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How to Select the Most Relevant 3D Roughness Parameters of a Surface

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Summary: In order to conduct a comprehensive roughness analysis, around sixty 3D roughness parameters are created to describe most of the surface morphology with regard to specific functions, properties or applications. In this paper, a multiscale surface topography decomposition method is proposed with application to stainless steel (AISI 304), which is processed by rolling at different fabrication stages and by electrical discharge tool machining. Fifty-six 3D-roughness parameters defined in ISO, EUR, and ASME standards are calculated for the measured surfaces. Then, expert software “MesRug” is employed to perform statistical analysis on acquired data in order to find the most relevant parameters characterizing the effect of both processes (rolling and machining), and to determine the most appropriate scale of analysis. For the rolling process: The parameter V_{mc} (the Core Material Volume—defined as volume of material comprising the texture between heights corresponding to the material ratio values of $p = 10\%$ and $q = 80\%$) computed at the scale of $3\ \mu\text{m}$ is the most relevant parameter to characterize the cold rolling process. For the EDM Process, the best roughness parameter is S_{PD} that represents the number of peaks per unit area after segmentation of a surface into motifs computed at the scale of $8\ \mu\text{m}$. SCANNING 36: 150–160, 2014. © 2013 Wiley Periodicals, Inc.

Key words: Sendzimir cold rolling, electrical discharge machining, surface roughness, 3D-roughness parameters, statistical analysis, bootstrap method, ANOVA

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Introduction

In many engineering industrial applications, the precise characterization of surface roughness is of paramount importance because of its considerable influence on the functionality of manufactured products (Whitehouse, 2011). To reduce the manufacturing cost, manufacturers are interested in developing simple and reliable control methodologies suitable for routine production environments, with a high degree of quantitative precision and data repeatability. The topographic method is by far the most implemented one in surface quality assessment of metallurgical or mechanical products. The roughness of machined surfaces is of prime importance across a very wide spectrum of technical and scientific activities; including not only tribologists and production engineers but also highway and aircraft engineers, hydrodynamicists, and even bioengineers (Stout and Blunt, 2000). In the particular cases of tribology, the surface roughness influences adhesion, brightness, wear, friction in wet or dry environment (Yang, 2008). Because of the increasing interests from science and industry, a proliferation of roughness parameters, possibly running into hundreds, has been triggered to describe the different kinds of surface morphology with regard to specific functions, properties or applications but also to characterize materials degradation submit to different tribological mechanisms. In spite of such parameter’s proliferation, termed by Whitehouse as “parameter rash” (Whitehouse, ’82), there is still no complete comprehensive view on the relevance of these roughness parameters. Moreover it was an arduous decision to make the choice between one (pertinent) parameter and another one. The objective of this article is to analyze alternative methodologies to determine quantitatively and objectively the most relevant roughness parameters. This methodology includes functional property of manufactured surface morphology. Moreover, multiscale analysis will be carry out to evaluate the most appropriate scale to characterize the process monitoring. For these reasons, a new methodology is proposed to characterize the morphological properties of a surface in relation to

its physical properties. According to the previous study (Najjar *et al.*, 2003), an expert system (Najjar *et al.*, 2006; Bigerelle *et al.*, 2007) was established to quantify the relevancy of roughness parameters which characterize the functionalities of surfaces at all scales including fractal aspects of the surface for isotropic or anisotropic surface (Van Gorp *et al.*, 2010). The developed computational system includes a recent powerful statistical technique called the bootstrap method which has been successfully used by the authors to compute adhesion properties of materials (Bigerelle and Anselme, 2005). In this paper, the developed methodology will be applied for the first time in 3D roughness parameters analysis.

The Multiscale Analyses of the Relevance of Surface Topography (Marst)

In this part, the MARST methodology is described by an easy-to-understand study of cold rolling process. This elementary study of surface topography will allow us to well appreciate the different steps of the methodology. Then, in Application of the Marst Methodology: Characterization of the Electrical Discharge Machining Process Section, a more realistic case will be treated.

Step 0: Experimental Aspect, the Cold Rolling Process

The studied rolling process reduces austenitic stainless steel strip from 3 to 0.49 mm. The rolling mill is a Sendzimir stand made up with two work rolls (diameter lower than 100 mm) which speed in a range of 300–650 m/min. During the rolling process, the rolls maintain pressure on the strip in order to reduce its thickness. Furthermore, a rear tension and a front tension are applied on the strip in order to guide the strip correctly at the mill entry. The final thickness is obtained after 10 rolling passes, with reduction ratio decreasing from 25% to 10%. Before being cold rolled, the hot rolled strip is treated in order to remove oxide scales (Mougin and Dupeux, 2003; Montmitonnet, 2006). For that purpose, the strip is shot blasted and pickled in hydro chloric acid bath. These industrial processes have an impact on down-stream processes by modifying surface characteristics such as roughness and plastic behavior. Indeed, the first three rolling passes are critical in the “scrub” of surface flaws. The roughness gradient between sheet and blasted cylinder is important. Large crushing asperities occur but are constrained by the trapping of lubricant in the valleys (Huart *et al.*, 2004). Thus, in order to select the most relevant 3D roughness parameters, three specimens are extracted from the industrial process. The first is the original shot blasted strip, the second is after one pass and the last is after three passes.

Step 1: Roughness Measurements

The white light interferometer (NewView, 7300, Zygo, Middlefield, USA) is employed for characterizing and quantifying surface roughness. Optical resolutions of 20× Mirau objective used are 0.71 μm for *x* and *y* axes based on Sparrow criteria which take into account the lens numerical aperture and 0.01 μm for *z*-axis. Indeed, spatial sampling based on camera pixel size (0.55 μm) is lower than the optical resolution. The inspected surface area is 700 μm by 525 μm obtained by stitching of each single measurement with 20% overlap.

