Human subjective response to aluminium coatings surfaces

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Abstract

The research described in this study establishes whether measured physical material parameters could be used as a predictor of the human subjective response to the tactile and visual stimuli characteristics of aluminium coatings surfaces. Twenty surfaces were used consisting of four uncoated aluminium substrates and four different type of coatings applied on each of the four uncoated substrates. Forty volunteers (20 female and 20 males) were asked to rate the surfaces using semantic differential scales. The results suggest that coatings obtained by matt polyurethane which contains a fine dispersion of silica micro-particles has the capability to veil the effect of the manufacturing process of the aluminium substrates on both the felt slipperiness and felt roughness. The dynamic coefficient of friction was found to be a good predictor of the felt slipperiness with a negative power law exponent of 0.86 (R^2 = 0.85), confirming that greater friction is associated with less felt slipperiness. The physical gloss was also found highly negatively correlated (R^2 = 0.87) with the felt slipperiness of the tactile stimuli suggesting that glossier surfaces could be mostly perceived sticky. These results provide useful suggestions relating to the sensory perception and experience of materials, helpful for the industrial and product design in numerous application fields such as automotive and electronics industry.

1. INTRODUCTION

When designing consumer products, materials selection plays a key role not only for establishing the functionality of the product but also to provide the right aesthetic and sensory perceptions relevant to its users. The sensorial properties of a material in a designed artefact affect the user experience of its pleasantness and the user-product interaction.[1] Tactile and visual stimuli of the product materials are the main source of sensorial information when interacting with products.[2, 3] Published research reports that understanding of the people sensorial perception of materials when using products is influential to assess the affective responses of users,[4, 5] and to design a desired interface of a product.[6, 7]

Much research has been performed is establishing the perceptual properties of plastics in several applications.[1] While most research studies have been focused on the touch perception of plastics and metals [8] not so much research has been done to investigate how the physical material properties of metals correlate with the touch perceptions of the those materials. Aluminium coated materials are widely used in consumer products.[9] The coatings of the aluminium parts not only help to confer adequate resistance against sunlight and scratch but also are means by which it is possible to confer aesthetics pleasantness to the product. Thus both the tactile and visual properties of the coatings can influence the pleasantness and aesthetics of the surfaces.[9] Existing research suggests that the user preference of a plastic surface can be made appealing by applying a coating finish.

Humans in daily life employ multiple senses to judge material properties of objects (Fujisaki et al, 2015, Tiest and Kappers, 2007. Previous studies have found that haptic and visual perception of material properties are highly correlated (Baumgartner et al., 2013), and that the dimensionality of haptic and visual perception of material properties were found both overlapping and complementary (Bhushan et al., 1997; Hollins et al., 2000).

Among the surface visual attributes, such as colour, texture, transparency, and gloss, the latter is not only considered as a purely physical property of the material but also defined as a visual perceptual attribute associated with the perception of the geometrical properties of the surfaces (Obein, 2004). Previous studies have addressed the significance of the glossiness in surface perception (D'Zmura and Lennie, 1986), and its characterization depends on both the properties of the visual response to gloss and the underlying physical stimulus (Obein, 2004). Psychophysical relationship between perceive gloss and physical gloss are typically found nonlinear, suggesting that humans are found to be more sensitive to variations in the matte and the high glossy regions.

Assessing the user's perception of physical properties may require time and effort due to the fact that the human subjective response may vary among people.[10] Each physical material parameter, such surface roughness or friction coefficient can elicit different sensations to different people when assessing a metal its degree of roughness. In order to select materials that elicit the desired sensations for a specific application, there is the need to predict the psychophysical (subjective) material properties from their physical (objective) properties.[10] The approach taken in this paper is therefore to explore the correlation between the subjective and objective materials properties and to establish if a prediction model can be fitted to the experimental data. Psychophysical correlations between the perceived value of the sensory attribute (subjective rating) of a stimulus and its physical (objective) intensity are typically expressed by Stevens' Power Law.[11] Stevens' power exponent provides a useful metric which converts the measurable physical objective quantities into perceived subjective quantities. Studies conducted on the assessment of the human perception of texture roughness by Stevens and Harris have analysed the felt roughness and smoothness of twelve emery cloths which is an abrasive made from powdered aluminium oxide.[12] A Stevens' power law with an exponent of 1.5 was found when correlating the felt roughness to the grit numbers of the emery. However, while the grit number is approximately inversely proportional to the particle size, it is not a measure of the physical roughness of the material property, i.e. the amount of height difference on the surface. Thus, their results can be considered relevant only for sandpapers and emery cloths. Ekman, Hosman, and Lindstrom have conducted a study where the felt roughness of the samples was rated on a preference scale [13]. Their samples consisted of writing paper piece, a cardboard piece and five sandpapers which were characterised in terms of their coefficient of friction. Their results showed that the felt roughness and the measured coefficient of friction were correlated by a Stevens' power function and that a high value of friction was correlated to a high value of felt roughness. However, the stimuli range used in their study was limited and thus cannot guarantee its general applicability.

The objective of this study was to evaluate measured physical material properties of aluminium coating surface as a potential predictor of the counterpart human subjective response to the material properties *The* physical properties of the surface were measured in terms of the mechanical characteristics of surface roughness, friction coefficient, surface free energy and surface glossiness of the prepared coatings. The human subjective response to aluminium surfaces properties was measured in terms of the sensory attributes of the material surface characteristics of felt slipperiness (slippery–sticky), felt roughness (smooth–rough) and perceived gloss (matt-gloss). The hardness and coldness of the aluminium were considered not influential given the thin layer of the coating applied on the aluminium substrates. The experiment was performed for different coating types under two sensory modality conditions: blindfolded and sighted conditions. Two different sensory modalities of Touch Only and Touch & Vision were selected for the subjective evaluation given that the visual sense may affect the touch perception (Xiao et al, 2016) REF). Finally, a regression analysis was conducted to establish any relationships between the human subjective response and the physical material properties of the aluminium surfaces.

2. MATERIALS AND METHODS

2.1 Selection of samples and coatings

In this study a matrix of materials samples was made consisting of 20 different planar surfaces which consisted of 4 basic uncoated aluminium substrates with different manufacturing processes, namely grinded, sand blasted finished, satin finishing and chemical polishing, and 4 different coatings deposited on each of the 4 basic uncoated aluminium substrates. Three replicas of each sample were prepared in order to use two of them for measurement of physical properties and the other one for subjective tests. For brevity, from here on the samples will be referred to as follows: XX.YY where XX are two letters describing one of the 4 substrate manufacturing processes and YY describing one of the 4 coatings (e.g. YY=UC in case of uncoated substrates).

The four basic uncoated aluminium substrates were supplied by Gruppo Gaser Ossido Duro S.r.l., Rozzano (MI), Italy and were manufactured with four different processes:

- Grinded or random orbital sander brushed (OR) with no regular deep scratches
- Sand blasted finishing (SB) with homogeneous roughness
- Satin finishing (ST) with a unidirectional satin texture, by immersion in a basic NaOH solution at high temperatures
- Chemical polishing (PS) with a high gloss, by immersion in an aggressive acid solution at nearly 100 °C

All the samples have a layer of native aluminium oxide with a thickness of 20-30 μm.

The coatings were all based on the same copolymer, a fluorinated resin suitable for outdoor applications (Lumiflon LF-910 LM) but different chemistries were employed so that crosslinking degrees and characteristics were obtained. The coatings applied were as follows:

- Sol-Gel (SG), a thin layer of a hybrid organic-inorganic fluorinated coating, with a mixture of silicon and zirconium oxides. This coating is characterized by high hardness.

- FEVEsil (FS), which is mostly composed of the organic part of the SG, weakly cross-linked. It has an intermediate thickness and low mechanical properties.
- Gloss Polyurethane (GP), a commercial thick coating with good mechanical properties. The crosslinking agent is an isocyanate-based compound.
- Matt polyurethane (MP), which has the same composition of the Gloss Polyurethane (GP) but also a fine dispersion of silica micro particles that migrate to the surface to give a peculiar matt finish to the coating.

All the coatings were transparent except MP samples which were the only translucent coating.

