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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 3Droughness 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 Vmc (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 mm is the most relevant parameter to characterize the cold rolling process. For the EDM Process, the best roughness parameter is SPD that represents the number of peaks per unit area after segmentation of a surface into motifs computed at the scale of 8 μm.

Keywords: Sendzimir cold rolling**,** Electrical discharge machining**,** Surface roughness, 3D-roughness parameters, Statistical analysis, Bootstrap method, ANOVA.

1 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 1982), there is still no complete comprehensive view on the relevance of these roughness parameters. Moreover, it is difficult to choose one (pertinent) parameter rather than another one. In our opinion, the main objective of methodology is to determine quantitatively and objectively the most relevant roughness parameters. It includes functional property of manufactured surface morphology. Moreover, multiscale analysis should be employed to evaluate the most appropriate scale that should be used for process monitoring. For these reasons, we propose in this paper a new methodology to characterize the morphological properties of a surface in relation to its physical properties. According to the previous study (Najjar et al. 2005), 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 aspect 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

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2 THE MULTISCALE ANALYSES OF THE RELEVANCE OF SURFACE TOPOGRAPHY (MARST)

In this part, we will describe the MARST methodology via a simple example of cold rolling process to well appreciate the different steps of the methodology. Then, in section 3, a more realistic case will be treated.

2.1 Step 0: Experimental aspect, the cold rolling process

The studied rolling process is used to reduce 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 to 650 $m \cdot min^{-1}$. 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 must be treated in order to remove oxide scales (Mougin *et al*. 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.

2.2 Step 1: Roughness measurements

The white light interferometer (NewView 7300, Zygo) is used for characterizing and quantifying surface roughness. Optical resolutions of x20 Mirau objective used are 0.71µm for x, y axes based on Sparrow criteria which take into account the lens numerical aperture and 0.01µm for z axe. Indeed, spatial sampling based on camera pixel size (0.55µm) is lower than the optical resolution. The inspected surface area is 700µm by 525µm obtained by stitching of each single measurement with 20% overlap.

2.3 Step 2: The multiscale decomposition

The Gaussian filter has been recommended by ISO 11562-1996 and ASME B46.1-1995 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 pass band filter because best parameters were not relevant in this study). Our system is used to filter all surfaces with different cut-off in order to obtain a multiscale decomposition. The 30 consecutive steps are used in this decomposition, with a cut-off varying from 2µm to 360µm. Figure 1 represents 2 high pass filters for the surface decomposition with two cut-off corresponding to L/4 and L/64 µm, L is the horizontal scanning length. When the cut-off decreases, microscopic details appear on filtered surfaces (Figure 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 7 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 1) 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.

Figures 2a and 2b represent the changes of the two parameters V_{mc} and S_{mc} versus decomposition scale (the 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 3 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}.

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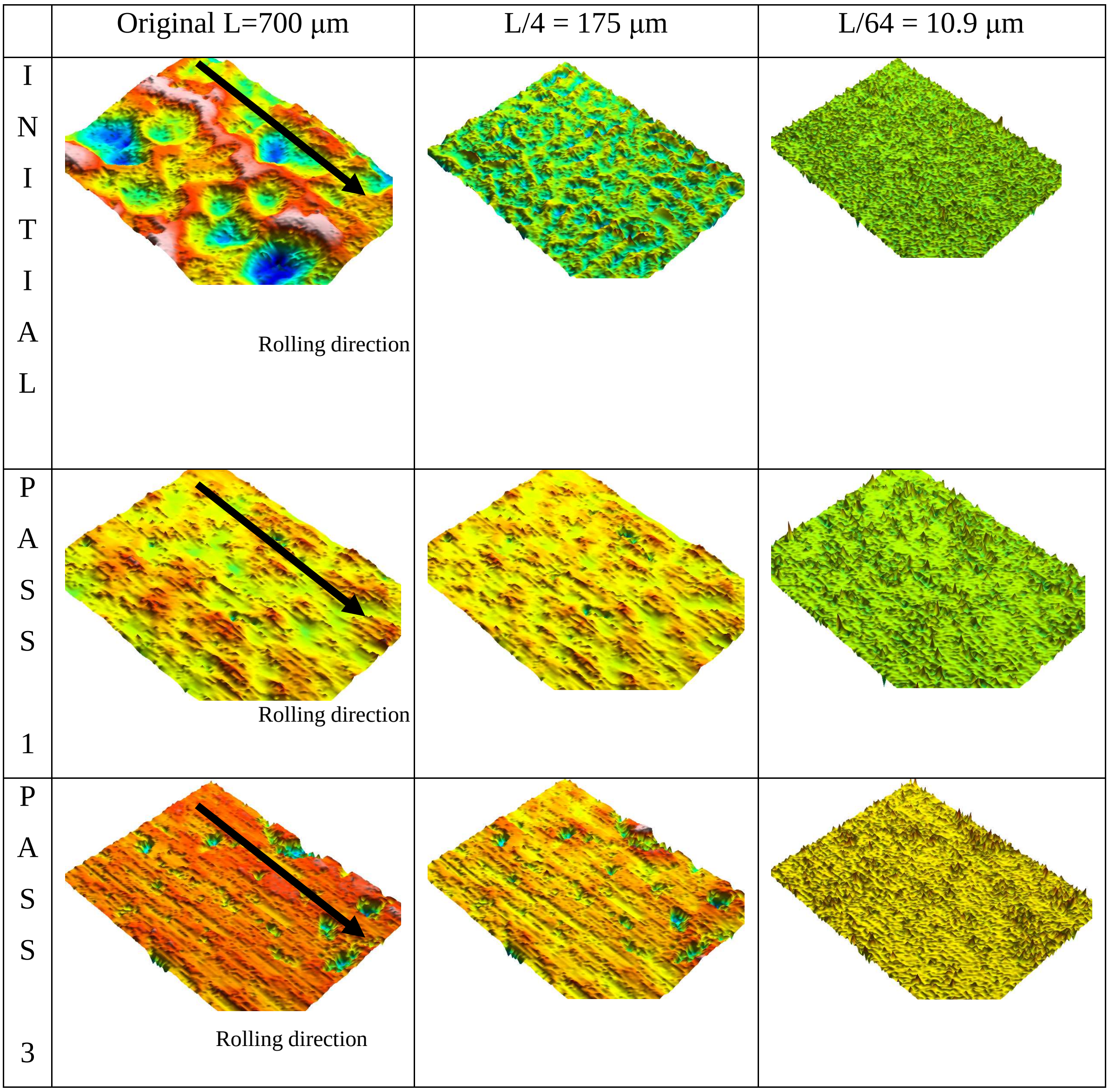