Step 2: The Multiscale Decomposition

The Gaussian filter has been recommended by ISO 11562-’96 and ASME B46.1-’95 standards for determining the mean line in surface metrology. This filter was adapted in order to filter the 3D surfaces with a given cut-off value (Yuan *et al.*, 2000). In this study, only the high pass filter will be presented (for the sake of simplicity, we omitted the results of low pass filter because best parameters were not relevant in this study). All surfaces were filtered with different cut-off (30) in order to obtain a multiscale decomposition. The 30 consecutive cut-offs are used in this decomposition, with a cut-off varying from 2 to 360 μm. Figure 1 represents two high pass filters for the surface decomposition with two cut-off corresponding to $L/4$ and $L/64$ μm where L is the horizontal scanning length. When the cut-off decreases, microscopic details appear on filtered surfaces (Fig. 1).

Then 3D Roughness parameters are computed. 3D roughness parameters are defined by the following standards: ISO 25178 define 30 parameters, EUR 15178N also define 30 parameters but some are identical to those of ISO 25178. Only 16 parameters are the latest ones, however S_z (maximum height of surface roughness) and S_{td} (texture direction) are calculated differently in both standards. Further, 7 3D roughness parameters related to surface flatness are defined by ISO 12781, and ASME B46.1 define seven similar parameters as ISO 25178 standard (with different predefined filters) and one new parameter S_{wt} (area waviness height). This gives in total 56 different 3D roughness parameters, which will be considered in this study.

The 3D roughness parameters (see Table I) can be classified into the following groups:

1. Amplitude parameters.
2. Spatial parameters.
3. Hybrid parameters.
4. Functional parameters.
5. Feature parameters.
6. Other 3D parameters.

Figure 2a and b represent the values of the two parameters V_{mc} and S_{mc} versus decomposition scale (the

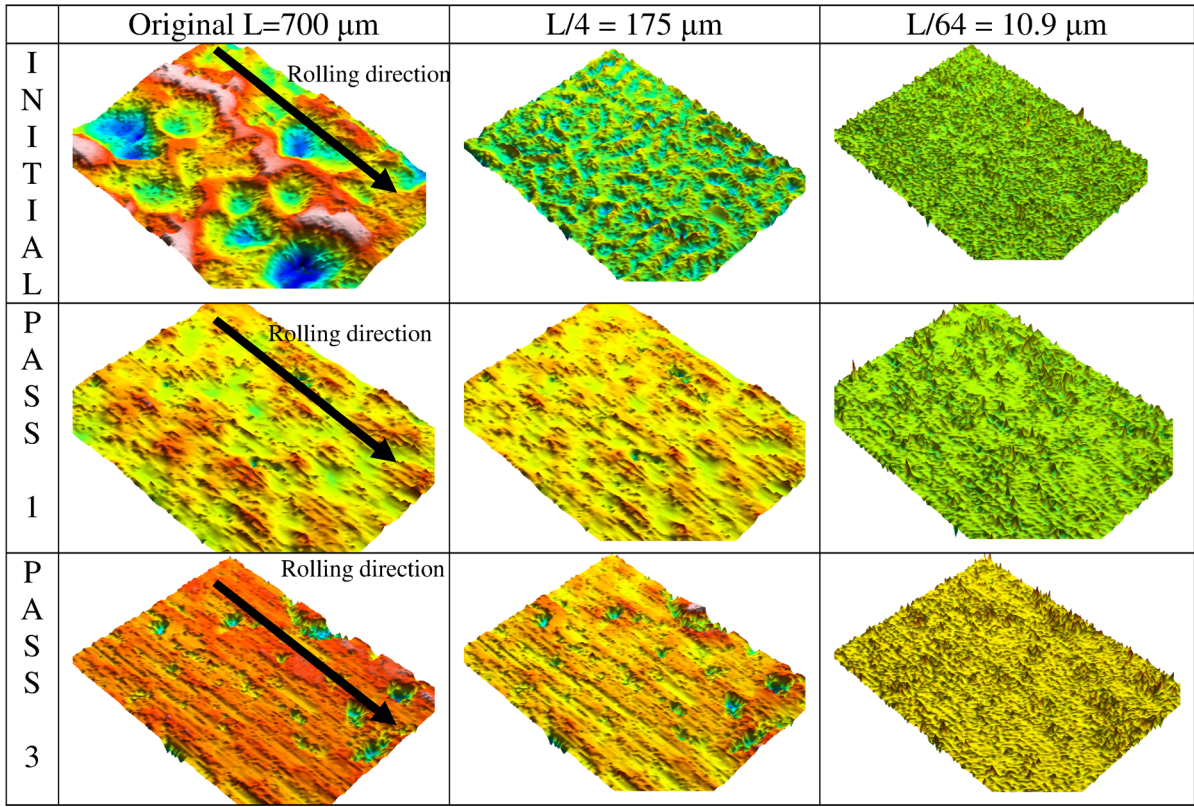


Fig 1. Cold rolled strip of AISI 304 measured before and after a first rolling process and after third rolling processes, measured surface size $700 \mu\text{m} \times 525 \mu\text{m}$. Examples of multiscale decomposition using Gaussian high pass filtering at cut-off $L/4 = 175 \mu\text{m}$ and $L/64 = 10.9 \mu\text{m}$.

Gaussian filter cut-off). It is observed that when the cut-off increases, lower frequencies on the surface are introduced and consequently the amplitudes of the parameters increase without regard to the process conditions. Because of the bootstrap analysis, it is noticed that the three process conditions present different values at different scales. However, the parameter S_{mc} presents a higher variation compared to V_{mc} . It can be suggested that V_{mc} is more relevant to describe the effect of tooling conditions than S_{mc} .

Step 3: The Measure of Parameters Relevancy by Variance Analysis

To measure the relevancy of the roughness parameters computed at a given spatial scale, an appropriate statistical tool will be used. The most relevant scale is investigated by variance analysis, which is essentially an implementation of the generalized linear model. The formula is as follows:

$$p_i(\varepsilon, k, n) = \alpha_0 + \sum_{j=1}^3 \alpha_{j,k_j}(i, \varepsilon) + \xi_{k,n}(i, \varepsilon), \quad (1)$$

where $p_i(\varepsilon, k, n)$ is value of the roughness parameter of the n th profile when the process parameters are taken

at the k th level (k denotes the initial surface after 1 rolling process, or after 3 rolling processes) for an evaluation length ε , $\alpha_j, k_j(i, \varepsilon)$ represents the influence on the roughness parameter value of the j th process parameter at the k_j th level. $\xi_{k,n}(i, \varepsilon)$ is a zero-mean Gaussian noise with standard deviation σ .

