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Assessing the discriminating power of roughness parameters using a roughness databank

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Abstract

This article presents a methodology based on the use of a surface databank, which aims at assessing the discriminating power of 3D roughness parameters. The presented databank is composed of fourteen different sets of surfaces belonging to two main tribological categories: integrity and functionality. Each set of surface is composed of two classes, called A and B. These classes are obtained by varying process conditions or study parameters. The proposed methodology is first thoroughly described in the general case of comparing two classes of one set of 3D surfaces. Then, sandblasted surfaces are used as an example before applying the methodology to the entire database.

1. Introduction

One main issue in surface topography consists in having a representative databank of surfaces. Having such a surface databank would be of primary interest for:

- (i) Ensuring traceability in surface algorithms (linked with data format or texture analysis systems). A surface databank can be used to compare results obtained with different measurement or analysis software in order to validate surface analysis systems. As an example, in the United States, the National Institute of Standards and Technology developed an Internet-based surface metrology algorithm testing system for parameter assessment and algorithm verification [1, 2]. There were similar developments led by the Physikalisch-Technische Bundesanstalt [3] in Germany and the National Physical Laboratory [4, 5] in Great Britain.
- (ii) Testing the relevancy of roughness parameters or roughness pre-treatments. The databank permits mass testing of the relevancy of roughness parameters or roughness pre-treatment. Furthermore, databank structure allows the use of statistical significance.
- (iii) Assessing which roughness parameters or filterings enable one class of processes to be distinguished from another. As an example, if the databank is only composed of tribological processes, then it can be used to look for the most relevant roughness parameters for the characterization of all the processes.
- (iv) Determining which kind of process was used to create the surface. In this case, the determination would be based on the given roughness parameters but it would require an extensive data to ensure the reliability of the results.

Whatever the databank uses, the following questions should be answered: which generic methodology can be used to test the robustness and/or relevance of an algorithm or method? How can this generic methodology be implemented?

The aim of this article is to show how to implement a statistical method using a surface databank in order to assess the discriminating power of roughness parameters. The databank of surfaces is composed of fourteen different sets of surfaces belonging to two main tribological categories: integrity and functionality. Each set of surface is composed of two classes, called A and B. These classes were obtained by varying process condi-

Table 1. Description of the tribological categories of the databank.

Category	Name	Description
Integrity	BEARING-	Contact fatigue of gears with two lubricants
	BELT----	Belt finishing
	BRUSHING	Superfinishing
	KNEE----	Wear of knee prosthesis
	PEENING-	Ball bearing
	POLISH--	Polishing
	TRIBO---	Lubrication assessment using a tribometer
	UHP-----	Precision hard turning
	USSHOT--	Ultrasonic shot peening
Functionality	BLASTING	Sandblasting
	HOAX----	Morphology of lipstick molds
	LAC-----	Hot mill rolling
	ROPING--	Roping assessment
	SENDZIMI	Sendzimir cold rolling

tions or study parameters. The proposed methodology is first thoroughly described using the comparison of the topography of two sets of surfaces and is then applied to the entire databank.

2. Methods

2.1. Databank description

The surfaces used in the databank correspond to fourteen different sets of surfaces belonging to two main tribological categories: integrity and functionality. More specifically, table 1 shows the nine sets of surfaces corresponding to integrity study and the five sets of surface obtained through the investigation of functionality.

Each set of surface is composed of two classes, called A and B. These classes are obtained by varying process conditions or study parameters. There are only two classes for each set of surface because a two-sample comparison is used to describe the methodology. Indeed, two-sample comparison can be performed with simple statistical interpretation as there are no relationship ambiguities between two cases. Furthermore, two-sample comparison corresponds to one of the most asked question in topography areas: what is the difference between two sets of surfaces and how can it be characterized?

Figure 1 shows measurement samples for the different tribological categories of the database. For the sake of brevity, only the process used as an example is thoroughly described hereafter. However, the different sets of surfaces, as well the measurement characteristics, are comprehensively presented in Goïc *et al* [6]. The set of surfaces used as an example of two-sample comparison are the sandblasted surfaces, called BLASTING in figure 1. The sandblasting process was made using a nozzle-to-surface distance of 5 cm, 60 s duration and an angle of 90°. The working pressure was equal to 1 bar for class A and 3 bars for class B. A white-light interferom-

eter (Zygo NewView™ 7300, Zygo Corp., USA) was used with a $\times 20$ objective to obtain twenty measurements of $1188 \mu\text{m} \times 891 \mu\text{m}$ with a step of $1.09 \mu\text{m}$ for each class using the stitching function.

2.2. Measurement file codification

In order to facilitate programming and computing, it should be noted that a proper formalization is required for the measurement files. This fact is often considered as obvious or even trivial but a good naming will help the comparison of the specimens.

A certain rigor should be applied when naming measurement files in order to gain time and avoid mistakes. A file name should at least be composed of the name entity, the discriminating features of the surfaces (as an example, A or B in a two-sample comparison) and the measurement number. Other characteristics may be added to the file name such as the measurement device, objective, zoom, etc if these features are relevant in the statistical analysis. A delimiter should be used in order to separate the different characteristics. The underscore is a good candidate. The same number of characters should be used for all the study entities (as well as for the discriminating features and measurement numbers). Finally, a logical order should be chosen for the characteristics: the study entity should be first, followed by the discriminating feature of the surface and finally the measurement number. An example of file codification would be: XXXXX_A_RR where XXXXX is the study name, A is the class and RR is the measurement number.