Figure 1. Cold rolled strip of AISI 304 measured before and after a first rolling process and after third rolling processes, measured surface size 700 x 525 µm. Examples of multiscale decomposition using Gaussian high pass filtering at cut off L/4 = 175 µm and L/64 = 10.9 µm.

2.4 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 in the sequence. 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

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Table I: 3D roughness parameters calculated and analysed in this study.

3D roughness parameters		
Symbol	Units	Name of parameter
Amplitude Parameters		
S_q	µm	Root mean square height
S_{sk}	-	Skewness
S_{ku}	-	Kurtosis
S_p	µm	Maximum peak height
S_v	µm	Maximum pit height
S_z	µm	Maximum height
S_a	µm	Arithmetic mean height
S_t	µm	Total height
Spatial Parameters		
S_{al}	mm	Auto-correlation length
S_{tr}	-	Texture-aspect ratio
S_{td}	°	Texture direction
S_{al}	mm	Fastest decay autocorrelation length
Hybrid Parameters		
S_{dq}	-	Root mean square gradient
S_{dr}	%	Developed interfacial area ratio
S_{ds}	1/mm²	density of summits
S_{sc}	1/mm	Arithmetic mean summit curvature
S_{fd}	-	Fractal dimension of the surface
Functional Parameters		
S_k	µm	Core roughness depth
S_pk	µm	Reduced summit height
S_{vk}	µm	Reduced valley depth
S_{r1}	%	Upper bearing area
S_{r2}	%	Lower bearing area
S_{pq}	-	Plateau root mean square roughness
S_{vq}	-	Valley root mean square roughness
S_{mq}	-	Material ratio at plateau-to-valley transition
S_{mr}	%	Areal material ratio
$\mathbf{S_{mc}}$	**µm**	**Inverse areal material ratio**
S_{xp}	µm	Extreme peak height
S_{dc}	µm	Areal height difference
Volume Functional Parameters		
V_m	mm³/mm²	Material volume
V_v	mm³/mm²	Void volume
V_{mp}	mm³/mm²	Peak material volume
$\mathbf{V_{mc}}$	**mm³/mm²**	**Core material volume**
V_{vc}	mm³/mm²	Core void volume
V_{vv}	mm³/mm²	Pit void volume
Functional Indices		
S_{bi}	-	Surface bearing index
S_{ci}	-	Core fluid retention index
S_{vi}	-	Valley fluid retention index
Feature Parameters		
S_{pd}	1/mm²	Density of peaks
S_{pc}	1/mm	Arithmetic mean peak curvature
S_{10z}	µm	Ten point height
S_{5p}	µm	Five point peak height
S_{5v}	µm	Five point pit height
S_{da}	mm²	Mean dale area
S_{ha}	mm²	Mean hill area
S_{dv}	mm³	Mean dale volume
S_{hv}	mm³	Mean hill volume
Flatness Parameters		
F_{LTt}	µm	Peak-to-valley flatness deviation of the surface
F_{LTp}	µm	Peak-to-reference flatness deviation
F_{LTv}	µm	Reference-to-valley flatness deviation
F_{LTq}	µm	Root mean square flatness deviation
Other 3D Parameters		
S_{mean}	µm	Mean height in absolute
S_{dar}	mm²	Developed area
S_{par}	mm²	Projected area
S_{Wt}	µm	Area waviness height
-	µm³	Mean volume of islands
-	µm	Mean height of islands
-	**µm²**	**Mean surface of islands**