The Sol-Gel coating was obtained by spin coating at 300 rpm for 40s and with a thermal curing at 150°C for 1 h. The coating called FEVEsil was prepared by a double deposition by spin coating at 300 rpm for 40s, cured for 1 h at 150°C after the first application and for another hour with the same conditions after the second one. The Gloss Polyurethane and Matt polyurethane coatings were kindly deposited by Innoventions, S.r.l., Cinisello Balsamo (MI), Italy, by spray coating with an air pressure of 5 bar and a nozzle diameter of 1.2 mm. After the deposition, the samples were cured for 24 hours at 50°C to allow solvents to evaporate.

2.2 Physical Materials Properties

The aluminium substrates and coatings physical characteristics were studied by surface's roughness, friction coefficient, free energy surface and surface's gloss measurements. An optical profilometer (Microfocus, UBM) was employed to evaluate the roughness parameters of the samples, using a detectable point density of 500 points/mm. Measurements were performed according to DIN 4768 standard on a 4 mm long evaluation profile with 500 points per millimetre. Different roughness parameters such as the arithmetic average of the absolute values of all the points of the profile, Ra, the root mean square roughness of all the points of the profiles measured, Rq, the skewness and the kurtosis were considered. The correlations between each of these roughness parameters and the subjective roughness were initially explored but a clear relationship was observed only between Rq and the felt roughness, as shown in the Results and Discussion section. For this reason, the root mean square roughness, Rq was selected as a roughness parameter suitable for this study. Friction coefficient was measured with two different types of synthetic skin, EcoLorica New Sporter and EcoLorica New Sueta supplied by Ecolorica S.r.l. (Torino, Italy), applying two different normal forces, 1.96N and 4.68N, with a Zwick-Line testing machine Z010 (Zwick Roell). The set-up implemented in this study was a rough approximation of friction mechanisms occurring between surfaces and skin, taking into account that the friction was measured by means of a velvet Lorica leather acting as a human skin surrogate.[14] Since the perception of texture is influenced by the touch of fingers in movement, in this study the dynamic coefficient of friction was considered.

Considering that the coefficient of friction can be affected both by the elastic modulus of materials and by the attractive and adhesive interactions between surfaces, other physical properties such as free surface energy computed from contact angle measurements and Young's modulus were measured. Surface free energies and the corresponding dispersive and polar components were evaluated by using OWRK (Owens-Wendt-Rabel-Kaelble) model [15] and measuring the optical contact angle at T_{amb} by means of an OCA20 instrument (Dataphysics Co., Germany). Liquid droplets of high-purity water (CHROMASOLV® Plus, for HPLC) and diiodomethane were dispensed on surfaces under investigation using a 500 mL Hamilton syringe and the corresponding contact angles were determined with the sessile drop method, using a CCD photo-camera to capture droplet images. The surface free energy, defined as the work needed to form a new surface area, was evaluated in this work because it accounts for all the intermolecular interactions occurring between two phases across their interface. These forces of attraction and repulsion occurring between any solid/liquid surfaces can contribute to increase friction and consequently to the subjective perception of slipperiness, as already reported.[16] The Atomic Force Microscope was used to perform nanoindentations on the films and

Young's moduli were determined using the force vs. indentation curves, as presented in a previous work.[17] The FEVEsil coating exhibited an elastic modulus of 0.15 ± 0.06 GPa, while the SG has an elastic modulus of 16.40 ± 4.6 GPa. GP and MP coatings showed a Young's modulus of 2.77 ±0.51. Regarding the physical measure of gloss, physical gloss was measured at 60° with a Minolta Multi Gloss 268. Gloss was measured on two different sample replicas in order to obtain an average and a standard deviation value. Table 1 presents the physical material properties measured for the twenty samples used in the tests.

Glass transition temperatures, T_g were also evaluated for the coatings SG and FEVEsil by means of Differential Scanning Calorimetry (DSC). A DSC 823e (Mettler-Toledo®) instrument was used for these measurements. The coatings were deposited by drop casting on baking paper and cured at 150°C for 1h. Then, they were analysed with three heating/cooling runs: from 25°C to 250°C 20°C/min, from 250°C to 0°C -20°C/min, and from 0°C to 250°C 20°C/min. A T_g values of 38 and 148 °C were observed for the FEVEsil and SG coatings, respectively. GP and MP coatings has a transition temperature of 120 °C, as reported in their technical datasheets. The lower glass transition temperature obtained for FEVEsil coatings was likely due to a lower crosslinking density, when compared to the other coatings under investigation.

Table 1. Physical material properties measured for the twenty aluminium samples used in the tests.

Sample ID	**Roughness Rq** ± SD **[μm]**	**Dynamic Coeff of friction** ± SD **[μD]**	**Gloss** ± SD **[g.u.]**	**Polar Component of surface energy γ_p [mN/m]**
OR.UC	**1.48** ± 0.23	**0.65** ± 0.03	**11.50** ± 0.40	**0.05**
SB.UC	**1.16** ± 0.09	**1.03** ± 0.01	**2.80** ± 0.01	**0.01**
ST.UC	**0.91** ± 0.05	**0.68** ± 0.02	**15.20** ± 0.10	**0.35**
PS.UC	**0.66** ± 0.04	**0.59** ± 0.02	**48.40** ± 11.20	**0.32**
OR.FS	**1.83** ± 0.21	**1.33** ± 0.05	**67.30** ± 3.10	**6.26**
SB.FS	**1.43** ± 0.13	**0.80** ± 0.06	**36.45** ± 0.50	**7.83**
ST.FS	**0.98** ± 0.05	**1.32** ± 0.03	**84.95** ± 1.90	**11.00**
PS.FS	**0.59** ± 0.04	**0.82** ± 0.05	**104.55** ± 3.50	**5.63**

OR.GP	**1.83** ± 0.21	**1.06** ± 0.03	**85.05** ± 0.40	**2.71**
SB.GP	**2.49** ± 0.16	**1.16** ± 0.02	**81.25** ± 2.10	**2.87**
ST.GP	**1.33** ± 0.17	**1.14** ± 0.02	**89.15** ± 0.10	**2.78**
PS.GP	**0.69** ± 0.05	**1.16** ± 0.04	**100.75** ± 0.20	**2.56**
OR.MP	**1.94** ± 0.15	**0.59** ± 0.01	**7.20** ± 0.10	**1.72**
SB.MP	**2.24** ± 0.17	**0.58** ± 0.01	**4.85** ± 0.20	**1.55**
ST.MP	**1.86** ± 0.14	**0.62** ± 0.02	**7.80** ± 0.01	**1.62**
PS.MP	**2.14** ± 0.13	**0.59** ± 0.01	**10.35** ± 0.10	**2.05**
OR.SG	**1.18** ± 0.11	**0.72** ± 0.01	**34.15** ± 0.80	**5.14**
SB.SG	**1.17** ± 0.09	**0.75** ± 0.03	**8.75** ± 1.10	**3.64**
ST.SG	**0.95** ± 0.05	**0.73** ± 0.01	**34.60** ± 3.70	**4.34**
PS.SG	**0.73** ± 0.11	**0.90** ± 0.05	**87.30** ± 7.20	**4.39**

The correlations between the two following physical properties were explored: i) physical gloss vs. roughness, Rq and ii) coefficient of friction vs. roughness, Rq.

GP and FS coatings exhibited a higher gloss when compared to SG and MP, as shown in Figure S1 (see please the Supporting Information). The values of gloss appeared to decrease by increasing the Rq for the most of the samples. Excluding GP and FS samples, a power low equation can be used to describe the correlation between the gloss and the roughness measured for the samples. However, including all the sample data, an equation describing the correlation cannot be found.

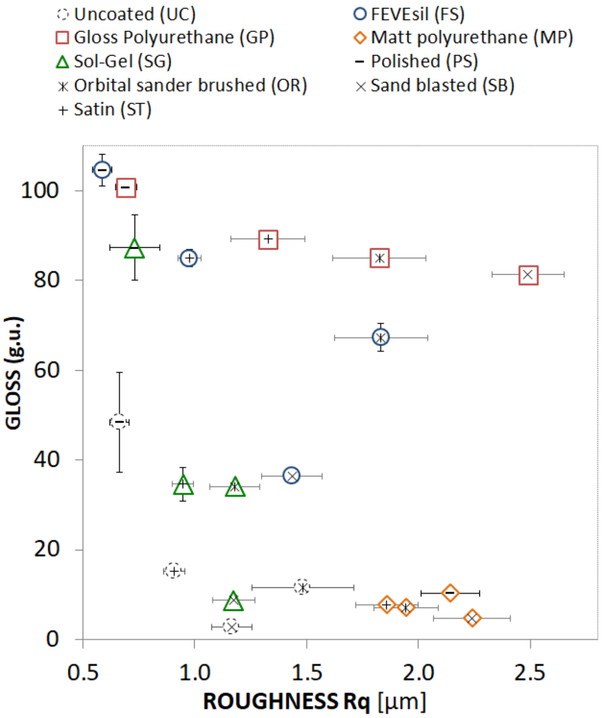

Figure S1. Physical gloss as a function of the surface roughness Rq for all the samples tested.