For each evaluation length, all of these influences are calculated by linear fitting. From them and for each process parameter and each interaction, between-group variability and within-group variability (corresponding to estimation errors of the roughness parameter of each group) are calculated. The result, denoted by $F(p_i, \varepsilon)$, is the ratio produced by dividing the “between-group” variability over the “within-group” variability. In other words, this result compares the effect of each process parameter on the roughness parameter’s value with its estimation error. Consequently, for a given process parameter, a value of $F(p_i, \varepsilon)$ near to 1 suggests an irrelevancy of the roughness parameter p_i estimated at the evaluation length ε to represent effects of the process parameter in consideration. Higher the value of $F(p_i, \varepsilon)$ is, more relevant the parameter p_i estimated at the scale ε becomes (see Van Gorp *et al.*, 2010 for more details). In this way, we can compare not only $F(p_i, \varepsilon)$ with regard to the evaluation length but also to the chosen roughness parameter. By checking the highest value of $F(p_i, \varepsilon)$, the most pertinent roughness parameter and its evaluation

TABLE I 3D roughness parameters calculated and analysed in this study

Symbol	Name of parameter	Standard
3D roughness parameters		
Amplitude parameters		
S_q (μm)	Root mean square height	ISO 25178
S_{sk}	Skewness	ISO 25178
S_{ku}	Kurtosis	ISO 25178
S_p (μm)	Maximum peak height	ISO 25178
S_v (μm)	Maximum pit height	ISO 25178
S_z (μm)	Maximum height	ISO 25178
S_a (μm)	Arithmetic mean height	ISO 25178
S_t (μm)	Total height	EUR 15178N
Spatial parameters (ISO 25178)		
S_{al} (mm)	Auto-correlation length	ISO 25178
S_{tr}	Texture-aspect ratio	ISO 25178
S_{td} ($^\circ$)	Texture direction	ISO 25178
S_{al} (μm)	Fastest decay autocorrelation length	ISO 25178
Hybrid parameters (ISO 25178)		
S_{dq}	Root mean square gradient	ISO 25178
S_{dr} (%)	Developed interfacial area ratio	ISO 25178
S_{ds} ($1/\text{mm}^2$)	Density of summits	EUR 15178N
S_{sc} ($1/\text{mm}$)	Arithmetic mean summit curvature	EUR 15178N
S_{fd}	Fractal dimension of the surface	EUR 15178N
Functional parameters		
S_k (μm)	Core roughness depth	EUR 15178N
S_{pk} (μm)	Reduced summit height	EUR 15178N
S_{vk} (μm)	Reduced valley depth	EUR 15178N
S_{r1} (%)	Upper bearing area	EUR 15178N
S_{r2} (%)	Lower bearing area	EUR 15178N
S_{pq}	Plateau root mean square roughness	EUR 15178N
S_{vq}	Valley root mean square roughness	EUR 15178N
S_{mq}	Material ratio at plateau-to-valley transition	EUR 15178N
S_{mr} (%)	Areal material ratio	ISO 25178
S_{mc} (μm)	Inverse areal material ratio	ISO 25178
S_{xp} (μm)	Extreme peak height	ISO 25178
S_{dc} (μm)	Areal height difference	ISO 25178
Volume functional parameters		
V_m (mm^3/mm^2)	Material volume	ISO 25178
V_v (mm^3/mm^2)	Void volume	ISO 25178
V_{mp} (mm^3/mm^2)	Peak material volume	ISO 25178
V_{mc} (mm^3/mm^2)	Core material volume	ISO 25178
V_{vc}	Core void volume	ISO 25178
V_{vv} (mm^3/mm^2)	Pit void volume	ISO 25178
Functional indices		
S_{bi}	Surface bearing index	EUR 15178N
S_{ci}	Core fluid retention index	EUR 15178N
S_{vi}	Valley fluid retention index	EUR 15178N
Feature parameters		
S_{pd} ($1/\text{mm}^2$)	Density of peaks	ISO 25178
S_{pc} ($1/\text{mm}$)	Arithmetic mean peak curvature	ISO 25178
S_{10z} (μm)	Ten point height	ISO 25178
S_{5p} (μm)	Five point peak height	ISO 25178
S_{5v} (μm)	Five point pit height	ISO 25178
S_{da} (mm^2)	Mean dale area	ISO 25178
S_{ha} (mm^2)	Mean hill area	ISO 25178
S_{dv} (mm^3)	Mean dale volume	ISO 25178
S_{hv} (mm^3)	Mean hill volume	ISO 25178
Other 3D parameters (from mountain software)		
S_{mean} (μm)	Mean height in absolute	No standard
S_{dar} (mm^2)	Developed area	No standard
S_{par} (mm^2)	Projected area	No standard
— (μm^3)	Mean volume of islands	No standard
— (μm)	Mean height of islands	No standard
— (μm^2)	Mean surface of islands	No standard