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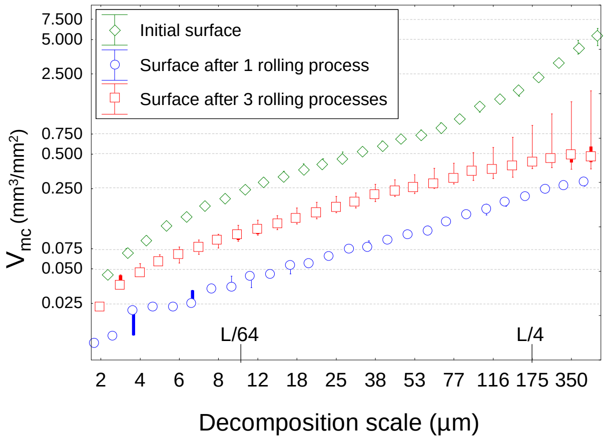
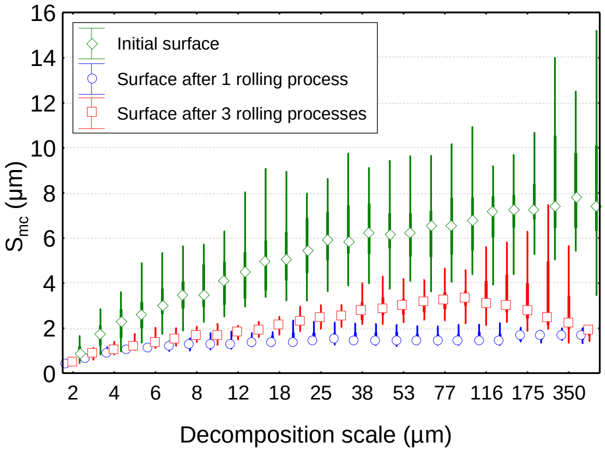


(a)



(b)

Figure 2. Evolution 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 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 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 $F(p_i,\varepsilon)$ versus the evaluation length for 3 roughness parameters: V_{mc}, S_{mc} and S_{ha}. By analyzing these figures, it can be concluded that:

- Relevance is better for V_{mc} when it is estimated at the low spatial scale of 3µm (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 a island surface is very relevant at a higher spatial scale (around 350µm, macroscopic scale) and appears to be a characteristic length of the tool processing, however physical meaning of this parameter remains questionable especially at a higher decomposition scale.

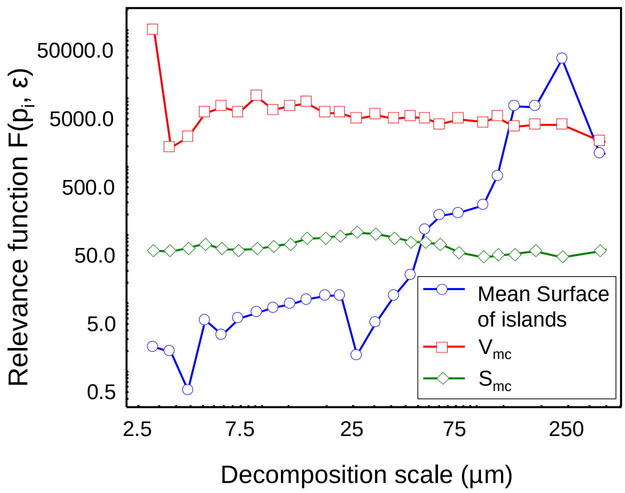
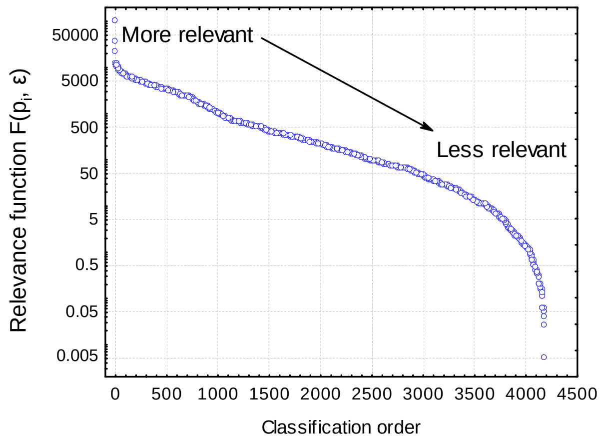
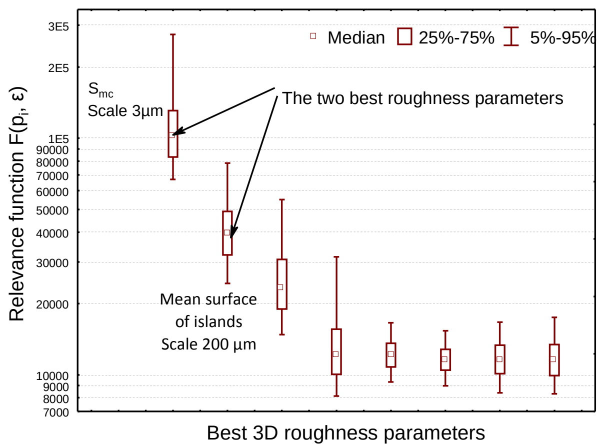


Figure 3. Evolution of the relevancy criterion F for Core materials volume V_{mc}, the relative material ratio S_{mc} and the mean surface of island versus the scale (filter cut off) to discriminate the three surface topographies described in Figure 1.