The measurement files could be encoded: as an example, the file AA_BB_CC could be renamed 0001. However, practice shows that using an encoding such as 0001 is a source of error as the user will eventually lose track of the physical meaning. Keeping the physical meaning inside the file name has several advantages. It enables the user to keep a logical order and organization of files. If the same number of characters is used for all the file names, the file visualization will be easier in any software as they all use tree logic in order to classify the file names. This file organization is particularly important when practicing data analysis because it helps to identify groups or classes.

2.3. Description of the methodology used for assessing the discriminating power of roughness parameters

The proposed methodology summarized in figure 2 is composed of three main stages. Stage 1 is dedicated to the measurement of the topography of the specimens. Stage 2 is the treatment of roughness. Stage 3 is the analysis of data.

For the sake of brevity, Stage 1 corresponding to the measurement details (device, objective, ...) for each set of surface is not described in this paper but can be found in [6]. All the measurement files should be named as advised in section 2.2. In figure 2, a two-sample comparison is represented as an example. Classes A and B of

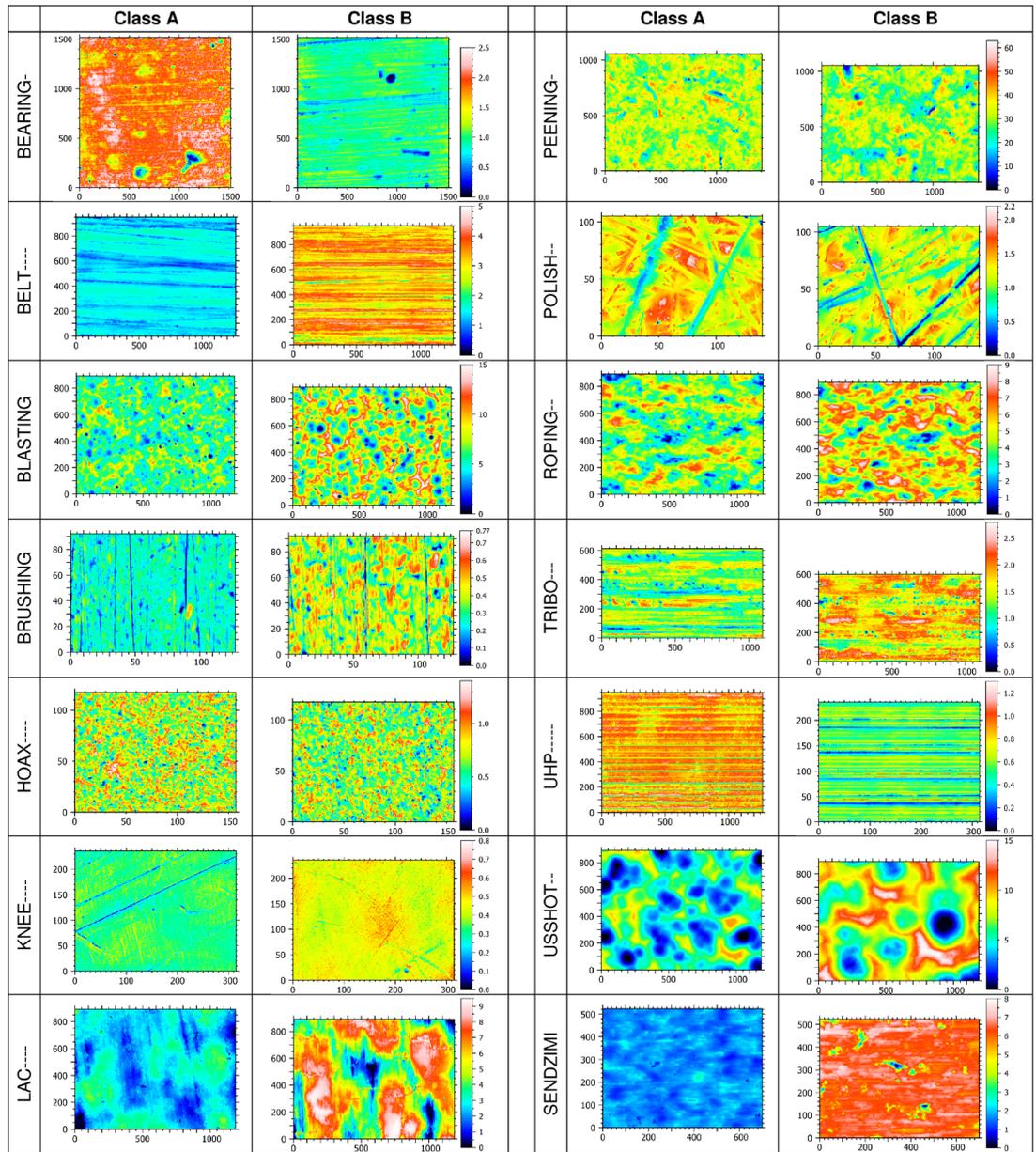


Figure 1. Examples of surfaces observed for the different tribological processes and studies of the database. All the scales are in micrometers.

the specimens can be obtained by varying the process parameters or the study conditions.