Figure S2 also presents the dynamic coefficient of friction measured on surfaces under study by means of the Lorica velvet as a function of roughness Rq (see please the Supporting Information). The average friction coefficients range from 0.6 to 1.3.

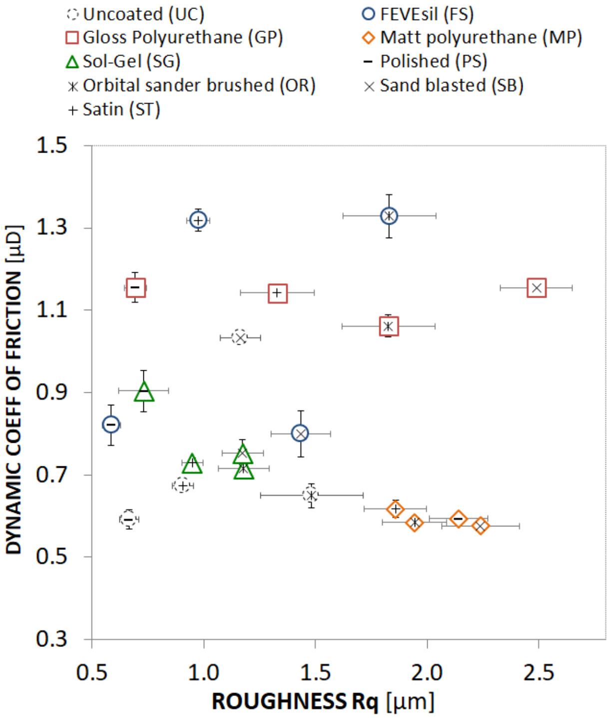

Figure S2. Dynamic coefficient of friction as a function of the surface roughness Rq for all the samples tested.

As shown in the Figure S2, no clear relationship was found between friction coefficient and the roughness. This could be due to the length of profiles evaluated for roughness measurements that was significantly lower than the evaluation length of dynamic friction coefficients. Notwithstanding this, the evaluation length for profilometry was not modified because it was selected in agreement with DIN 4768 standard which establishes the methods to characterize the surface roughness.

3. TEST METHOD

The test method involved direct ratings of the felt tactile and visual response to the physical material properties of the aluminium surfaces.

Two different sensory modalities (Touch Only and Touch & Vision) were selected for subjective evaluation of the aluminium surfaces to explore if the sensation given by the visual sense may affect the touch perception of the aluminium surfaces. It was decided not to perform the Vision only condition since the experiment aimed to test a condition as close as possible to what a user would do in daily life in product usage using both touch and vision modalities simultaneously, and also because it is known that tactile cues may affect the visual perception of material properties (Kerrigan et al., 2010). Felt slipperiness, felt roughness and perceived gloss of the test aluminium samples were assessed.

The experiments were thus performed in two different test conditions:

- Touch only to rate slipperiness and roughness of the surface (blindfolded condition);
- Touch and Vision to rate slipperiness, roughness and perceived gloss (sighted condition).

A ten-point Likert scale using five-level semantic categories (Figure 1) was employed to determine direct estimation of the human subjective response to aluminium surface. The Likert scale presents values from 1 to 10 to range between bi-polar attributes of sticky/slippery, smooth/rough, gloss/matt to evaluate the felt slipperiness, felt roughness and perceived gloss respectively. Due to bias of slightly different meanings that each participant may attach to the descriptive label, a schematic graphical representation of the various semantic attributes used were drawn next to the labels, as shown in Figure 1, so as to avoid large inter-subject differences. Participants were therefore instructed to use the 10-point Likert scale by first selecting the label which best described their perception, and then selecting a number to express the rating.

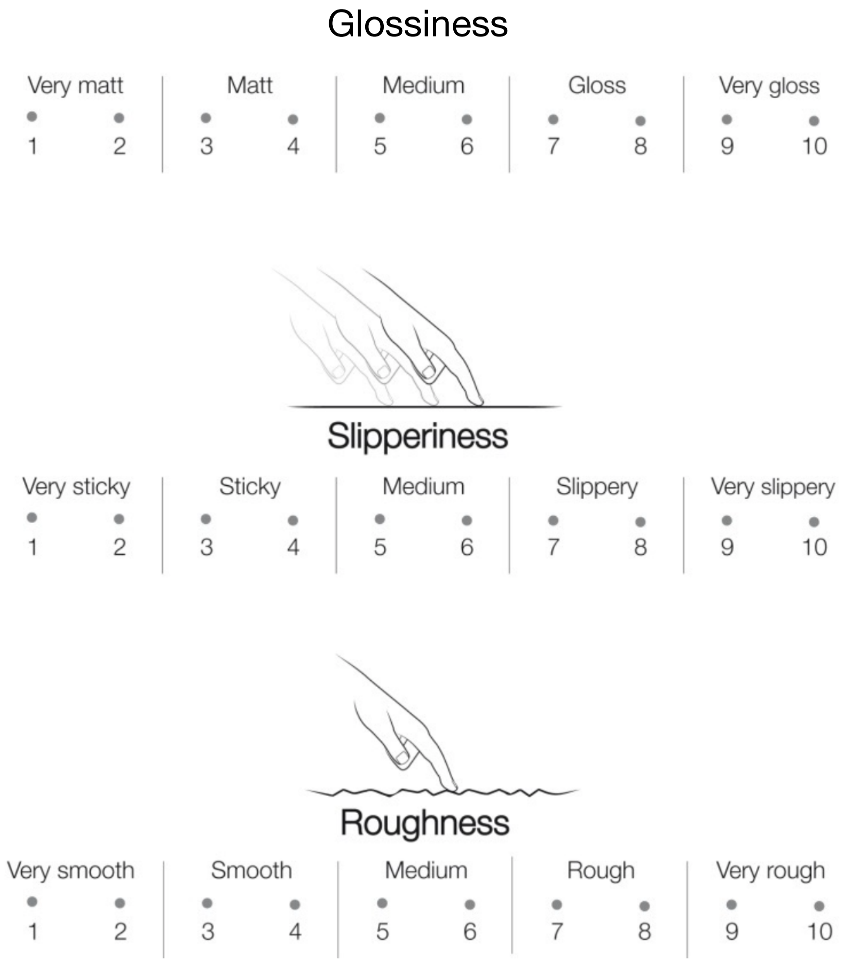

Figure 1. The 10-point Likert scale used for the subjective evaluation ratings.