(a)



(b)

Figure 4. Classification of the 3D roughness Parameters according to relevancy criterion F to discriminate the three

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surface topographies (a) described in Figure 1, (b) the most relevant parameters with their confidence intervals associated to the relevancy function F(pi, ε) obtained by bootstrap method.

In summary, these figures show that the range of relevant evaluation length depends on the type of roughness parameter. This multi-parameter representation of surface roughness has been reported in various works and some efforts have been put previously to develop a method for selecting relevant parameters (Scott *et al.* 2005, Narayan *et al.* 2006, Jordan *et al.* 2006, Berglund *et al.* 2010, Bigerelle *et al.* 2005b).

2.5 Step 4: The classification of roughness parameters

It is possible to classify the relevancies of all parameters by classifying their F-values in descending order (Figure 4a). In order to include the robustness of the relevance of roughness parameters, bootstrap is used that allows estimating 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 1993, Hall 1992). The basic idea of the bootstrap is to create 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 (Figure 4b).

The parameter V_{mc} is the most relevant one computed at the scale of 3µm and has the same relevance as the mean of the island surface measured at the scale of 300µm. The second most relevant roughness parameter is the "mean surface of islands" computed at the macroscopic scale roughness (300µm). Figure 5 shows that the discrimination of this parameter appears after a scale of 50µm 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.

2.6 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 very good because no overlap appears and V_{mc} well discriminates the effect conditions.

2.7 Final Step: Physical Interpretations of selected parameters

Initially, there are many valleys creating the space that are easily filled by the lubricant. After each consecutive rolling process, there are fewer voids for lubricant available. Due to the anisotropic texture along a rolling direction, the lubricant can leak outside the contact zone easily through the narrow network of valleys. The lubricant is supposed to flow according to the Couette equation having added the pressure gradient term (Stachowiak *and al.* 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 peculiary 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 is lower (Wilson and Walowit 1971).

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.

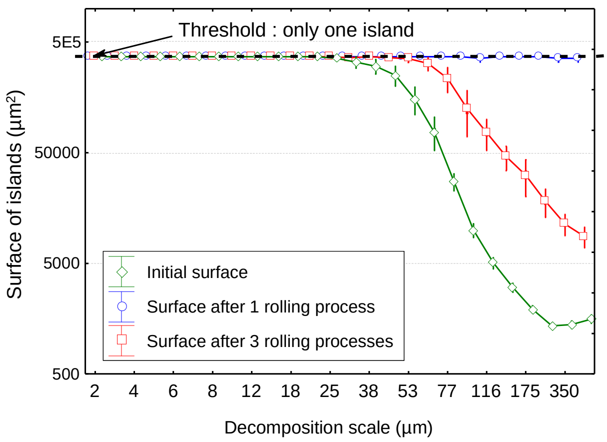

Figure 5. Evolution of the mean surface of islands versus the decomposition scale (Gaussian filter cut off) corresponding to the three surface topographies described in Figure 1.

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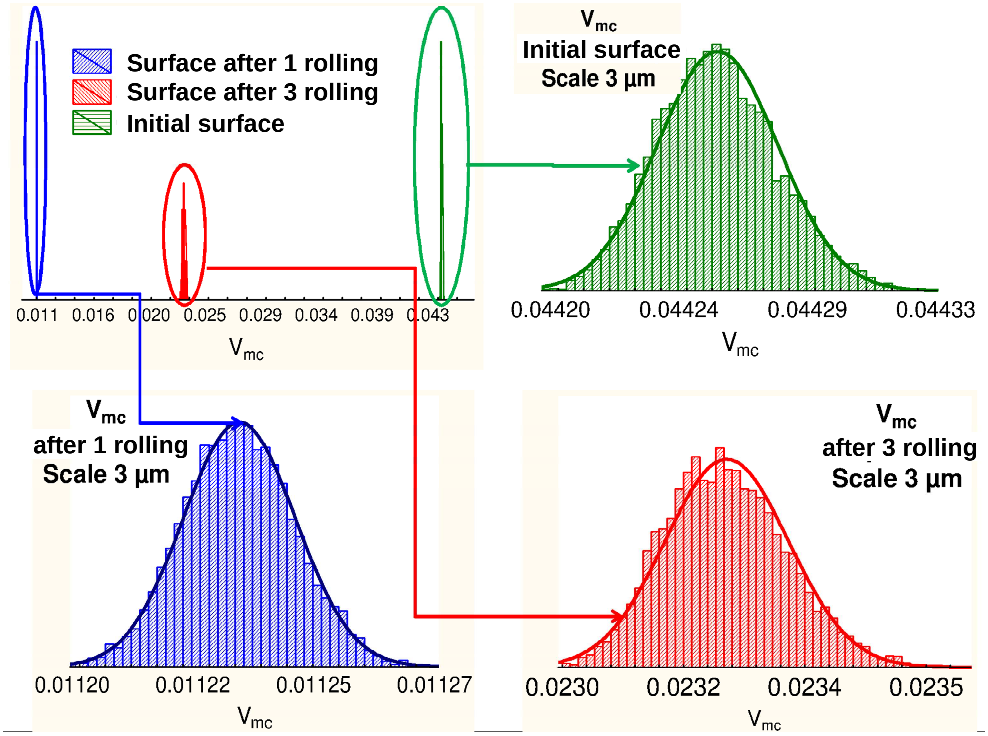