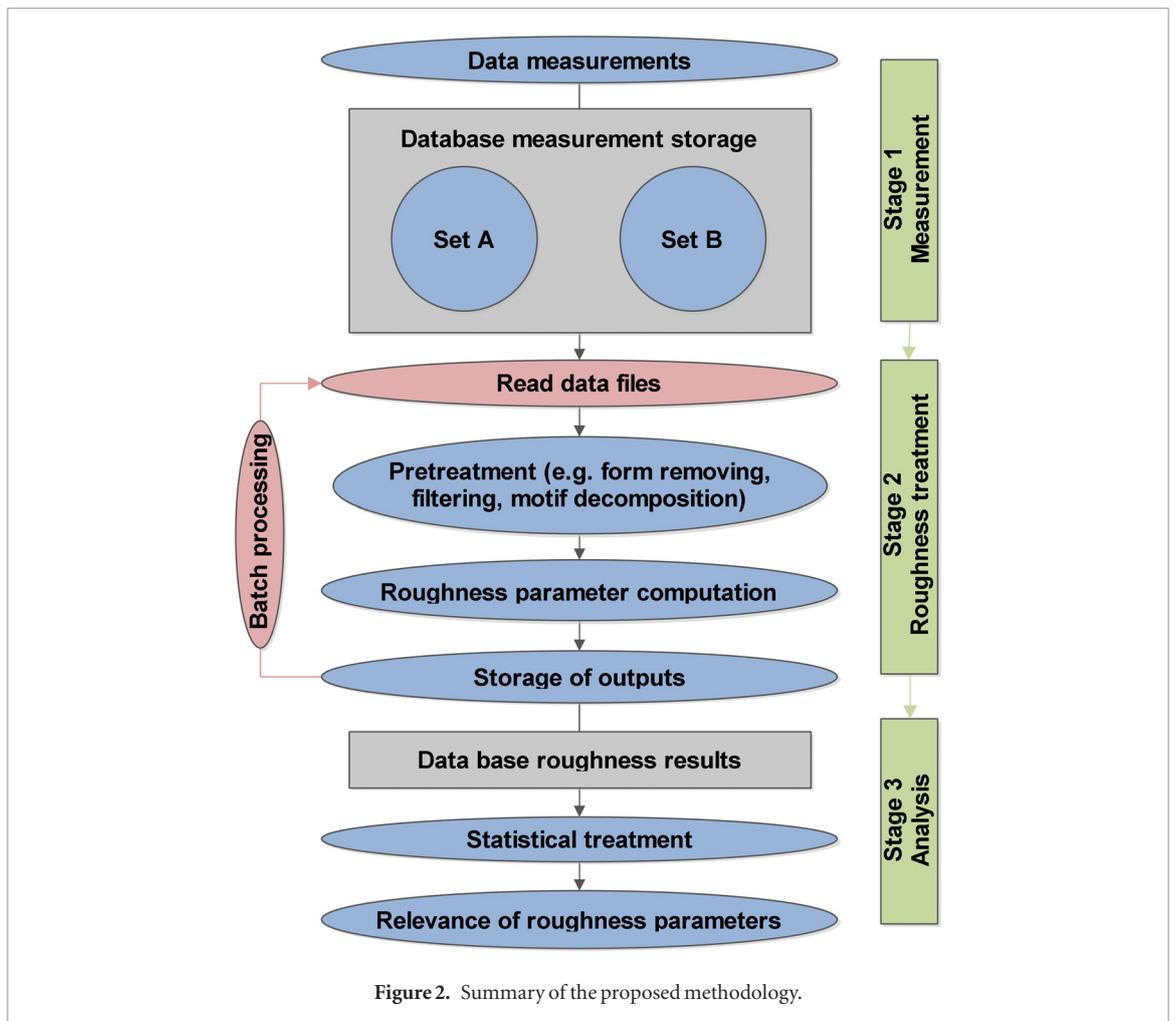
In Stage 2, all the data measurements are first pre-treated. These pre-treatments are generally composed of form removing and filtering. Then, the required roughness parameters are computed. The pre-treatments and roughness computations should be made using batch processing, which permits faster computation. As an example, Gwyddion [7], which is free and open source software, offers batch processing functionality with certain file formats.

MountainsMap[®] (DigitalSurf[™]) is used in this paper for batch processing but this software could be replaced by any other software allowing batch processing. First, an analysis protocol is defined and saved as a template in MountainsMap[®] (.mnt files). One or several templates can be used to pre-treat the surfaces and to compute the required morphology parameters. As an

example, a template could be created for form-removal only, another for filtering and a last one for the computation of roughness parameters.

Then, batch instructions need to be generated. In the presented example, a home-made surface expert system called MesRug [8] is used to generate a log file containing all the required instructions. Figure 3 shows an extract of those instructions.

In this example, the surface file is called BLASTING_A_0001.sur and the template is named V_00.mnt. The name V_00.mnt was chosen to keep the batch instructions as general as possible but it could be replaced by FORMREMOVAL.mnt if the template is only dedicated to form removal or by RPARAM.mnt if the aim of the template is to compute roughness parameters. The .sur extension is MountainsMap[®] native format. The corresponding csv file is called V_00_BLASTING_A_0001.csv while the map



```

AUTOSAVE OFF
Mountains@ software does not save the opened document even if it has been modified.

NEW_DOCUMENT
A new document is created.

LOAD_STUDIABLE "f:\batch_mountains\BLASTING_A_0001.sur"
The measurement BLASTING_A_0001.sur is loaded in the opened document.

APPLY_TEMPLATE "f:\batch_mountains\V_00.mnt"
The template analysis called V_00.mnt is applied.

EXPORT_CSV_BY_LINE "f:\batch_mountains\V_00_BLASTING_A_0001.csv"
The numerical results computed in the opened document are exported to an ASCII file called
V_00_BLASTING_A_0001.csv.

SAVE_STUDIABLE "f:\batch_mountains\V_00_BLASTING_A_0001.sur" BANK:2
The specified map (here number 2 of the opened document) is saved as
V_00_BLASTING_A_0001.sur using the specified path.
  