Test protocol

Each participant adhered to the same test protocol where a predetermined sequence of tasks, each of fixed time duration, was performed. At the beginning of the test, each participant was given an information sheet and a consent form. Following their agreement to undertake the experiment, all participants were asked to sign the consent form and their physical characteristics, health and history of previous working experience were collected using a short questionnaire. The experiment was then explained to the test participant using the same verbal instructions for all participants. All data were analysed anonymously. All participants were tested in the same room. They were required to remove any watches or jewellery. Each participant was asked to clean their hands before commencing each session of the experiment. In order to avoid environmental effects on the skin sensitivity,[18] room temperature was maintained in the range from 20 to 25 °C. In order to ensure that all the samples were seen in the same light situation by the participants, the lighting was kept constant and fixed at the top of the samples on the ceiling of the room, thus replicating a light condition as an observer would see an object in a lighted room. There were no windows in the room to avoid sunlight bias. The order of presentation of the test samples was fully randomised for each test participant in order to reduce any bias of learning and fatigue effects. The sample set was repeated two times in order to evaluate the individual's ability to assess samples using the Likert scale. Also, a "practice" set was included at the start of the experiment in order that the participant could familiarise with the test methodology. In order to set a reference in giving answers, it was presented to each participant two samples which were representative of the extreme ends of the particular scale they were using. The responses from this set were not considered. The responses were recorded from the subsequent set of trials. The Likert scale was places about 1m ahead at eye level. An active dynamic touch was used in this study where the participants moved their fingers over the surface to touch, feel and press the sample surface. The participants were instructed to use the same pressure for each sample. The participants were further instructed to assess each sample independently without comparing to the previous one in order to avoid possible bias due to the order of presentation of the samples.[19] In the first experiment (Touch only), the participant was blindfolded and was asked to assess all samples without seeing them but only by moving his/her fingers on the test samples. All participants were requested to put their arms in a box to hide the samples from view. Each sample was presented individually to the test participant during a 15-second duration. After this time he/she was asked to rate the felt material attribute on the Likert scale. A break of 30 second was given after the first set of twenty assessment trials to avoid annoyance effects. Each test included thus 40 trials divided in two sets of twenty samples each. The participants were first asked to rate the slipperiness (where 1 represents very sticky and 10 represents very slippery) and then the roughness (where 1 represents very smooth and 10 represents very rough) for each sample. In the second experiment (Touch and Vision), the participant was asked to assess again all samples by touching and seeing them at the same time for the evaluation of the slipperiness and the roughness and the perceived gloss (where 1 represents very matt and 10 represents very gloss). A total of 80 tests (20 samples x 2 repetitions x 2 modalities) were performed for each test participant for a total duration of about 50 minutes each. The research study was assessed and approved by the Ethics Committee of the Politecnico di Milano before the study and it was conducted according to the ethical principles expressed in the Declaration of Helsinki. The test protocol adhered to the health and safety guideline of the University.

Test subjects

In this study, a total of 40 volunteers between university staff and students, divided into 23 technicians (engineers and designers) and 17 non-technicians, were asked to take part in the test. The participants were required to be between 18 and 65 years of age. In order to reduce one well known source of bias during the judging process the sampling was performed in such a manner as to ensure equal numbers of male and female participants in the group. Efforts were made to also achieve a relatively similar distribution of the demographic descriptor of age, height and weight to avoid bias from the effect of body mass on the tactile perception. All test participants were found to be in good physical and a cognitive condition for their tactile and the visual sensation following a short questionnaire performed during the practice test before starting the experiment. The mean and standard deviation of the physical characteristics of test participants are presented in Table 2.

Table 2. Summary statistics (mean and standard deviation) for the test participants.

Test participants statistics	Total number	Age [years]	Standard Deviation	Height [cm]	Standard Deviation	Weight [kg]	Standard Deviation

Male	20	31	13,6	181	10,6	74,7	10,6
Female	20	36	13.1	164	11,7	58,4	15,8

4. RESULTS AND DISCUSSION

4.1 ANOVA Test

A total of 80 (40 participants x 2 presentations) rating scale estimates were collected for each test sample. A mean scale estimate for each of the 20 test material samples was then calculated. A two-factor ANOVA test[20] was performed using the type of coatings and the type of manufacturing process as the two independent variables in order to identify any statistically significant differences among the measured subjective ratings. No significant differences were found between the blindfolded (Touch only) and sighted (Touch and Vision) conditions at a $p = 0.05$ level of significance. This result may suggest that the information added by the visual sense did not alter the tactile perception for the same sample of the aluminium surfaces studied in this study. Although previous studies have found that haptic and visual perception of material properties were highly correlated (Baumgartner et al, 2013), and that the roles of visual modalities and haptic modalities may be overlapping and complementary when rating material properties (Bhushan et al, 1997; Hollins, et al., 2000;), the results of this study may be due to the fact that the visual surface cues, such as color, texture, and reflectance patterns as well as 3-D shape, of the different coating surfaces used in this study was not predominant such to affect the tactile perception of each samples. Indeed the surface colour of the different coated samples was almost at the same intensity and similar to those of typical aluminium surfaces.

Also, no significant differences were found between female and male participants across all tests performed. Table 3 presents the subjective mean scale values for each test material sample for the Touch and Vision conditions.

Table 3. Subjective mean value using the Likert scale for the twenty samples tested (n= 40 people) for the Touch and Vision conditions.

	SLIPPERINESS	**ROUGHNESS**	**PERCEIVED GLOSS**
Sample ID	**Mean values** ± SD	**Mean values** ± SD	**Mean values** ± SD
OR.UC	**7.6** ± 1.4	**6.9** ± 1.7	**3.9** ± 1.6
SB.UC	**8.8** ± 1.3	**3.5** ± 2.2	**1.5** ± 1.2
ST.UC	**7.9** ± 1.9	**2.5** ± 1.3	**5.4** ± 1.8
PS.UC	**6.3** ± 2.1	**2.1** ± 1.2	**7.6** ± 1.6
OR.FS	**4.4** ± 1.6	**6.2** ± 1.3	**5.8** ± 1.6
SB.FS	**6.4** ± 2.0	**4.7** ± 1.5	**3.3** ± 1.6
ST.FS	**4.2** ± 1.9	**2.4** ± 1.0	**7.8** ± 1.4
PS.FS	**4.1** ± 1.9	**2.4** ± 1.1	**8.6** ± 1.2
OR.GP	**4.0** ± 1.5	**5.8** ± 1.4	**6.8** ± 1.7
SB.GP	**4.0** ± 1.9	**3.6** ± 1.2	**6.5** ± 1.8
ST.GP	**3.8** ± 1.6	**3.1** ± 1.1	**8.1** ± 1.9
PS.GP	**4.0** ± 1.7	**2.9** ± 1.0	**8.6** ± 1.4
OR.MP	**7.4** ± 1.3	**7.7** ± 1.1	**3.4** ± 1.6
SB.MP	**7.8** ± 1.7	**7.8** ± 1.2	**1.2** ± 0.5
ST.MP	**7.5** ± 1.3	**7.3** ± 1.2	**3.5** ± 1.8
PS.MP	**7.4** ± 1.5	**7.9** ± 1.1	**4.7** ± 1.8
OR.SG	**6.3** ± 1.7	**6.1** ± 1.5	**4.6** ± 1.8
SB.SG	**7.8** ± 1.6	**5.4** ± 1.8	**1.8** ± 1.2
ST.SG	**6.1** ± 2.0	**3.4** ± 1.3	**6.0** ± 1.7
PS.SG	**5.2** ± 1.9	**2.4** ± 1.1	**7.9** ± 1.8

Statistically significant differences were found between the subjective ratings for the four different coatings and manufacturing process at a $p = 0.05$ level of significance. This result suggests that the type of coating was found to have a significant effect on the felt slipperiness and felt roughness of the aluminium surfaces samples as also shown in Figures 2(a) and 2(b). In particular it can be seen that, except from the matt polyurethane (MP) dataset, the effect of using different coatings had mainly the tendency of decreasing the felt value of slipperiness and roughness of the surfaces when compared to the uncoated (UC) surface. On the other hand, in terms of the manufacturing process the felt slipperiness and felt roughness of the MP coatings were found not to be significantly affected by the manufacturing process of the substrates. This could be probably attributed to the thickness of the MP coatings which were able to veil the effect of the manufacturing process on the felt slipperiness, shown in Figure 2(a), and on the felt roughness, shown in Figure 2(b). Similarly, for the gloss polyurethane (GP) coatings, the felt slipperiness was found not to be significantly affected by the manufacturing process of the substrates. This result would suggest the capability of the GP coatings to veil the effect of the manufacturing process only on the felt slipperiness. Regarding the visual perception of the surfaces, both the manufacturing process and type of coatings employed were found to affect the perceived gloss ratings as shown in Figure 2(c). These results could be due in part to the fact that the different coatings used were mainly transparent and thus did not fully veil the effect of the manufacturing process of the substrate on the perceived gloss.