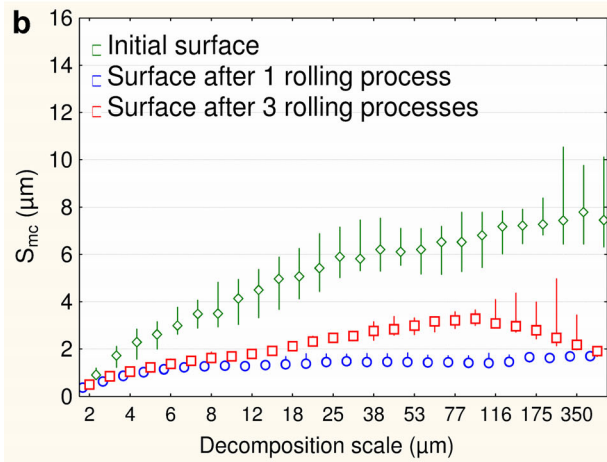
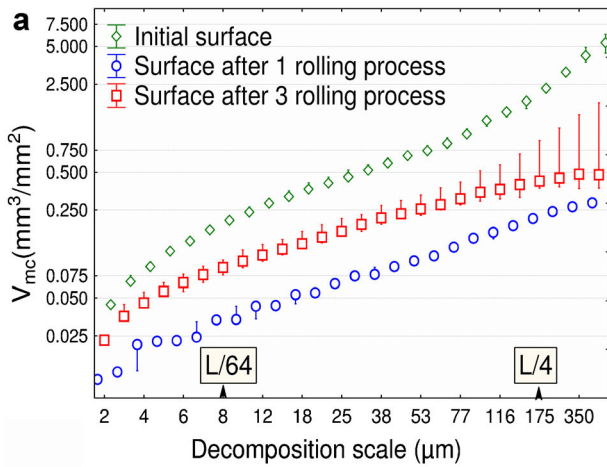


Fig 2. Change of the core materials volume, V_{mc} (a) and the relative material ratio, S_{mc} (b) versus the scale (filter cut-off) corresponding to the three surface topographies described in Figure 1.

length can be selected to describe the influence of a given process parameter. In the case of a cold rolling process, Figure 3 presents the changes of $F(p_i, \epsilon)$ versus the evaluation length for three roughness parameters: V_{mc} , S_{mc} , and S_{ha} . By analyzing these figures, it can be concluded that:

- Relevance is better for V_{mc} at the low spatial scale of $3 \mu\text{m}$ (microscopic scale).
- The relevance of S_{mc} is quite constant at all scales, does not depend on the scale and is less pertinent compared to V_{mc} .
- The mean of an island surface is highly relevant at higher spatial scale (around $350 \mu\text{m}$, macroscopic scale) and appears to be a characteristic length of the tool processing. However physical meaning of this parameter remains questionable especially at higher decomposition scales.

In summary, these figures show that the range of relevant evaluation length depends on the class of roughness parameters. This multi-parameter representation of

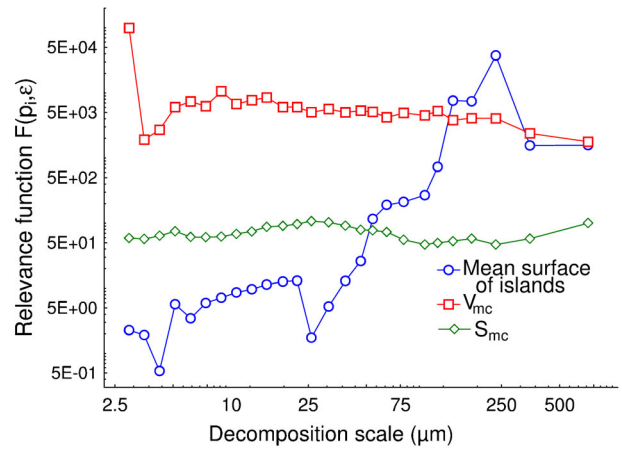


Fig 3. Change of the relevancy criterion F for Core materials volume V_{mc} , the relative material ratio S_{mc} and the mean surface of island versus the scale (filter cut-off) to discriminate the three surface topographies described in Figure 1.

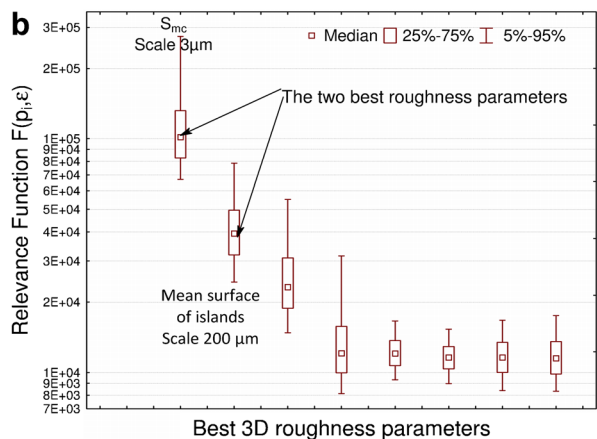
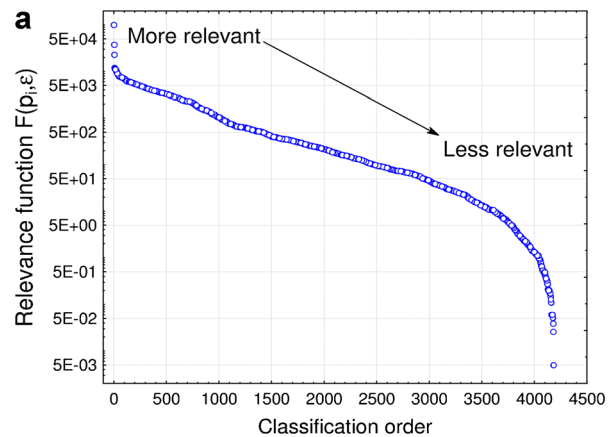


Fig 4. Classification of the 3D roughness parameters according to relevancy criterion F to discriminate the three surface topographies (a) described in Figure 1, (b) the most relevant parameters with their confidence intervals associated to the relevancy function $F(p_i, \epsilon)$ obtained by bootstrap method.

surface roughness has been reported in various works and some efforts have been put previously to develop a method for selecting relevant parameters (Bigerelle and Anselme, 2005; Scott *et al.*, 2005; Jordan and Brown, 2006; Narayan *et al.*, 2006; Berglund *et al.*, 2010).

Step 4: The Classification of Roughness Parameters

It will be appropriate to organize the relevancies of all roughness parameters by classifying their F values in descending order (Fig. 4a). In order to take account of the robustness of the relevance of all roughness parameters, bootstrap is to estimate the error in the computation of the coefficients of statistical modeling. For these reasons, we shall introduce a recent technique called the bootstrap which is a resampling technique (Efron and Tibshirani, '93; Hall, '92). The basic idea of the bootstrap consists in creating a new dataset by randomly sampling with replacement from the original data set and then performing the same statistical analysis as carried out on the original data set. This original bootstrap method applied to the analysis of variance allows obtaining variability on the F values (Fig. 4b).