```

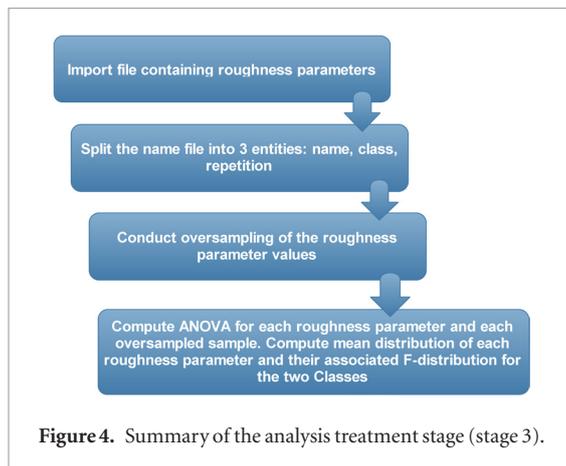
Figure 3. Extract of commands used as batch instructions with the software MountainsMap®. The commentaries are written in italic blue.

file obtained with the template is saved as a sur file using a name that concatenates the template name and original surface name: V_00_BLASTING_A_0001.sur. It should be noted that the template name is concatenated before the study name to obtain an easier visualization of the files in case of the use of several templates.

If the aim of the template was to compute roughness parameters, then the obtained csv files contain all the chosen roughness parameters computed using Mountains® software. More specifically, this file contains the chosen roughness parameter names associated

with their numerical values, units as well as the measurement file name with which it is calculated. In order to perform morphological statistical treatments, these files need to be concatenated and organized.

In the analysis treatment stage (Stage 3), a statistical analysis of the results is performed. The testing of the relevance of the parameters is based on statistical hypothesis testing and bootstrapping. Statistical hypothesis testing enables the user to decide whether groupings of data by class are meaningful. Among statistical hypothesis testing, analysis of variance (ANOVA)



is used to determine whether the means of the examined groups are different. To do so, ANOVA uses F-tests to statistically test the equality of means. The computed F-statistic is equal to the ratio of between-group variability to the within-group variability. It should be noted that the computed F-tests are equivalent to *T*-tests in this example as two-sample comparisons are made. Hereafter, the F-statistic is used as a tool for assessing the relevancy of roughness parameters for the description of morphology differences between surfaces. The higher the F-statistic value is, the more influential the tested parameter is. If the F-statistic value is lower than 1 then the tested parameter is not relevant. F-statistic values are computed for each tested roughness parameter. To get an impression of the variation of the F-statistic values, bootstrapping is used. Bootstrapping is a statistical technique of sampling with replacement. It is used to examine whether the examined data is homogeneous. Bootstrapping avoids using hypotheses about the statistical behavior of the statistical measure. It avoids using statistical inference on F as the frequency measure is looked at. Bootstrapping is used to get a set of F-statistic values to compute means and confidence intervals. In this study, the number of bootstraps is set to 10 000. The different steps of statistical analysis are summarized in figure 4.

3. Methodology application

3.1. Roughness treatment used in the example

In order to illustrate this methodology usefulness, it is first applied to both classes of sandblasted specimens (called BLASTING in figure 1) and then to the entire database.

Several kinds of roughness parameters could be assessed in order to test the topography differences between classes A and B. In this example, motif analysis is used to describe the topography differences between class A and class B. This method is derived from purely graphical methods and was first introduced by Scott [9]. This method is based on the application of watershed algorithms. Motif identification and characterization enables the topology of the surface to be described instead of giving average statistical parameters of the

surface. It can be used to characterize the connectivity of surface valleys for applications such as seals, lubrication, etc. Here the proposed analysis is original as morphological parameters are computed for each identified motif. The aim is to assess which morphological parameter best enables two classes of specimens to be discriminated.

The chosen pre-treatment is as follows: the surfaces are leveled to remove form (using a polynomial of degree 1). Then, the surfaces are decomposed into motifs using watershed segmentation (ISO 25178-71 [10]): peaks and their associated structures (hills, contours of dales) are identified. The segmentation filter options are set as follows: a smoothing median 3×3 filter is used to avoid the detection of local peak due to noise and the pruning criterion ensures that the motif height is lower than 5% of the maximum height S_z (ISO 25178-71 [10]). After peak detection, each motif can be characterized using the morphological parameters described in table 2. The number of motifs (called *n* in the following figures) is also used to try to characterize the topography differences between class A and class B.

In the following examples, one question will be answered: which motif parameter is the most relevant for the description of the topography differences between classes A and B?

3.2. Application to sandblasted surfaces

In this first example, the methodology is applied to one set of surfaces: the sandblasted specimens. As indicated in section 2.1, two classes were obtained by varying the process conditions: class A corresponds to the use of a working pressure equal to 1 bar whereas the working pressure for equal to 3 bars for class B.