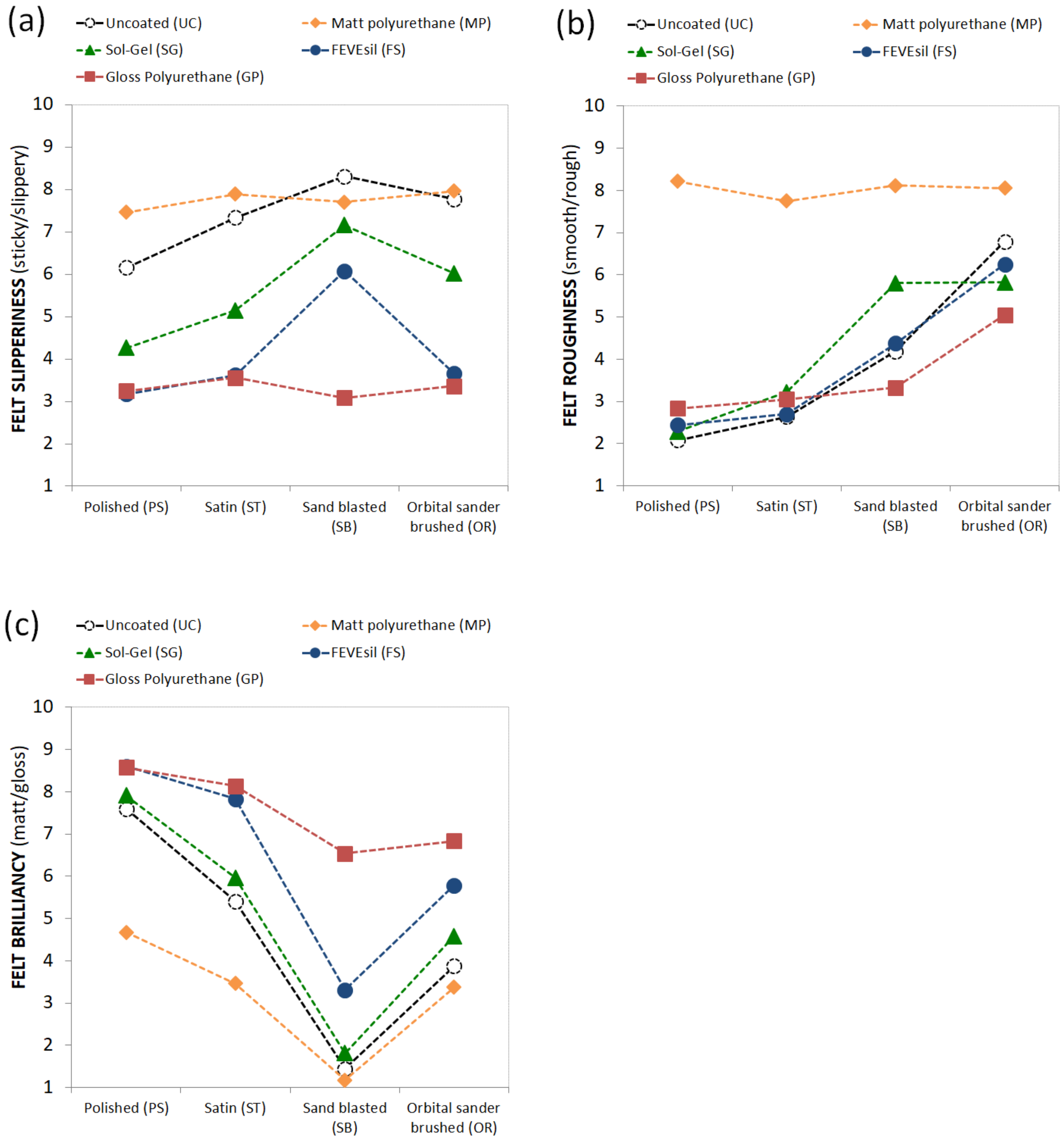

Figure 2. ANOVA test results for (a) felt slipperiness (b) felt roughness and (c) perceived gloss across the four different aluminium surface coatings and the uncoated substrates tested.

4.2 Psychophysical correlations

The subjective values of roughness, slipperiness and perceived gloss were statistically correlated to the physical measures of the surface characteristics in order to establish whether the measured physical material parameters could be used as a predictor of the human subjective response to aluminium coating surfaces. In addition, possible correlations were also measured among the subjective values themselves to explore if there were any influence between the tactile and visual perception of material surface. Psychophysical correlations were obtained by means of Stevens' power Law. A regression analysis was employed using a least-squares fit. The following correlations were analysed:

Physical / Subjective correlations

- Roughness Rq / Felt Roughness
- Roughness Rq / Felt Slipperiness
- Dynamic Coefficient of friction / Felt Roughness
- Dynamic Coefficient of friction / Felt Slipperiness
- Polar component / Felt Slipperiness
- Gloss / Perceived Gloss
- Gloss / Felt Slipperiness

Subjective / Subjective correlations

- Perceived Gloss / Felt Roughness
- Perceived Gloss / Felt Slipperiness
- Felt Roughness / Felt Slipperiness.

Evaluation of the Physical Surface Roughness as a potential predictor of Felt Roughness and Felt Slipperiness

Figure 3(a) presents the subjective rating values of felt roughness and the surface roughness Rq for all samples tested. In this study, Rq, as the root-mean-square deviation from the average measured height, was selected as the physical measure of surface roughness. Other roughness parameters were initially considered to describe the physical roughness of samples, such as the arithmetic mean deviation from the average height Ra, the skewness and the kurtosis which describe the height distribution and the probability density of the distribution, respectively. Compared to these, Rq was found to correlate better with the felt roughness. When correlating the felt roughness ratings with the surface roughness Rq of the coatings without considering data for uncoated substrates, the power law growth function in the range of surface roughness Rq from 0.6 to 2.3 µm, as shown in Figure 3(b), is given by:

$$\text{Felt Roughness} = 3.5872 \cdot Rq^{0.9608} \qquad (R^2 = 0.79) \tag{1}$$

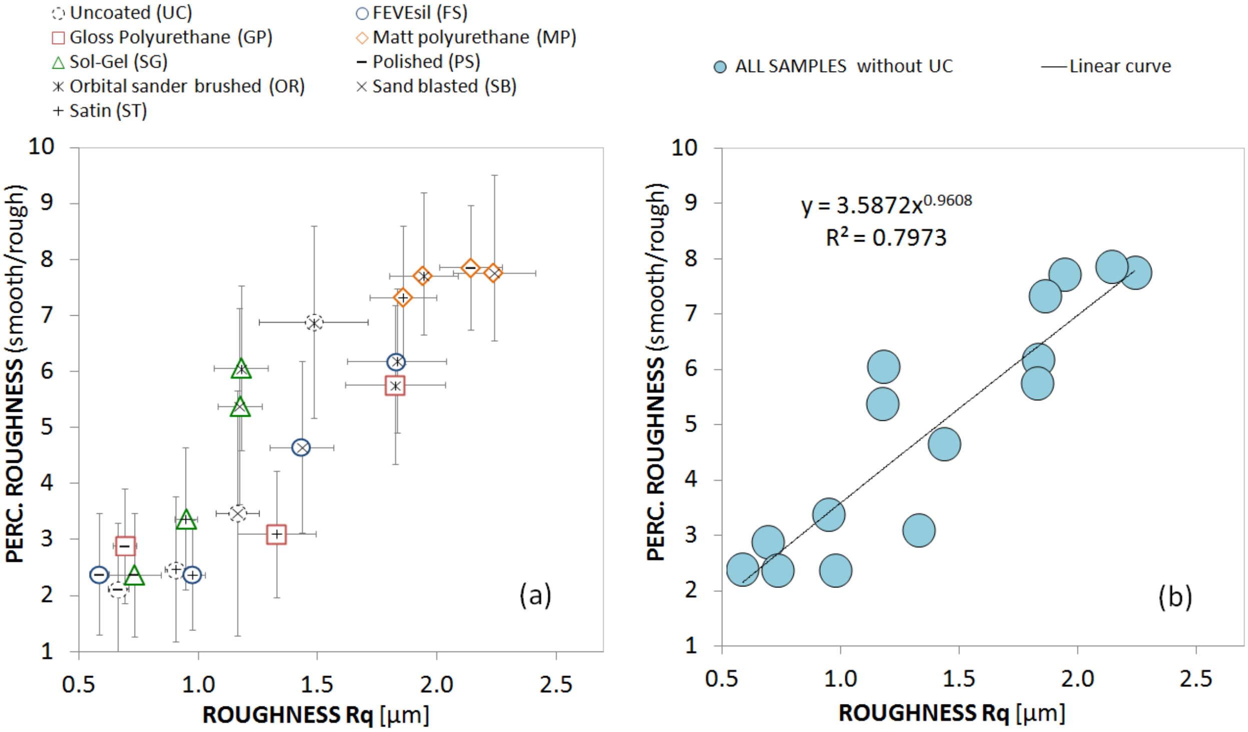

Figure 3. (a) Mean subjective rating values of *felt roughness (smooth/rough)* as a function of the *surface roughness Rq (µm)* for all samples tested. (b) Power law growth function of the *felt roughness (smooth/rough)* as a function of the *surface roughness Rq (µm)* for all samples without those uncoated (UC).