The parameter V_{mc} is the most relevant one computed at the scale of $3 \mu\text{m}$ and has the same relevance as the mean of the island surface measured at the scale of $300 \mu\text{m}$. The second most relevant roughness parameter

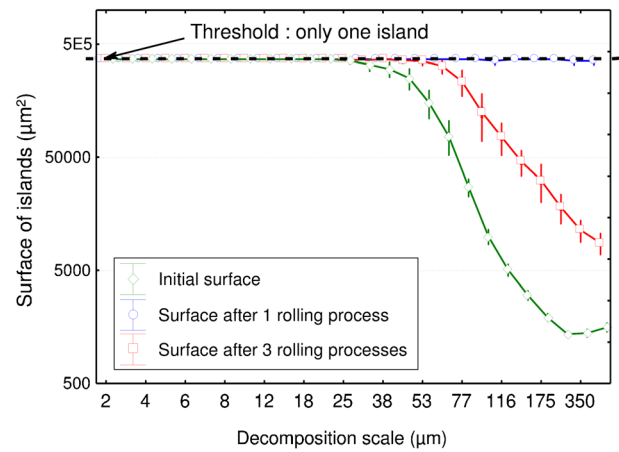


Fig 5. Change of the mean surface of islands versus the decomposition scale (Gaussian filter cut-off) corresponding to the three surface topographies described in Figure 1.

is the “mean surface of islands” computed at the macroscopic scale roughness ($300 \mu\text{m}$). Figure 5 shows that the discrimination of this parameter appears after a scale of $50 \mu\text{m}$ and the threshold depends on the surface itself. An interesting property of the proposed method is that there is no meaningful correlation between V_{mc} and S_{ha} and both parameters describe different physical mechanisms.

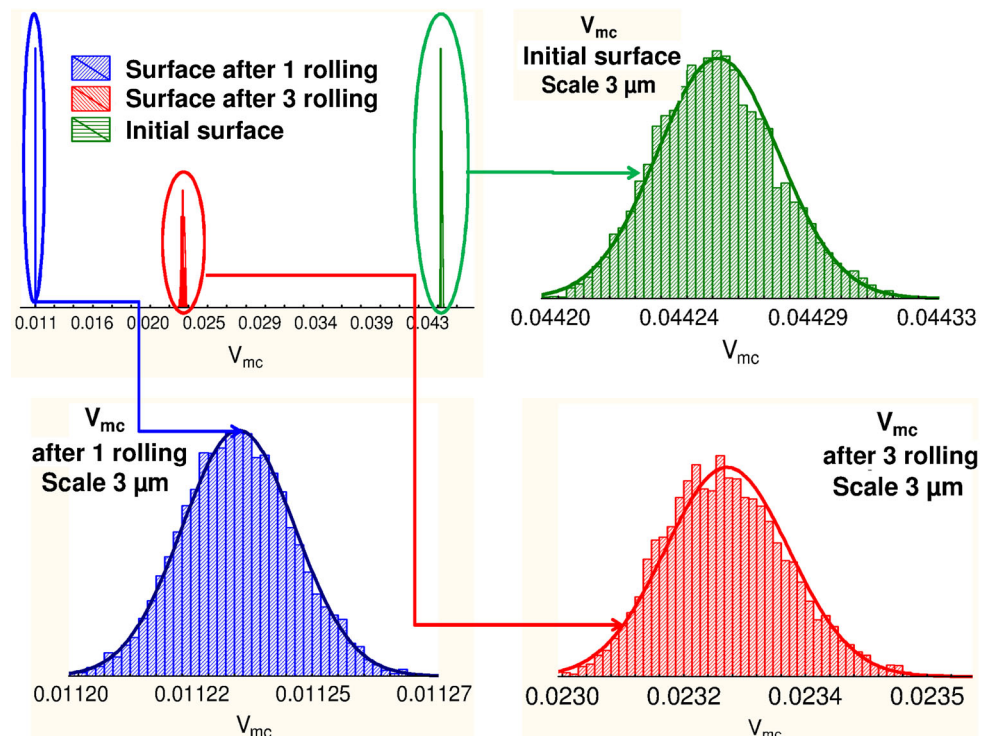


Fig 6. Bootstrap histograms of the mean values of V_{mc} roughness parameters compute at the scale of $3 \mu\text{m}$ for three surface topographies described in Figure 1.

Step 5: Bootstrap and Probability Density Function of the Most Relevant Parameters

Once the most relevant 3D roughness parameter has been found, next step in the analysis is to calculate the mean probability density function (PDF) of the most relevant parameters for the three processes considered in this study. Figure 6 represents the value of these PDF (histograms) of the roughness parameter V_{mc} for the three process conditions. It can be observed that the relevance is unmistakable because no overlap appears

and V_{mc} unambiguously discriminates the effect conditions.

Final Step: Physical Interpretations of Selected Parameters

Initially, valleys create the gap filled effortlessly by the lubricant. After each consecutive rolling process, fewer voids are available for lubricant. Due to the anisotropic texture along a rolling direction, the