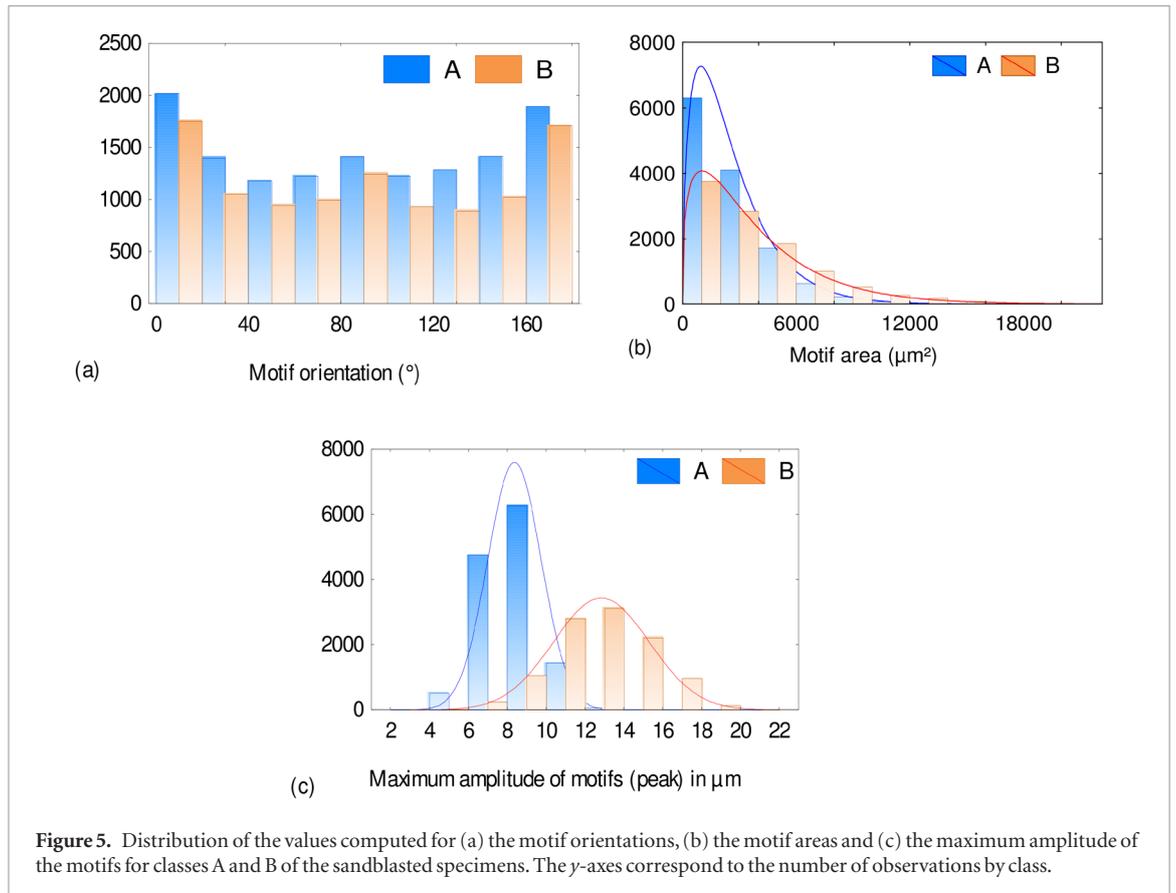
The methodology is applied to the sandblasted specimens to determine which motif parameter best describes the morphology differences between classes A and B. Figure 5 shows the distribution of the values of three morphological parameters: (a) the motif orientations, (b) the motif areas and (c) the maximum amplitude of the motifs for both classes. No clear conclusions on the relevance of these parameters can be drawn with a simple observation of the distribution of these different values. The relevance of the motif parameters should be determined using a quantitative indicator.

Figures 6 and 7 respectively show the distributions of F-statistic and the bootstrapped mean obtained for (a) the motif orientations, (b) the motif areas and (c) the maximum amplitude of the motifs. The motif orientations have a F-statistic value close to 1: it means that this parameter is not relevant for describing the morphology differences between class A and class B. Figure 7 shows that the bootstrapped mean distributions are superimposed. This result was expected, as the sandblasting process induces no motif orientation.

The motif areas have a higher F-statistic value (around 1250) and the bootstrapped means of class A and class B are clearly separated. The motif areas of class A and class B are statistically different: class

Table 2. Description of the morphological parameters used to describe the identified motifs.

Parameter name	Description
Height	Distance between the highest saddle point of the motif and its peak
Area	Horizontal area of the motif
Volume	Material volume of the motif, above the highest saddle point
Epitch	Pitch i.e. mean horizontal distance between the central peak of the analyzed motif and the peaks of the neighboring motifs
Emax	Maximum pitch i.e. maximum horizontal distance between the central peak and the peaks of the adjacent motifs
Emin	Minimum pitch i.e. minimum horizontal distance between the central peak and the peaks of the adjacent motifs
ValZ	Z-extremum i.e. maximum amplitude of the motif
Coflat	Co-flatness i.e. maximum vertical distance between the central peak and the peaks of the adjoining motifs
Dequi	Equivalent diameter i.e. diameter of the disk having an area equal to the one of the motif
AngDmin	Minimum diameter angle i.e. angle of the smallest diameter of the motif measured from its center of gravity, in degrees, with 0° at the right side, -90° at the top, 90° at the bottom
AngDmax	Maximum diameter angle i.e. angle of the largest diameter of the motif measured from its center of gravity, in degrees, with 0° at the right side, -90° at the top, 90° at the bottom
Aspect	Aspect ratio i.e. ratio between the maximum and minimum diameter of the motif
Circu	Roundness i.e. ratio between the area of the motif and the area of the disk having as diameter the maximum diameter of the motif
Compac	Compactness i.e. ratio between the equivalent diameter and the maximum diameter
Orient	Orientation i.e. angle of the biggest axis of the motif. It is comprised between 0° and 180° , measured in the trigonometric direction (with 0° at the right side)



B shows larger motif areas. The motif parameter that best characterizes the morphology differences between class A and class B is the maximum amplitude of the motifs. As shown in figure 6(c), the F-statistic values are very high (around 31 000), which means that the results of class A and class B are statistically highly

different. As illustrated by figure 7(c), the maximum mean amplitude of the motifs is notably larger for class B.

After examining three morphological parameters, the methodology is applied to all the morphological parameters listed in table 2.