As it can be seen from Figure 3(b) the growth function for the felt roughness as a function of the physical surface roughness value presented an exponent close to unity, suggesting that a linear function may exist between the two variables with a coefficient of determination R^2 of 0.79. This result may suggest that the surface roughness parameter of the surface coatings could be considered as a good predictor of the subjective roughness felt when rubbing the hand and fingers on the aluminium surface. These results are also in line with the study performed by Wongsriruksa *et al.,*[8] who observed a positive correlation between the measurement of Ra and the felt roughness under blindfolded and sighted conditions for an ample set of materials such as polymer, woods and metals. The surface roughness parameters, however, was found not to be a best predictor of the felt slipperiness as shown in Figure 4 where the coefficient of determination R^2 was found less than 0.5.

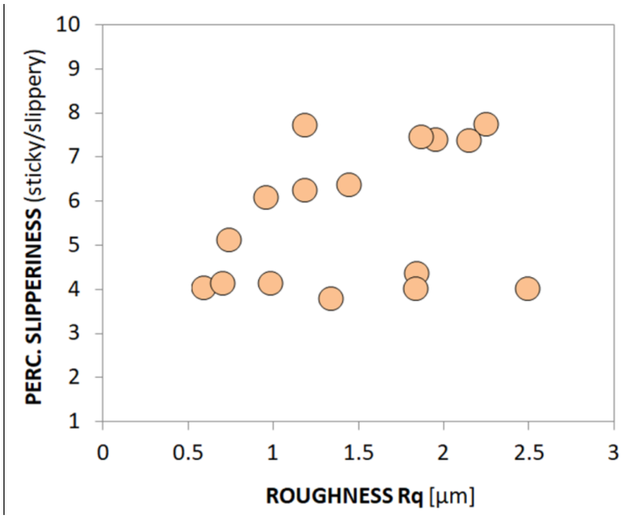

Figure 4. Mean subjective rating values of the *felt slipperiness (sticky/slippery)* as a function of the *surface roughness Rq (*µ*m)* for all samples without those uncoated (UC).

Evaluation of the Dynamic Coefficient of Friction as a potential predictor of Felt Roughness and Felt Slipperiness

Figure 5(a) presents the subjective rating values of felt slipperiness as a function of the dynamic coefficient of friction (DCoF) for all samples tested. When correlating the felt slipperiness ratings with the dynamic coefficient of friction parameter of the coatings without considering the data for uncoated substrates, the power law growth function in the range from 0.6 to 1.3 µD, as shown in Figure 5(b), is given by:

$$\text{Felt Slipperiness} = 4.7537 \text{ x DCoF}^{-0.857} \qquad (R^2 = 0.79) \qquad (2)$$

The results show that the dynamic coefficient of friction correlates well with the felt slipperiness in accordance with Stevens' psychophysical power law. This may be due to the fact the friction coefficient was measured by means of a velvet Lorica leather acting as a human skin surrogate, and thus closely approximating people real perception of surface texture.[14] The set-up implemented in this study was therefore an approximation of friction mechanisms occurring between surfaces and skin. Notwithstanding the approximation, this result would confirm the slipperiness perception experiment conducted by Smith and Scott,[21] who determined a correlation coefficient of 0.85 between subjective perceptions of friction and the coefficients of friction measured individually for each subject as the ratio between the mean tangential force and the mean normal force during stroking the surfaces.

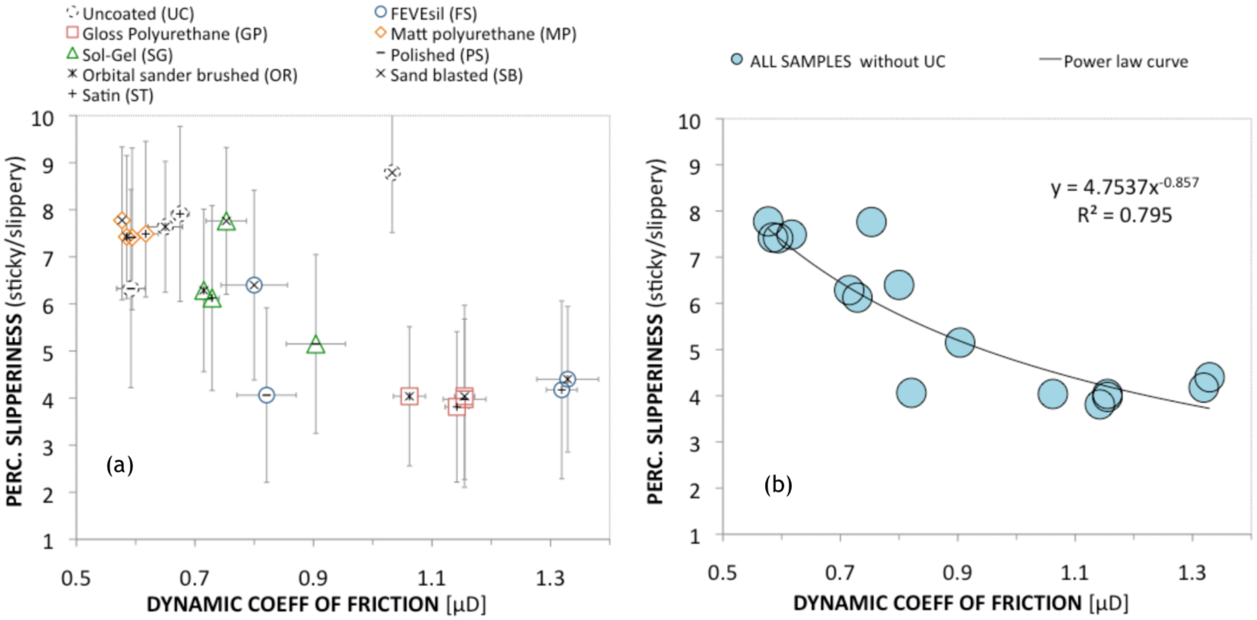

Figure 5. (a) Mean subjective rating values of *felt slipperiness (sticky/slippery)* as a function of the *dynamic coefficient of friction (μD)* for all samples tested; (b) Power law growth function of *felt* s*lipperiness (sticky/slippery)* as a function of the *dynamic coefficient of friction (μD)* for all samples without those uncoated (UC).

Participants were able to distinguish quite easily between the coatings under investigation. While the organic component was identical in the gloss polyurethane (GP) and matt polyurethane (MP) coatings, these two coatings were different in terms of the coefficient of friction. MP samples were in fact felt and measured significantly more slippery than the GP samples, without any effect induced by the manufacturing processes (see Figure 5a). This result was likely due to silica micro-particles which were present in the GP coatings and enhanced the perception of slipperiness. In addition to this, the high thickness of both the MP and the GP coatings led to minimise any effects of aluminium substrates upon friction. There was a large variation in the coefficient of friction determined for the

FEVEsil coating samples, even though the felt slipperiness for the FEVEsil coatings on sand blasted finishing substrate (SB.FS samples) was higher than the other FEVEsil samples. This result may be attributed to the finish of sand blaster substrates, considering that the SB uncoated substrate was also felt more slippery than the other uncoated substrates as shown in Figure 5(a). Moreover, the low thickness of FS coatings probably allowed the roughness of the sand blasted surfaces to emerge. As far as the Sol-Gel coatings are concerned, they were rated stickier than the matt MP samples and less than the gloss GP samples. This result may be due to the inorganic SiO_2 and ZrO_2 phases present in the hybrid Sol-gel coatings that increase the perception of slipperiness in comparison with the GP samples. On the other side, GP samples contain no inorganic components and their organic components enhance the stickiness felt. Moreover, this result presented by the Sol-Gel coatings may be also due to their coefficient of friction (0.72 to 0.90 μD) which were found to be higher than those measured for the MP coatings (0.58 to 0.62 μD) and lower than those for the GP coatings (1.06 to 1.16 μD).

