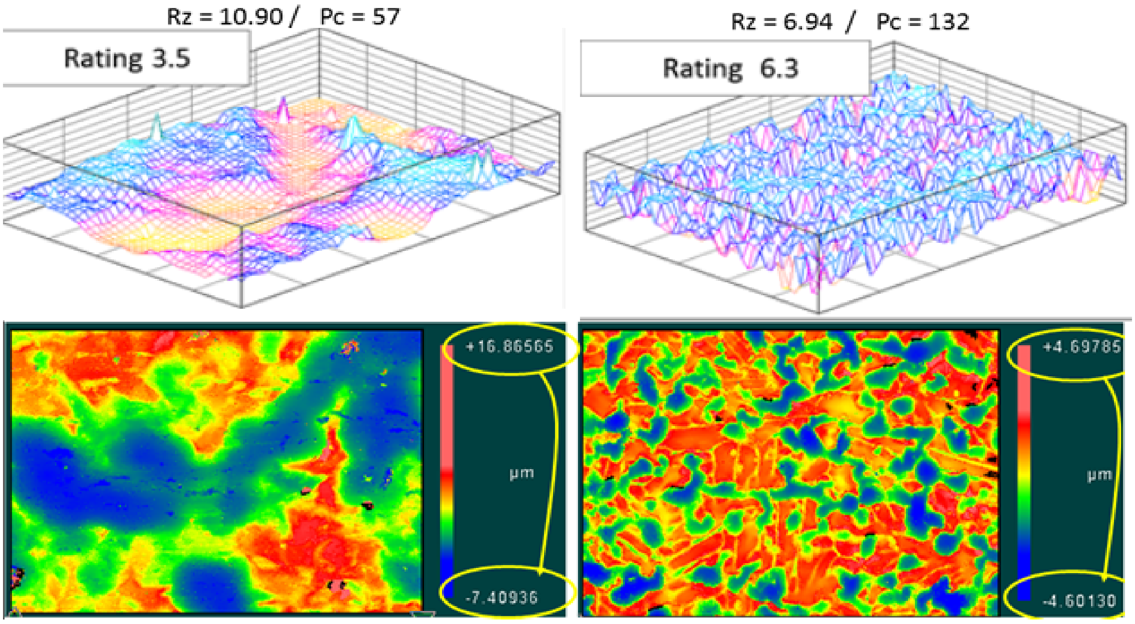


Figure 7: Sheet metal surface topography of best and worst rating and the corresponding 2D roughness parameters Rz and Pc.[8]

Results of the surface topography evolution from sheet metal to clear coat of the best and worst rating sheet metal conditions are shown in Figure 8.

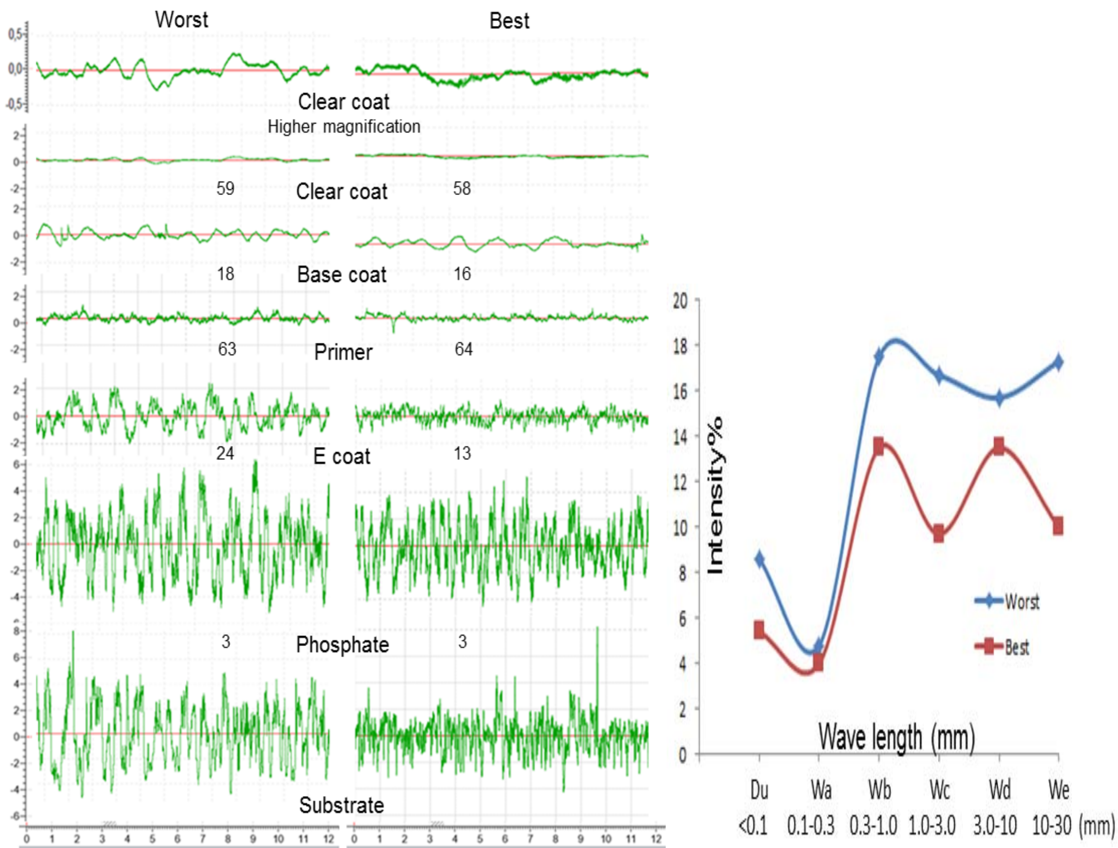


Figure 8: Left: Surface topography evolution from sheet metal to clear coat of the best and worst rating sheet metal conditions. Right side of this figure: the corresponding spectral curves.[8]