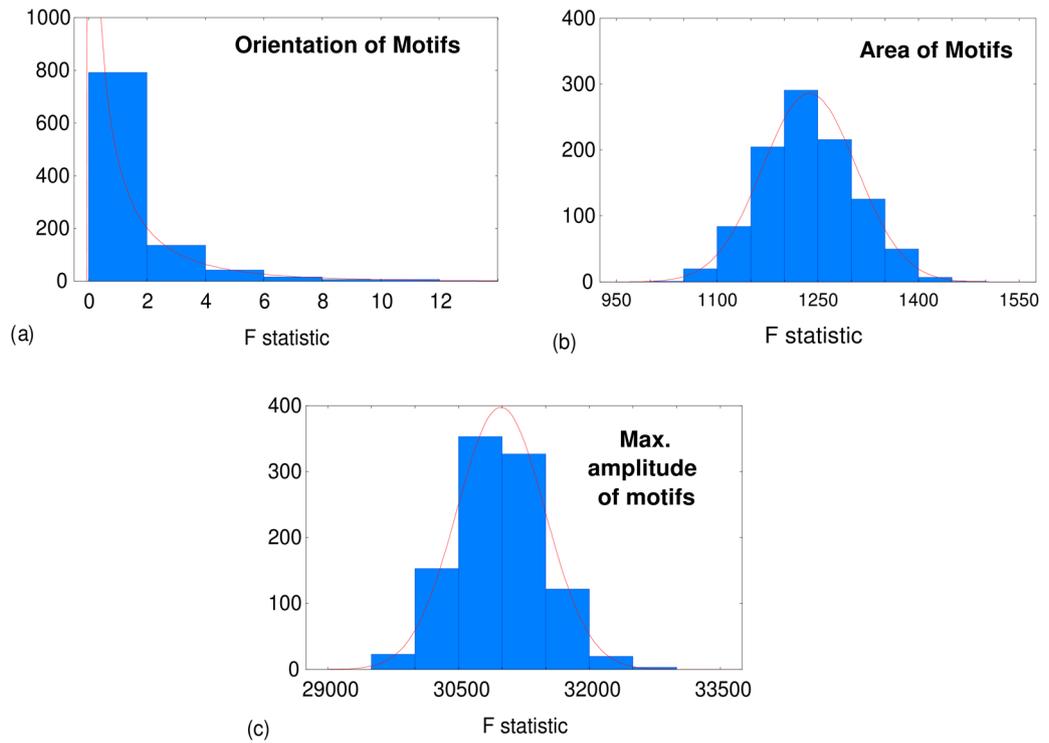


Figure 6. F-statistic distribution obtained when testing classes A and B for (a) the motif orientation, (b) the motif areas and (c) the maximum amplitude of the motifs for the sandblasted specimens. The y -axes correspond to the number of bootstraps by class.

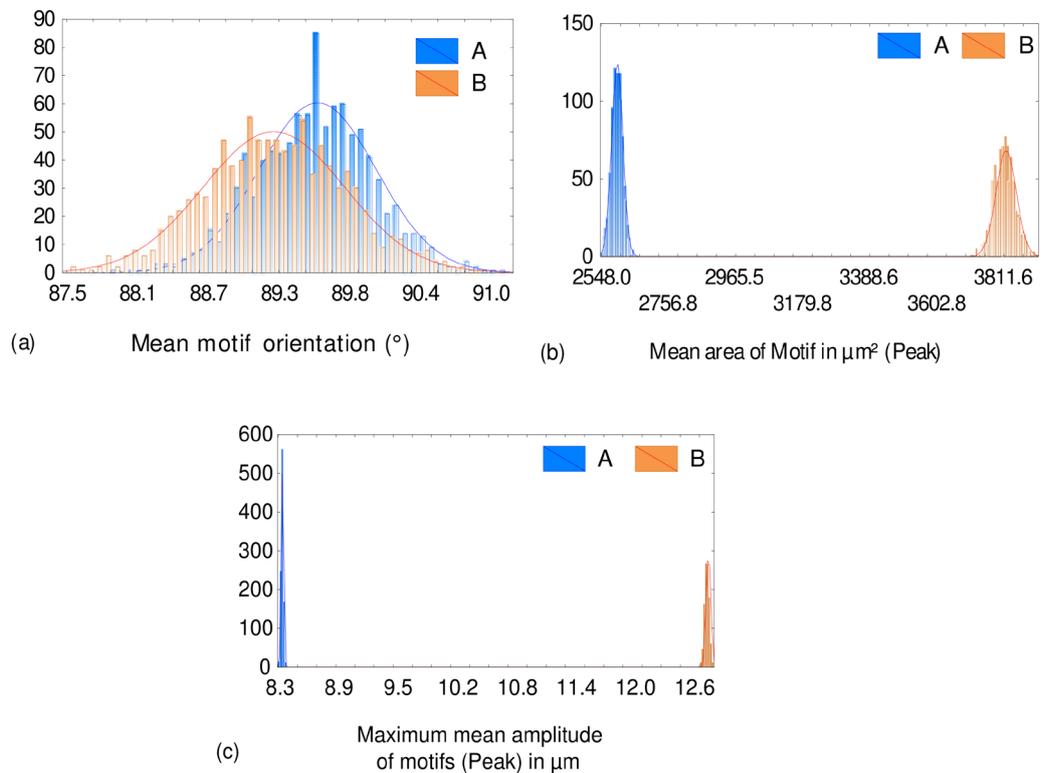


Figure 7. Bootstrapped mean of classes A and B for (a) the motif orientation, (b) the motif areas and (c) the maximum amplitude of the motifs for the sandblasted specimens. The y -axes correspond to the number of bootstraps by class.