Figure 6. Bootstrap histograms of the mean values of Vmc roughness parameters compute at the scale of 3 µm for three surface topographies described in Figure 1.

3 APLICATION OF THE MARST METHODOLOGY: CARACTERIZATION 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.

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

21 different samples are tooled with EDM process, forming a very wide range of roughness whose amplitude R_a varies from 1.2µm to 15µm. 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 64A 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 roughness levels with an amplitude roughness parameter (R_a) comprised between 1.2µm and 15µm (grades 1 to 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)

3.2 Step 1: Roughness measurements

Roughness Measurements: 3D roughness measurements were achieved on an Interferometer using a x20 objective (Zygo, USA). The axial resolution of the machine is around 10 nm and the plane resolution is around 710 nm (Figure 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.

3.3 Step 3 to 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 8 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

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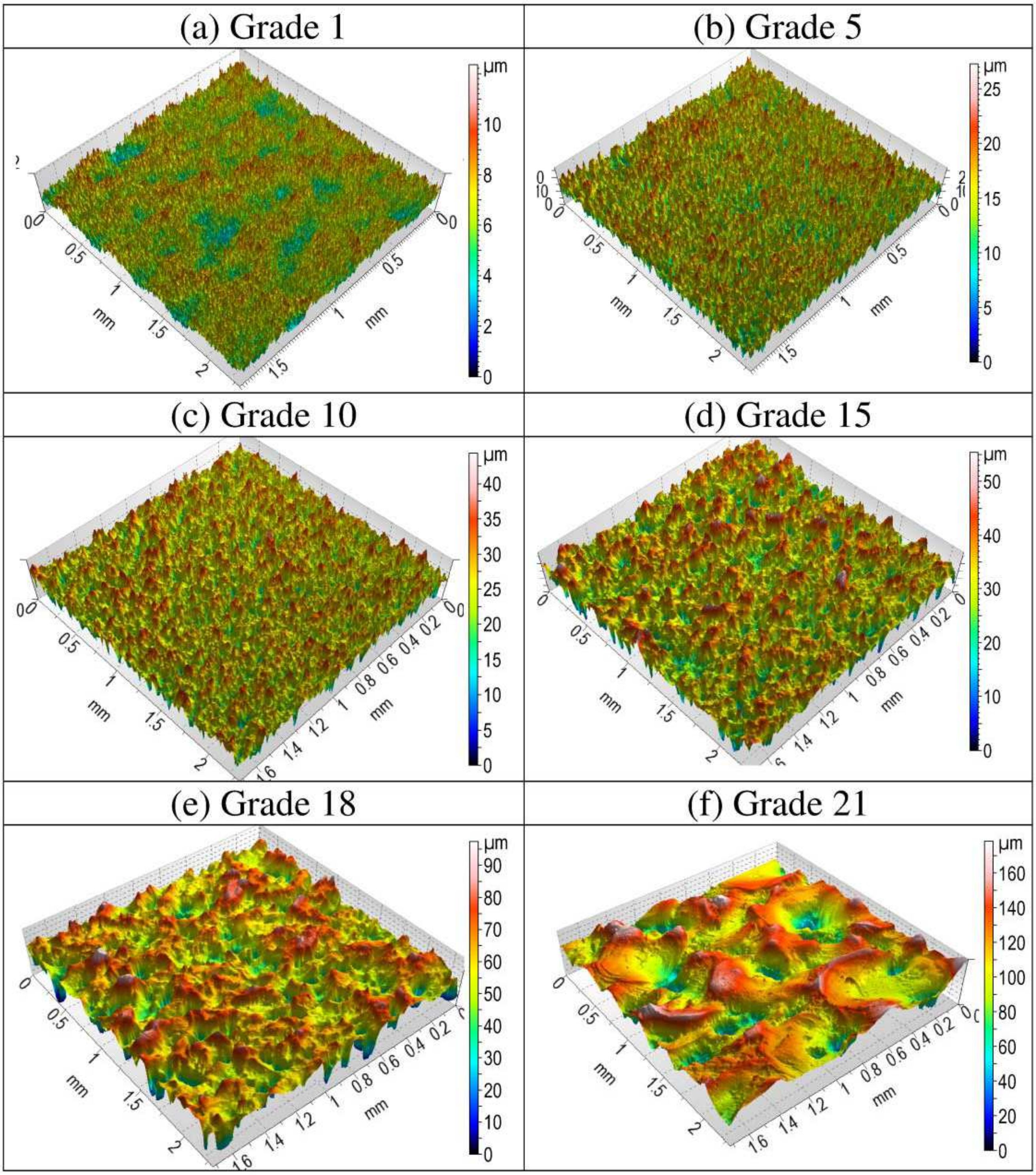

Figure 7. 3D experimental measurements of electro-eroded surfaces at six EDM grades.