Figure 6 presents the subjective rating values of felt roughness as a function of the dynamic coefficient of friction (DCoF) for all samples tested. As it can be seen not a clear relationship was found between the two variables. The data suggest that the felt roughness may be inversely proportional to the dynamic coefficient of friction parameter: greater friction is associated with less felt roughness. This result would be in contrast with the study by Ekman *et al.,*[13] who showed that the felt roughness was positively correlated with the friction coefficient. However, their study investigated the felt roughness of sandpapers and piece of writing papers and not metals. Moreover, their study was limited to only seven samples which cannot guarantee its general applicability. Considering that the friction coefficient can be influenced both by the elastic modulus of materials and by the attractive and adhesive interactions between surfaces, the correlations of the felt slipperiness with the free surface energies computed from contact angle measurements as well as with the Young's modulus were explored. With regard to the results obtained for uncoated samples, very low values were measured for the polar components of surface energies as well as high estimates of felt slipperiness were recorded. This was at first quite surprising, although these results can be attributed to the presence of contaminants coming from the manufacturing of aluminium oxide surfaces that cannot be totally removed even after extensive washing with solvents and detergents.

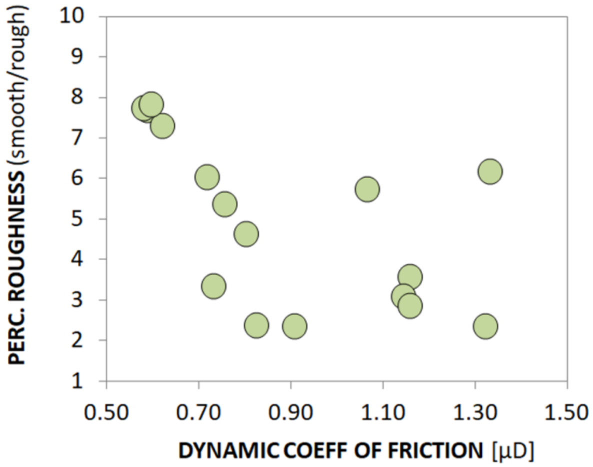

Figure 6. Mean subjective rating values of felt roughness (smooth/rough) as a function of the dynamic coefficient of friction (μD) for all samples tested.

Excluding data for uncoated samples, a clear and well-defined correlation between the felt slipperiness and the polar components γ_p of surface energy was not found as shown in Figure 7(a) and 7(b). However, the slipperiness appeared to be affected by the polar component γ_p. More precisely, an increase in γ_p led to a decrease in the felt slipperiness, while no influence of dispersive component was noticed. This can be explained considering that the bonding energy of polar interactions can be up to 10 times higher than the bonding energy of the dispersion forces.[22] Consequently, the surface with the higher polar component of surface energy will form stronger interactions with the Lorica leather and the skin, providing a larger friction coefficient. Indeed, the outer layer of human fingers pads is composed in a large proportion of keratin, one of the most abundant fibrous structural proteins in animals. The keratin can be hydrated by moisture secreted from the sweat pores and therefore the water present in the sweat can form polar interactions between human fingers and coatings. In case the surface exhibits a high surface energy polar component, a subjective perception of slipperiness will decrease, thus increasing the felt stickiness. Although a power law correlation could not be found, it is possible to suppose that surface energy, particularly its polar component, can play a complex role in the slipperiness perception, being responsible of adhesive forces between sliding surfaces (human fingers and coated aluminium).

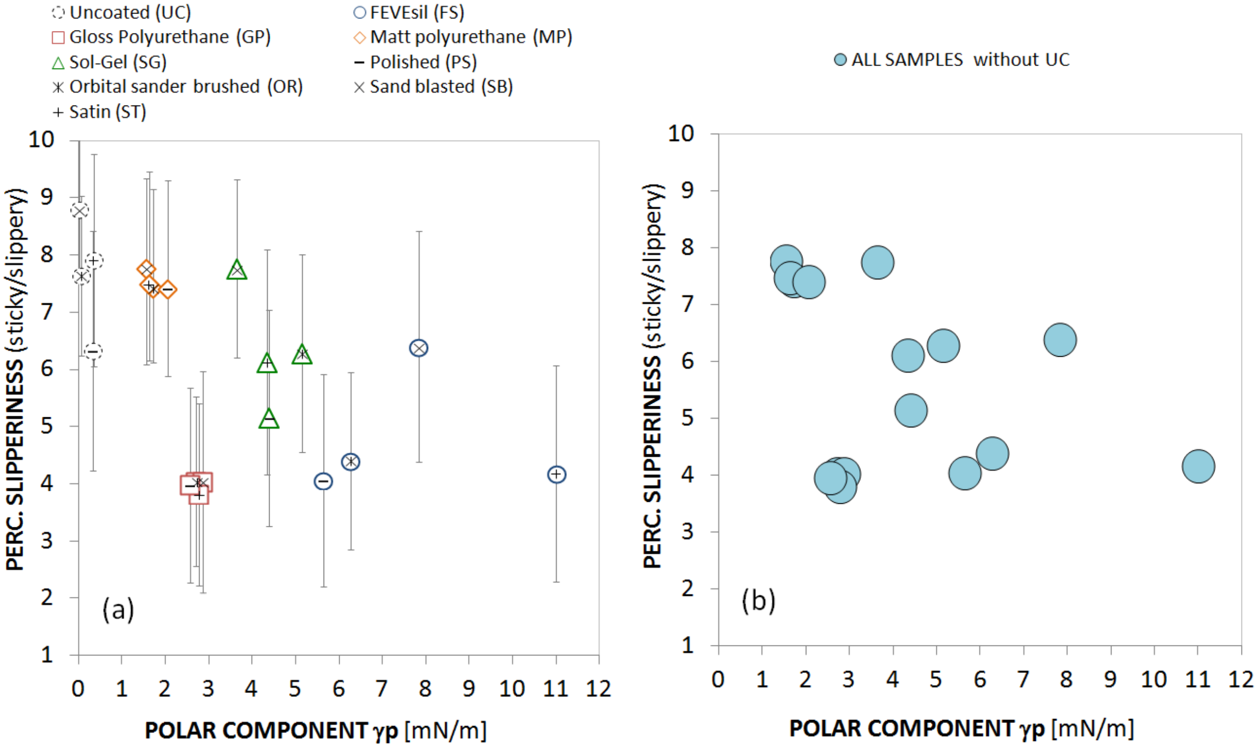

Figure 7. (a) Mean subjective rating values of *felt slipperiness (sticky/slippery)* as a function of the *polar component of surface free energies* γ_p *(mN/m)* for all samples tested; (b) Subjective rating values of *felt slipperiness (sticky/slippery)* as a function of the *polar component of surface free energies* γ_p *(mN/m)* for all samples without those uncoated (UC).

Evaluation of the Physical Gloss as a potential predictor of Perceived Gloss and Felt Slipperiness

Figure 8(a) presents the subjective rating values of perceived gloss as a function of the physical gloss parameter for all samples tested. When correlating the perceived gloss ratings with the physical gloss of the coatings without considering the data for uncoated substrates, the power law growth function is given by

$$\text{Perceived gloss} = 0.9811 \cdot \text{Gloss}^{0.454} \qquad (R^2 = 0.77) \qquad (3)$$

A well-defined positive correlation was found between the perceived gloss and gloss of samples (R^2 = 0.77) as shown in Figure 8(b). This result suggests that participants were able to appreciate differences in the glossiness of coatings under investigation and that the gloss measured by a glossmeter could be used as a predictor of how a material will be perceived in terms of glossiness.