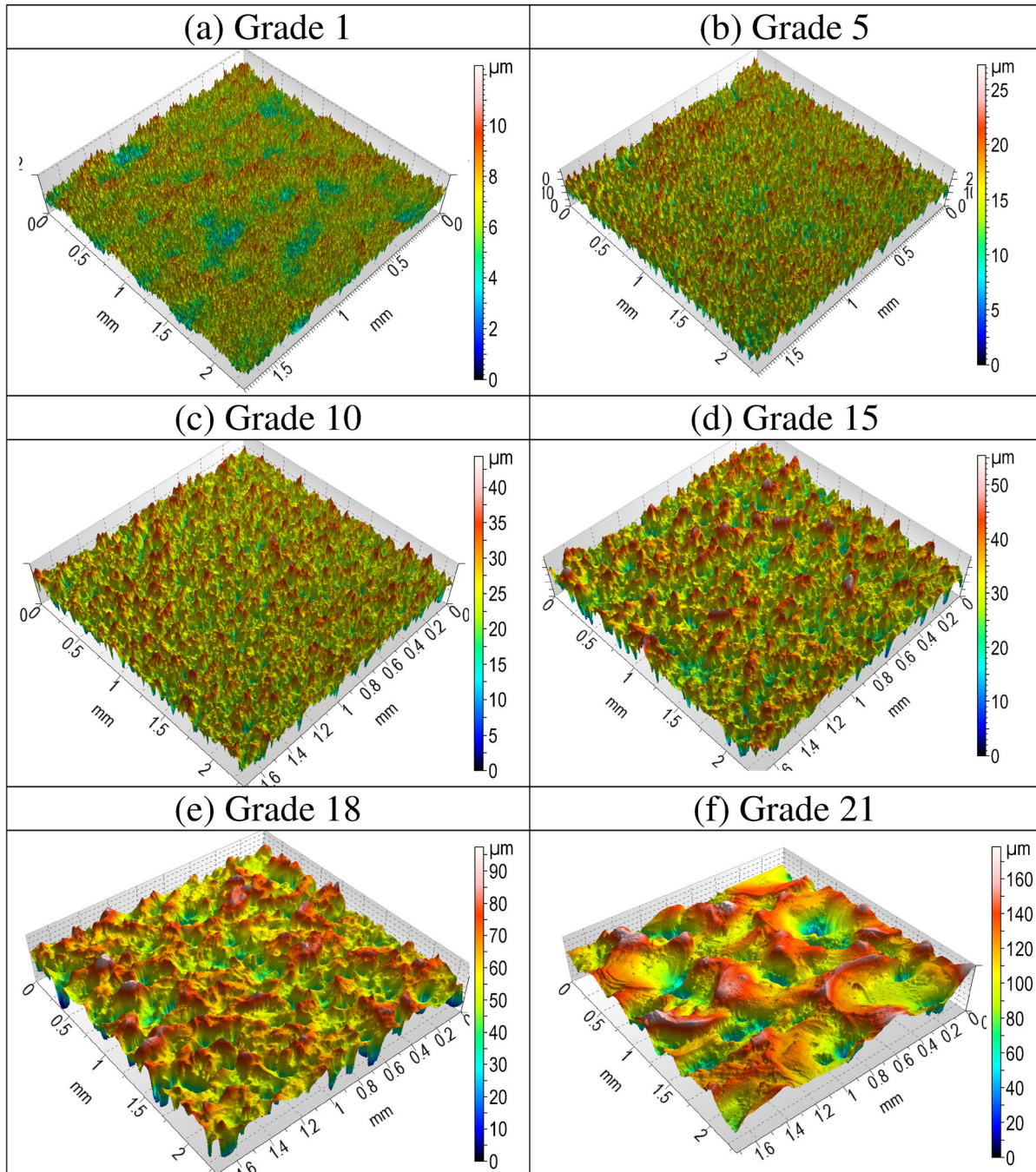


Fig 7. 3D experimental measurements of electro-eroded surfaces at six EDM grades.

lubricant can leak outside the contact zone painlessly through the narrow network of valleys. The lubricant is supposed to flow according to the Couette equation (Stachowiak and Batchelor, 2005): the lubricant flows in the inlet area from valley to valley due to pressure gradient. Such a flow will be highly influenced by the roll and strip speeds. This is peculiarly true if the distance between each valley is small enough to create the flow. Furthermore at the roller entry, lubricant thickness is directly linked with rolling parameters. Thus, thickness is reduced as the bite angle increases and the speed becomes lower (Wilson and Walowit, '71).

This explains the decreasing tendency of the voids represented by V_{mc} . However, after three rolling passes, voids volume tends to increase. Indeed, through the different passes, the lubricant hardly flows from valley to valley due to a sparse pits network. The only way for the lubricant to escape is at the inlet entry where the valley is squeezed out by roller. This effect decreases as roll speed is increasing and the roll bite angle is lower. It is expressed by Wilson and Walowit equation where the lubricant thickness tends to be higher as the strip thickness is reduced after every consecutive rolling process.

Application of the Marst Methodology: Characterization of the Electrical Discharge Machining Process

Isotropic topographies over a wide range of dimensions are tooled by electrical discharge machining (EDM). The EDM process produces strongly isotropic, fractal and self-similar surfaces.

Step 0: Experimental aspect, the Electrical Discharge Machining (EDM)

Twenty-one different samples are tooled with EDM process, forming a very wide range of roughness whose amplitude R_a varies from 1.2 to 15 μm . The EDM: a 5 mm thick plate of pure Titanium (Ti) was electro-eroded by EDM using a spark erosion machine provided by Charmilles (Switzerland). A copper electrode with a diameter of 20 mm was used with a tension of 220 V. Intensity and gap was controlled from 0.5 to 64 A for intensity and from 0.02 to 0.25 mm for the gap (distance between sample and electrode) such as the first sample is the smoother and the last sample is the rougher. Then the plate was cut in order to obtain 21 samples with 21