Figure 8 shows the mean, median, 5th and 95th percentiles of the F-statistic values obtained for all the tested motif parameters. The most relevant parameters have higher F-statistic values and are thus located on the

left part of the relevance graph. The 5th and 95th percentiles are respectively the values below which 5% and 95% of the observations may be found. The maximum amplitude of the motifs (ValZ) is the most relevant

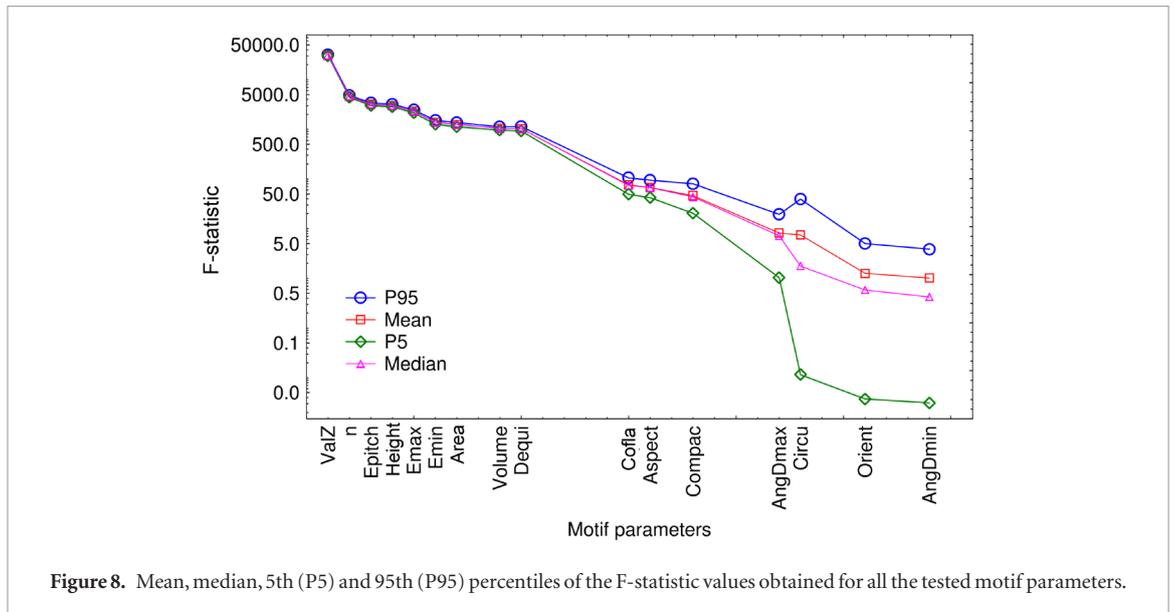


Figure 8. Mean, median, 5th (P5) and 95th (P95) percentiles of the F-statistic values obtained for all the tested motif parameters.

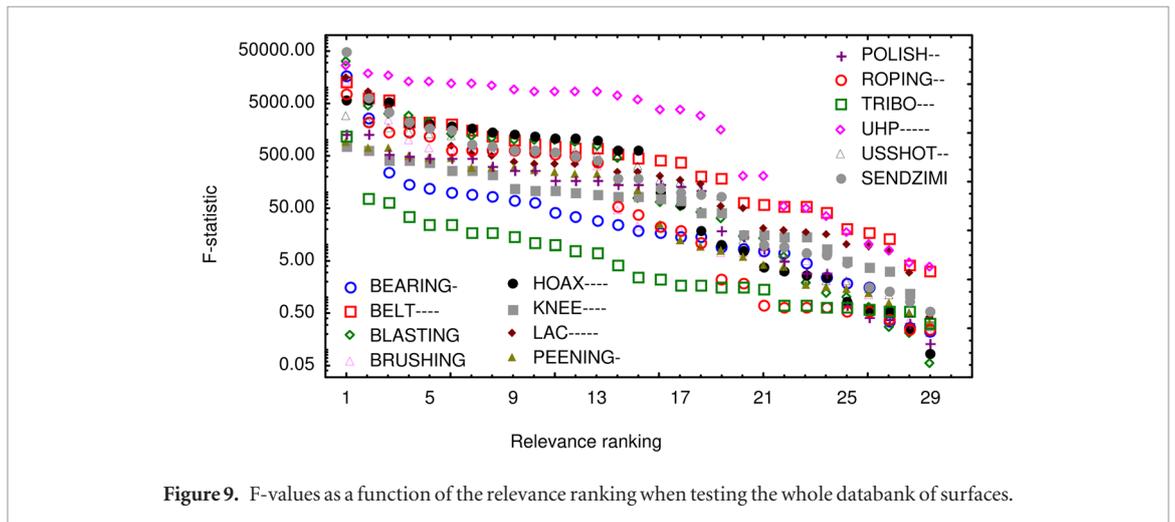


Figure 9. F-values as a function of the relevance ranking when testing the whole databank of surfaces.

motif parameter for the description of the morphology differences between class A and class B, for the sand-blasted specimens.

3.3. Analysis of the whole databank

The same methodology is now applied to the whole databank presented in section 2.1. The same segmentation parameters are used.

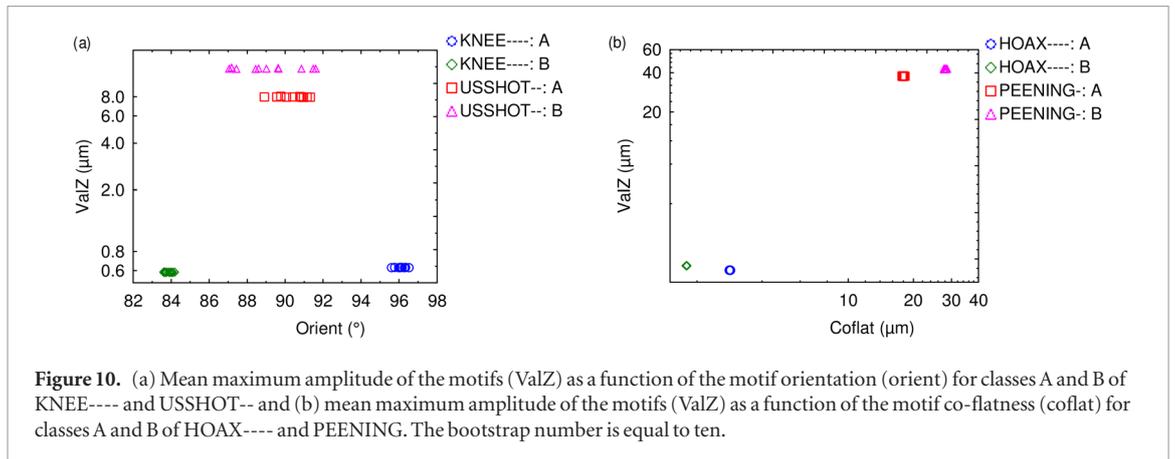
For each process, different F-statistic values are found for the tested morphological parameters. To give an overview of the F-statistics, they are ranked in descending order as shown in figure 9. The largest F-statistic is ranked number 1. Table 3 lists the best motif parameters obtained for the whole databank with the corresponding median F-values and the associated 95th and 5th percentiles. The maximum amplitude of the motifs is the best motif parameter for the whole databank of the surfaces, except for the surfaces corresponding to knee prosthesis wear (KNEE----) and the morphology of the lipstick molds (HOAX----).