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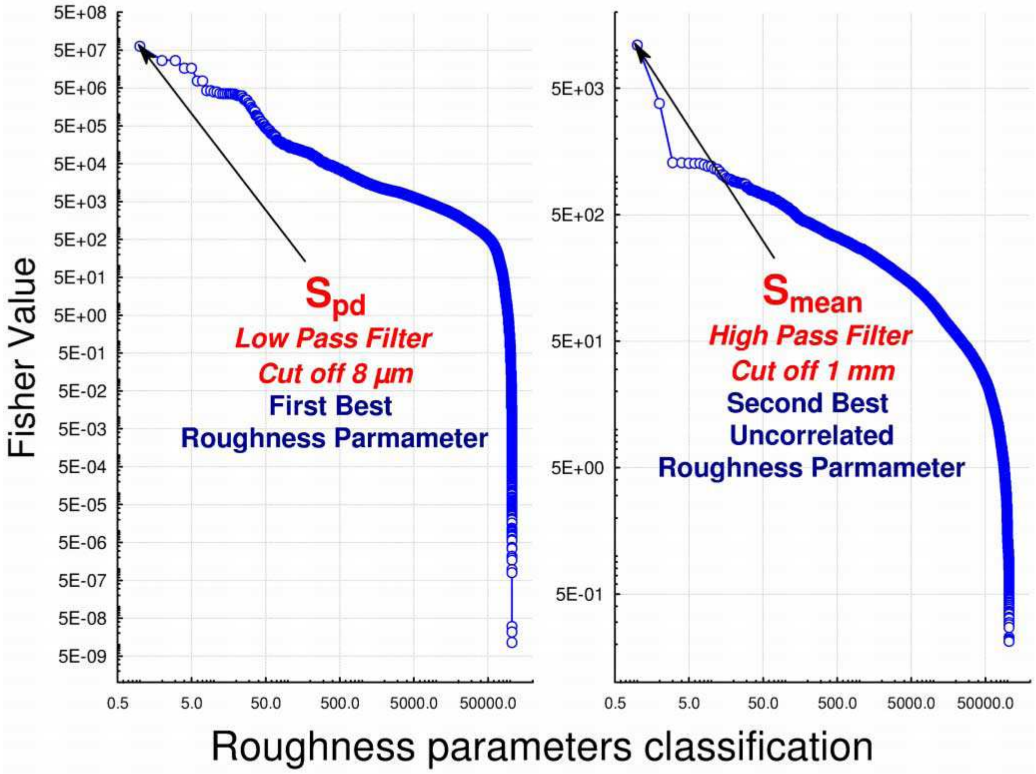

Figure 8. Graph of relevance of the best pair of uncorrelated pair of roughness parameters S_{pd} and S_{mean}. Higher the Fisher value, more relevant the roughness parameter.

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 second best relevance is obtained thanks to the use of 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 characterize by a number of peaks) and an amplitude (one characterize by a mean of maximal amplitude). From this analysis it is shown by figure 9, the following results can be stated:

- 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.
- However, some regime appears in this tendency with the number of the peaks formation and not really in the maximal amplitude of the roughness.

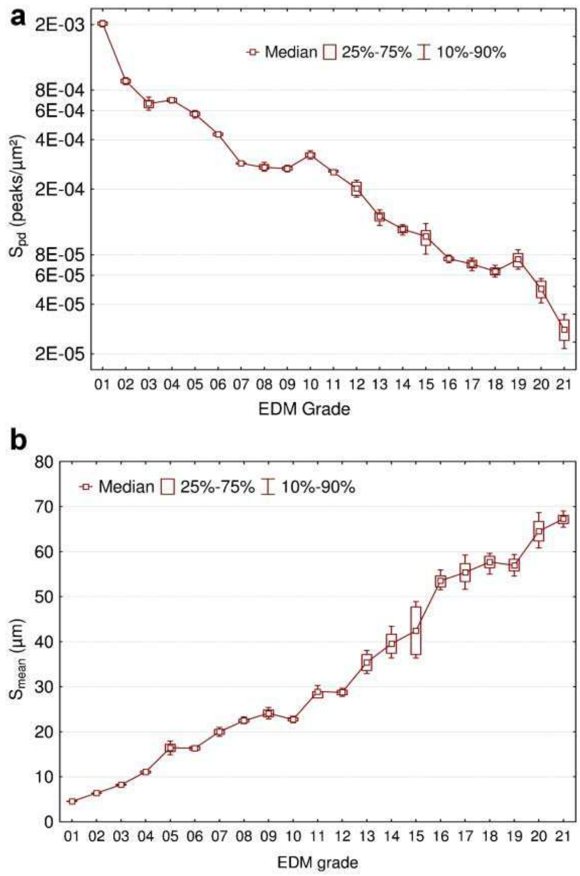

Figure 9. Value of the two best relevant roughness parameters S_{pd} (a, number of peaks) and S_{mean} (b, maximal mean roughness amplitude) versus the EDM grade. Mean confidence intervals are obtained from bootstrap. Boxes are linked by the median value of the mean distribution.