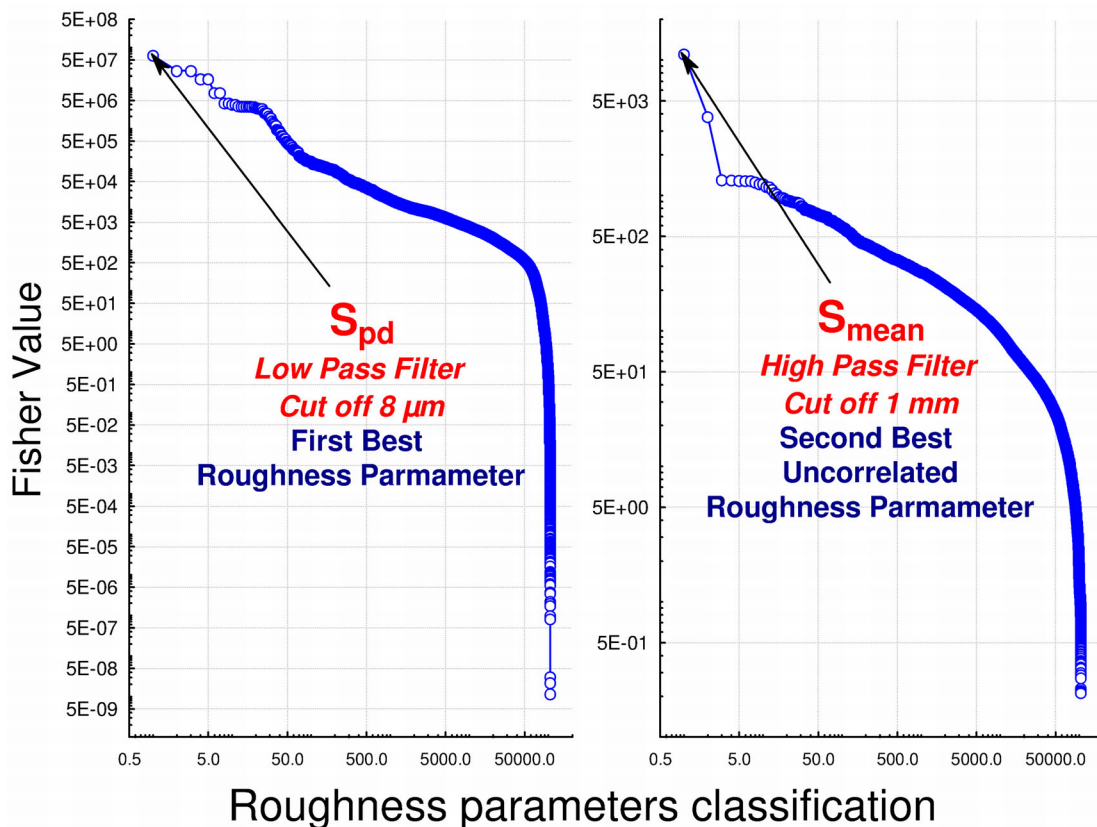


Fig 8. Graph of relevance of the best pair of uncorrelated pair of roughness parameters S_{pd} and S_{mean} . Higher the Fisher value, more relevant the roughness parameter.

roughness levels with an amplitude roughness parameter (R_a) comprised between 1.2 and 15 μm (grades 1–21). X-ray photoelectron spectroscopy (XPS) analysis confirmed that the surface chemistry was identical for all 21 samples and composed of titanium oxides (data not shown).

Step 1: Roughness Measurements

Roughness Measurements: 3D roughness measurements were achieved on an Interferometer using a 20 \times objective (Zygo). The axial resolution of the machine is around 10 nm and the plane resolution is around 710 nm (Fig. 7). The surfaces obtained by electro-erosion present an isotropic structure formed by successive peaks and valleys. No specific direction or periodical structure is visible on surfaces. Higher the grade, higher the roughness amplitude, larger peaks-or-valleys.

Step 3–5: Core of the MARST Analyses

Figure 8 represents the plot of the relevance of the first and second uncorrelated parameters. The best roughness parameter is S_{pd} that represents the number of peaks per unit area after segmentation of a surface into motifs (hills and dales). This segmentation is carried out in accordance with the watersheds algorithm. This parameter (ISO 25178) S_{pd} replaces the (EUR 15178N) parameter S_{ds} . The peaks taken into account for the (EUR 15178N) parameter S_{ds} are detected by local neighborhood (with respect to eight neighboring points) without discrimination between local and significant peaks. The (ISO 25178) parameter S_{pd} is calculated in the same way, but takes into account only those significant peaks that remain after a discrimination by segmentation (Wolfpruning of 5% of S_z). As it is shown, the MARST methodology permits us to classify roughness parameters according to their relevancies. Another routine allows finding the roughness parameter that will be less correlated with the most relevant roughness parameter but keeping a high degree of relevance. Then, the amplitude parameter S_{mean} is the amplitude parameter S_{mean} . This parameter is complementary to S_{pd} . MARST methodology has found that the two “uncorrelated” parameters are a frequency one (characterizes the number of peaks) and an amplitude one (characterizes the mean of maximal amplitude). From this analysis (Fig. 9), the two following results can be stated:

1. The lower the EDM grade (lower discharge power), the higher the peaks, but lower the maximal mean amplitude of the roughness. Higher discharges create highest peaks that decrease their numbers per unit area.

2. However, different regimes appear in this tendency with the number of the peaks formation and not really in the maximal amplitude of the roughness.

- A saturation of the mean amplitude for the highest grade (grade 19–21) due to the weight of each droplet formed during discharge that decreases peak radius curvature and then peak amplitude.
- A saturation of the number of peaks (grade 7–11) and not present for their associated amplitudes. This saturation is a transition due to peaks percolation. To analyze this phenomenon, a morphological analysis will be performed on peaks/valleys topographies. The surface is vectorized by searching all the furrows contained on a surface. Figure 10 represents these furrows before the threshold (grade 6), at the threshold (grade 7–11) and after the threshold (12). It can be observed that the number of peaks stays quite constant and is due to “depercolation” of the roughness, leading to a constant number of peaks during this process.