The motif parameter that best describes the morphology differences between class A and class B for the surfaces related to knee prosthesis wear (KNEE----) is

Table 3. Best motif parameters obtained for the whole databank of surfaces, associated with the corresponding median, 95th (P95) and 5th (P5) percentiles of the F-values.

	Process	Parameter	P95	Median	P5
1	BEARING-	ValZ	18 346	17 740	16 479
2	BELT----	ValZ	13 346	12 862	12 293
3	BLASTING	ValZ	31 603	30 986	30 057
4	BRUSHING	ValZ	13 286	12 751	11 635
5	HOAX----	Cofla	6258	6134	6085
6	KNEE----	Orient	846	794	753
7	LAC-----	ValZ	16 545	15 344	14 015
8	PEENING-	ValZ	1060	937	869
9	POLISH--	ValZ	1514	937	869
10	ROPING--	ValZ	8038	24 322	23 331
11	TRIBO---	ValZ	1293	7738	7282
12	UHP-----	ValZ	28 534	1197	1065
13	USSHOT--	ValZ	3272	2845	2662
14	SENDZIMI	ValZ	50 307	48 861	46 880

the orientation of the motifs. The wear of the examined knee prosthesis occurred mainly in a specific direction caused by the knee movements. Figure 10(a) shows the



values obtained for the mean maximum amplitude of the motifs (ValZ) as a function of the mean orientations of the motifs (Orient) for two sets of surfaces: KNEE---- and USSHOT--. Ultrasonic shot peening involves shots going in all the directions. The impacts have thus similar orientations even if the shot diameters are different between class A and class B. On the contrary, the surfaces corresponding to KNEE---- show similar values for the parameter ValZ but different motif orientations. It thus explains why the parameter Orient is found to be the most relevant for the description of the morphology differences between class A and class B for the KNEE---- surfaces.

The best motif parameter for the surfaces related to HOAX---- is the co-flatness of the motifs, which is the maximum vertical distance between the central peak and the peaks of the adjoining motifs. Figure 10(b) shows the values obtained for the mean maximum amplitude of the motifs (ValZ) as a function of the mean co-flatness of the motifs (Coflat) for two sets of surfaces: HOAX---- and PEENING-. For the surfaces related to PEENING-, there is a difference of roughness amplitude between class A and class B. This is well described by the parameter ValZ but also by the parameter Coflat: as roughness increases, the parameter Coflat increases. This dimensional analysis shows different results for the surfaces corresponding to HOAX----: the parameter Coflat shows an inversion between class A and class B. These different classes were obtained using different elastomers for the molding of lipstick: one mold produced bright lipstick because it created tight ripples (class A) while the other mold produced a lipstick showing lower gloss as the ripples were more spread. These differences of ripple spreading changed the morphology and distribution of the motifs. The surfaces related to class A showed larger amplitude variations and heterogeneity than class B, thus giving rise to higher co-flatness values.

Applying the presented methodology on the whole databank showed that the motif parameter identified in the two-sample comparison of sandblasted specimens (i.e. the maximum amplitude of the motifs) is also relevant for many other types of the surfaces (12 out of 14). Most of the examined surfaces are linked to

tribological phenomena. It thus shows the relevance of the maximum amplitude of the motifs for the description of tribological phenomena. Even if the number of surfaces of this databank is low, it shows how surface databanks are of primary interest for assessing the discriminating power of roughness parameters. A larger databank of surfaces (e.g. around 200 sets of surfaces) should be used to give a more statistical characterization of the discriminating power of this parameter.

4. Conclusion

This paper aimed at presenting a methodology enabling the comparison of two different surfaces and the identification of the most relevant parameter for the description of the morphology differences between those surfaces. This methodology could be widened to multiscale comparison. In this case, the analysis would be reproduced for each type of filter (i.e. low-pass, high-pass or band-pass) and for each tested cut-off length. Applying this methodology on a multiscale analysis would lead to find the most relevance scale for distinguishing morphology differences between classes A and B, as well as its associated roughness parameter.

The presented methodology can be applied using any roughness software and enables the user to quickly identify the discriminating roughness parameters for the studied classes of surfaces. This methodology can also be used in order to choose between two device settings or between two devices.

This methodology could be applied to more than two classes or could be applied in order to examine correlations.

This paper also enabled the need for archiving surfaces (and their associated characteristics) to be underlined. A good archiving and traceability are essential to widen surface morphology understanding. In the presented examples, most processes or studies were about tribological phenomena. Testing different motif parameters on the entire database enabled a common feature to be identified, which was reflected by the high relevance of the maximum amplitude of the motifs. Such a study could be carried out on any kind of fields (e.g. mechanical, biological, optical, ...).

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