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- A saturation of the mean amplitude for the highest grade (19 to 21) due to the weight of each droplet formed during discharge that will decrease its radius curvature and then amplitude.
- A saturation appears for the number of peaks (during grade 7 to 11) and not for their associated amplitudes. This saturation is a transition due to peak percolation. To analyze this phenomenon, a morphological analysis will be performed on peaks/valleys. The surface is vectorized by searching all the furrows contained on a surface. Figure 10 represents theses furrows before the threshold (grade 6), at the threshold (grade 7 to 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.

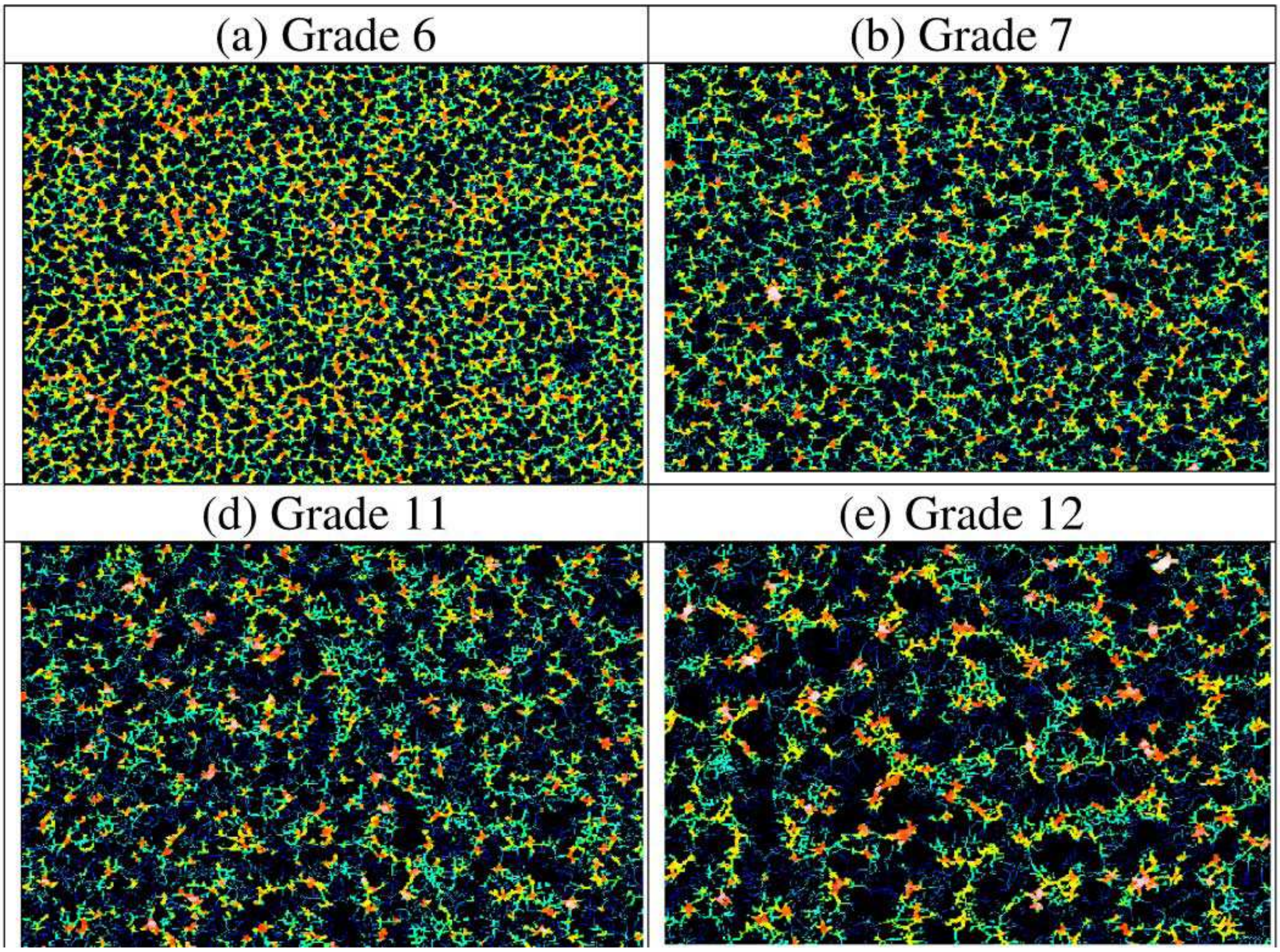

Figure 10. Vectorization of the furrows contained on EDM surfaces for four EDM grade.