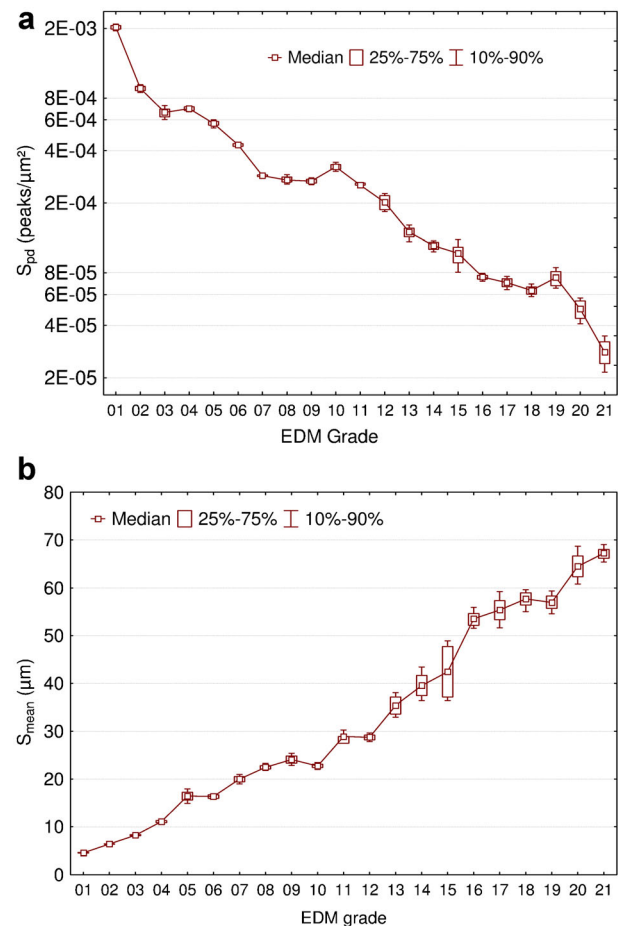


Fig 9. Value of the two best relevant roughness parameters S_{pd} (a, number of peaks) and S_{mean} (b, maximal mean roughness amplitude) versus the EDM grade. Mean confidence intervals are obtained from bootstrap. Boxes are linked by the median value of the mean distribution.

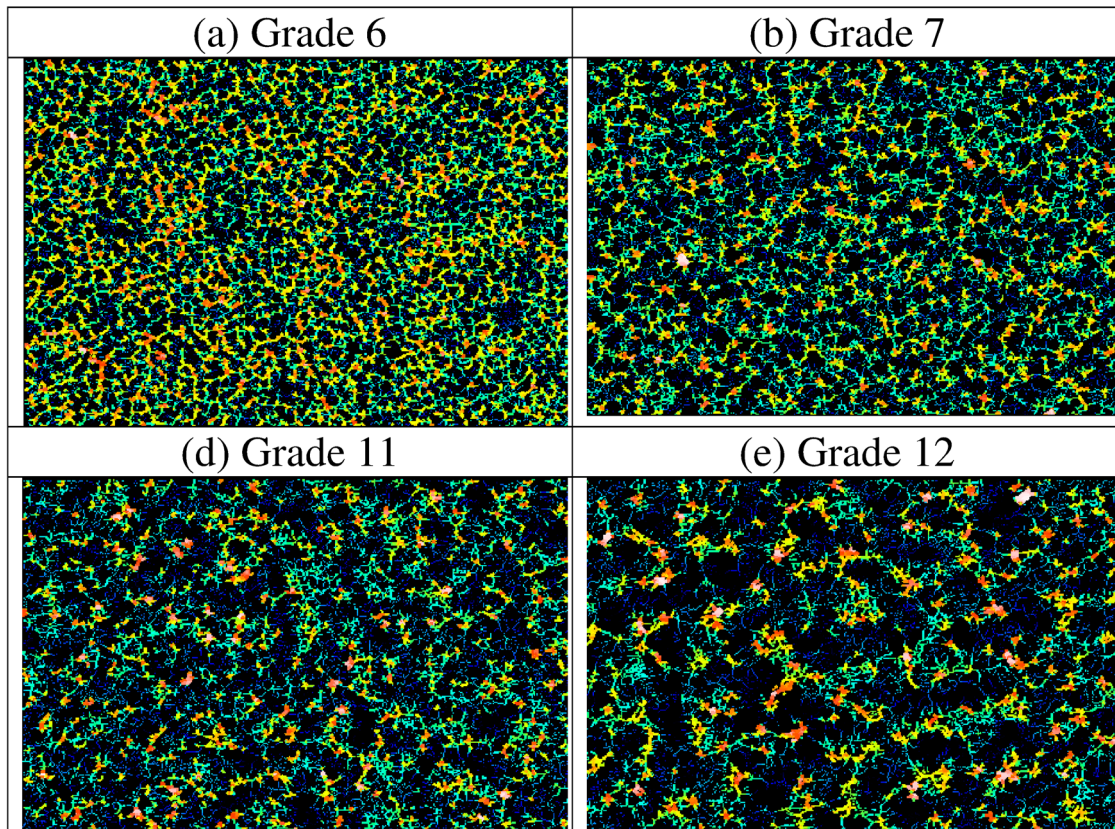


Fig 10. Vectorization of the furrows contained on EDM surfaces for four EDM grade.

Conclusions

This paper proposes a new and original methodology designed to select, without preconceived opinion, the 3D roughness parameters relevant for discriminating different topographies with regard to a specific application. Analysis of variance enabled to define and estimate a quantitative indicator for each roughness parameter and their associated decomposition scale. By using the recently developed Bootstrap method, it is possible to define and calculate a 90% confidence interval on the value of this indicator. Among 56 tested 3D roughness parameters, the results of this methodology revealed:

- For the Rolling process: The V_{mc} parameter (the Core Material Volume—defined as volume of material comprising the texture between heights corresponding to the material ratio values of $p = 10\%$ and $q = 80\%$) is the most relevant parameter to characterize the cold rolling process. It is important to mention that the scale at which this parameter is the most relevant is $3 \mu\text{m}$. This methodology allows understanding the mechanism of steel deformation during cold rolling and consecutive change of surface roughness after every rolling process.
- For the EDM Process: The best roughness parameter is S_{PD} that represents the number of peaks per unit

area after segmentation of a surface into motifs computed at the scale of $8 \mu\text{m}$.

The most relevant parameters can be selected and used to control the quality of processes in manufacturing environment. Proposed methodology can be used to control other processes like tool's wear evaluation, quality of produced paper, quality of machined surface, honed or polished surfaces. However, a complementary analysis must be performed in the future to gather the roughness parameters that are correlated.

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