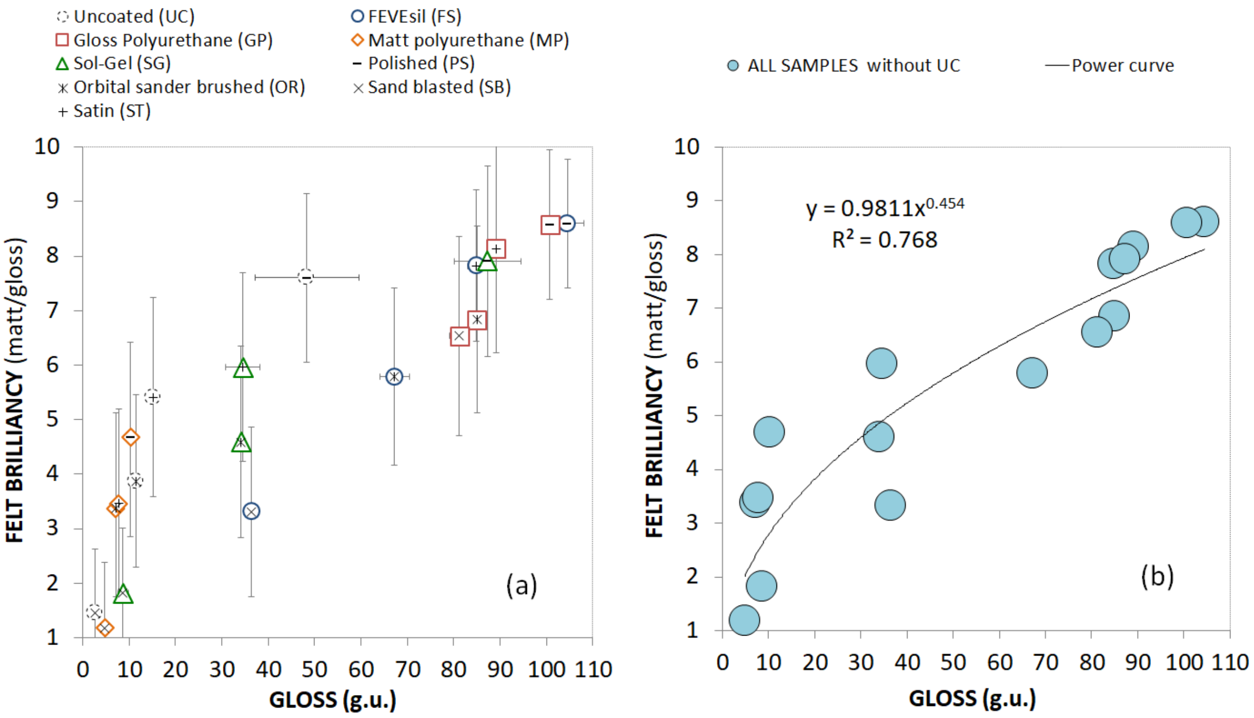

Figure 8. (a) Mean subjective rating values of *perceived gloss (matt/gloss)* as a function of the *physical gloss* for all samples tested; (b) Power law growth function of the *perceived gloss (matt/gloss)* as a function of the *physical gloss* for all samples without those uncoated (UC).

Figure 9(a) presents the subjective rating values of felt slipperiness as a function of the physical gloss parameter for all samples tested. When correlating the felt slipperiness ratings with the physical gloss of the coatings without considering the data for uncoated substrates, the power law growth function is given by

$$\text{Felt Slipperiness} = 12.586 \cdot \text{Gloss}^{-0.238} \qquad (R^2 = 0.87) \qquad (4)$$

A high negative correlation was found between the physical measure of the gloss of coatings and the felt slipperiness ($R^2 = 0.87$) as shown in Figure 9(b).

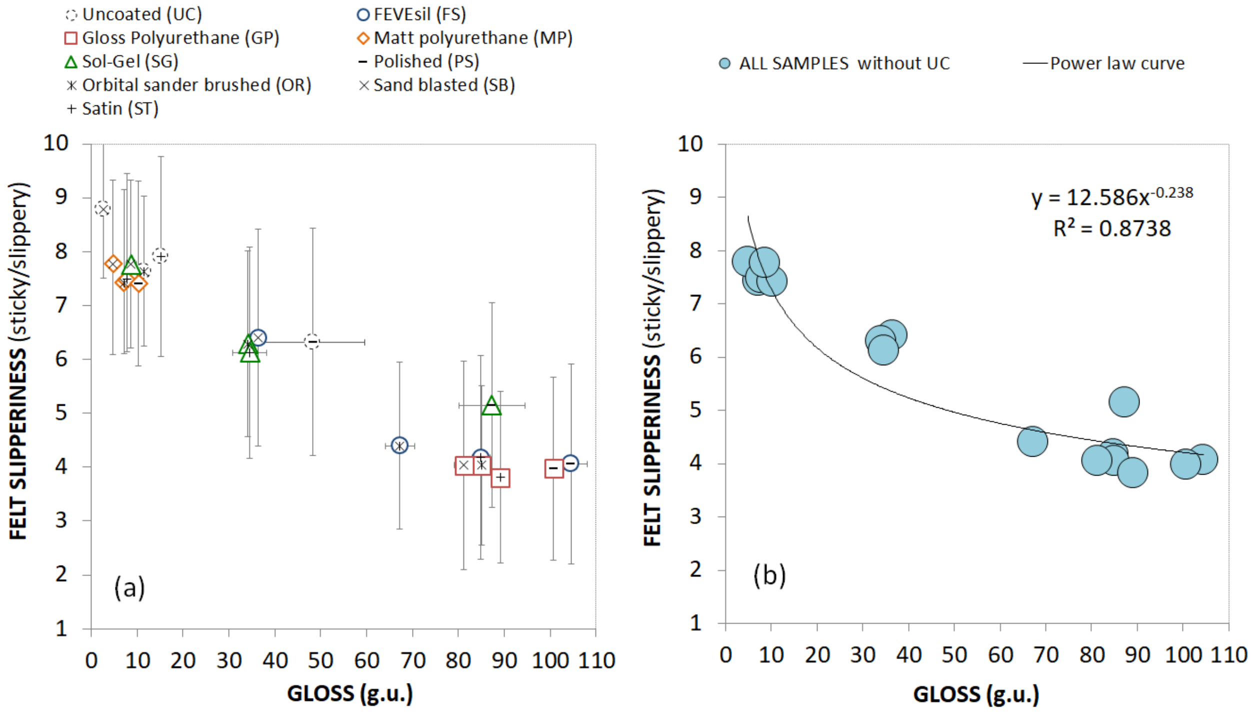

Figure 9. (a) Mean subjective rating values of *felt slipperiness (sticky/slippery)* as a function of *physical gloss* for all samples tested; (b) Power Law growth function of *felt slipperiness (sticky/slippery)* as a function of the *physical gloss* for all samples without those uncoated (UC).

The result that the physical gloss may affect the perception of slipperiness was expected considering the negative correlation generally found between the perceived gloss and the felt slipperiness shown in Figure S4. These relationships may suggest that glossier surfaces could be mostly perceived sticky than those with a matt finish as well as sticky samples could be felt less glossy and shiny than slippery ones.

5. CONCLUSIONS

This study aimed to determine whether measured physical material parameters of aluminium coating surfaces could be used as a predictor of the human sensory perception of the coating surfaces for the purpose of conferring the right sensory experiences to their users. Twenty surfaces were used consisting of four uncoated aluminium substrates and four different type of coatings applied on each of the four uncoated substrates. Semantic differential scales were administered to forty participants to assess the subjective responses to tactile stimuli from the coating surfaces, using the following two-word pairs: slippery-sticky for felt slipperiness, smooth-rough for felt roughness and matt-gloss to assess the perceived gloss of the surfaces. Significant effect of the type of coating was found on the subjective response to aluminium coating surfaces. The results suggest that coatings obtained by matt polyurethane (MP) which contained a fine dispersion of silica micro-particles had the capability to veil the physical material characteristics of the aluminium substrates when assessed in terms of felt slipperiness and felt roughness. Whereas both the manufacturing process and the type of coating used were found to significantly affect the perceived gloss ratings. The results also suggest that the surface roughness parameter of the surface coatings could be considered as a good predictor of the felt roughness when rubbing the hand and fingers on the aluminium surface and that a linear function may exist between the two variables with a coefficient of determination R^2 of 0.79. The dynamic coefficient of friction was found to be a good predictor of the felt slipperiness with a negative power law exponent of 0.86 (R^2=0.85) suggesting that greater friction is associated with less felt slipperiness. The physical gloss was found highly negatively correlated (R^2 = 0.87) with the felt slipperiness of the tactile stimuli suggesting that glossier surfaces could be mostly perceived sticky. The results presented in this study provide a clearer understanding of how objective and physical properties of aluminium and surface coatings correlate with subjective perceptions of material properties, giving useful guidelines for the industrial design of successful products.

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