4 CONCLUSION

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 mm. 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 SPD that represents the number of peaks per unit area after segmentation of a

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surface into motifs computed at the scale of 8 µm.

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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6 REFERENCES

ASME B46.1. 1995. Surface Texture: Surface Roughness. New York: Waviness, and Lay, American Society of Mechanical Engineers.

Berglund J., Brown C.A., Rosen B.G., Bay N. 2010. Milled die steel surface roughness correlation with steel sheet friction. CIRP Annals Manufacturing Technology 59(1): 577-580.

Bigerelle, M., Anselme, K. 2005. Bootstrap analysis of the relation between initial adhesive events and long-term cellular functions of human osteoblasts cultured on biocompatible metallic substrates. Acta Biomaterialia 1:499-510.

Bigerelle M., Gautier A., Iost A. 2007. Roughness characteristic length scales of micro-machined surfaces: A multi-scale modelling, Sensors and Actuators B: Chemical 126:126-137.

Efron B, Tibshirani RJ. 1993. An Introduction to the Bootstrap. New York: Chapman and Hall.

EUR 15178N. 1993. The development of methods for the characterisation of roughness in three dimensions", Stout, Sullivan, Dong, Mainsah, Luo, Mathia, Zahouani, Commission of the European Communities, EUR 15178 EN.

Hall P. 1992. The Bootstrap and the Edgeworth expansion. , New York: Springer-Verlag.

Huart S., Dubar M., Deltombe R., Dubois A., Dubar L. 2004. Asperity deformation, lubricant trapping and iron fines formation mechanism in cold rolling processes. Wear 257: 471-480.

ISO 11562: 1996, Geometrical Product Specifications (GPS) – Surface Texture: Profile Method -- Metrological Characteristics of Phase Correct Filters (International Organization for Standardization, Geneva, 1996).

ISO 25178-2:2012 Geometrical product specifications (GPS) - Surface texture: Areal - Part 2: Terms, definitions and surface texture parameters.

ISO 12781-1:2011 Geometrical Product Specifications (GPS) - Flatness - Part 1: Vocabulary and parameters of flatness.

Jordan S.E., Brown C.A. 2006. Comparing texture characterization parameters on their ability to differentiate ground polyethylene ski bases.

Wear 261:398-409.

Montmitonnet P. 2006. Hot and cold strip rolling processes. Computer methods in applied mechanics and engineering 6604-6625.

Mougin J., Dupeux M. 2003. Adhesion of thermal oxide scales grown on ferritic stainless steels measured using the inverted blister test. Materials Science and Engineering A 359:44-51.

Najjar D., Bigerelle M., Iost A. 2003. The computer based Bootstrap method as a tool to select a relevant surface roughness parameter. Wear 254:450-460.

Najjar D., Bigerelle M., Migaud H., Iost A. 2006. About the relevance of roughness parameters used for characterizing worn femoral heads. Tribology Internationnal 39:1527-1537.

Narayan P., Hancock B., hamel R., Bergstrom T.S., Brown C.A. 2006. Differentiation of the surface topography of various pharmaceutical excipient compacts. Mat. Sci. Eng. A430(1-2):79-89.

Scott R.S., Ungar P.S., Bergstrom T.S., Brown C.A., Grine F.E., Teaford,, Walker A. 2005. Dental microwear texture analysis within-species diet variability in fossil hominins. Nature 205 436(4):693-695.

Stachowiak G. W., Batchelor A. 2005. Engineering tribology. 3 ed. Oxford: Elsevier Butterworth-Heinemann.

Stout K., Blunt L. 2000. Three-dimensional Surface Topography. 2 ed. London: Penton Press

Van Gorp A., Bigerelle M., El Mansori M., Ghidossi P., Iost A. 2010. Effects of Working Parameters on the Surface Roughness in Belt Grinding Process: the Size-scale Estimation Influence. Int. J. Mater. Prod. Tech. 38:66-77.

Yang C. 2008. Role of Surface Roughness in Tribology: From Atomic to Macroscopic Scaledfdfdfdfd. Berlin: GmbH.

Wilson W.R.D., Walowit J.A. 1971. An isothermal hydrodynamic lubrication theory for strip rolling with front and back tension. Tribol. Convection I. Mech. E C86171:164–172.

Whitehouse D. J. 1982. The parameter rash — is there a cure? Wear 83(1):75-78.

Whitehouse D. J. 2011. Handbook of Surface and Nanometrology, New York: CRC Press, Taylor & Francis.

Yuan Y. B., Vorburger T.V., Song J. F., Renegar T. B. 2000. A Simplified Realization for the Gaussian Filter in Surface Metrology. Proceedings of X. International Colloquium on Surfaces. Aachen: Shaker Verlag GmbH 133-144.