In this figure the relationship between surface roughness of the clear coat and the spectral intensity (measured on the clear coat) can be observed.

When painting appearance is in discussion a question always arises: How much does the stamping process affect painting appearance? The answer that might be given is associated with roughness changes which are mainly related to the strain path on the FLD and the knowledge of all the variables that affect it. Figure 9 gives an idea of how sheet metal thinning can be deleterious to painting appearance. Further details on these subjects may be obtained from Nunes.(8)

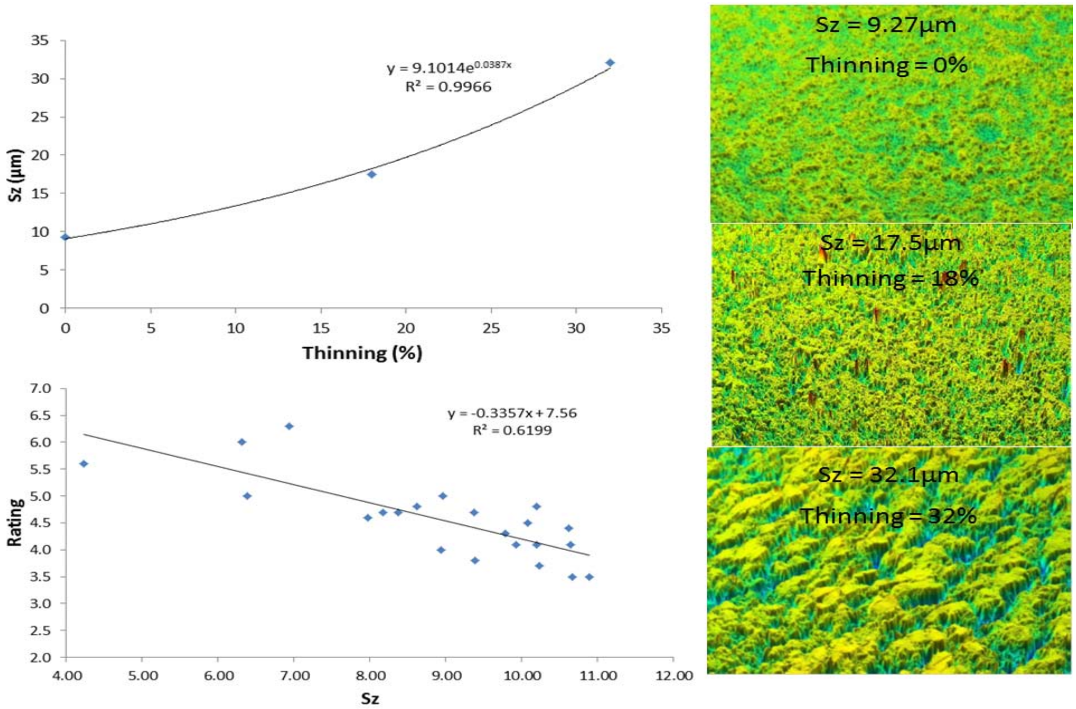


Figure 9: Indirect relationship between thinning and painting appearance.(10)

4 CONCLUSIONS

Based on the main aim of this study which was to analyze surface topography evolution for cold rolled steel sheets from blank to painting and its effect on painting appearance for automotive industry, the present work lead to the following conclusions:

1. Surface topography from sheet metal car body is transmitted along the painting process however with a decreased intensity to the clear coat surface which, in turn, influences final painting appearance;
2. The more sensitive roughness parameters analyzed on the present work can be divided in two groups: Functions of peak and valley height (2D: Ra, Rz, Rq and 3D: Sa, Sz, Sp, Sk, Sq, Smr2, Cclm, Vv, Vmc, Vvc and Vmp) and functions of peak and valley density (2D: Pc and 3D: Spd and αclm);
3. Sheet deformation during stamping causes roughness alteration/evolution. The “function of height“ parameters increase in an exponential form with steel sheet thinning , causing a decrease in painting appearance;
4. Concerning the painting evaluation methods utilized in the present study, spectral curves have shown to be more precise than rating(R). It was shown that the wavelength range results can be separated and sub-divided into five scales whereas rating shows wavelength range results which are unified into one number, calculated from the composition of only two scales of wavelength (SW and LW).

5. The present work has as a future goal the development of a methodology that correlates FLC curves and Painting Appearance in a way to satisfy both stampability and paintability criteria.

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