Multiscale Topography Analysis of Waterjet Pocketing of Silica Glass Surfaces

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Abstract. Glass workpieces are mainly planar and obtained by diamond cutting however if free-form surfaces are required, manufacturing process is usually based on shaping grinding wheels. Multi-axis waterjet cutting, an other means of obtaining planar workpieces, could also be used to machine complex shapes with appropriate manufacturing strategies. Water jet pocketing could also be achieved but it brings challenging issues since the high pressure jet composed of water and abrasive particles must be contained inside the machined pocket. Water jet glass machining optimization requires understanding of numerous parameters such as interaction between the jet and the brittle material behavior or the identification of the jet himself. We focus our investigation on bottom pocket surfaces to study these parameters. Pocket bottom surfaces are characterized by multi-scale defects: shape defects influenced by the tool path and the manufacturing strategy, macro-craters at waviness scale due to the jet interactions, micro-craters at roughness scale due to particles impacts, sub-surface damages (SSD) at micro-roughness scale. This paper focuses on the study of macro and micro craters. We propose a decomposition of the multi-scale defects using modal filtering. Residual topography will then be analyzed to characterize the surface damages.

1. Introduction

Waterjet manufacturing process is used to achieved cutting of various materials by means of a high-pressure waterjet optionally mixed with abrasive grains. The waterjet flows from a pump to a cutting head where abrasive grains can be added in a mixing chamber before the abrasive waterjet is expelled through the nozzle. If abrasive waterjet can cut samples with a thickness of several tens of millimeters, it can also and paradoxically, achieve pocket milling by defining appropriate machining parameters that would allow the material not to be pierced through.

One of the advantages of waterjet machining, the lack of thermal distortion on the workpiece, as well as the machining versatility of this process has lead to investigate the industrial feasibility of metallic workpieces waterjet milling [2]. The manufacturing strategy as well as the cutting head speed are obviously key parameters to achieve pocketing but many other parameters also influence the quality of the surface finish [3] [4].

Abrasive waterjet is also widely used for brittle materials cutting however abrasive waterjet pocketing of glass has not yet been achieved. Brittleness of glass brings challenging issues when material removal process is involved (e.g. grinding [1]. Smooth surface finish, in particular, is hard to obtained since material removal would induce surface damages as well as sub-surface damages (SSD). Being able to shape a glass workpiece with the versatility of a 5-axis cutter would bring innovative prospects for glass industry.

We propose to study the influence of the machining parameters on the surface finish of pockets. Abrasive waterjet machining induces different scales of damages that need to be characterize accordingly. Previous studies carried out on waterjet pocketing have mainly only used roughness average to characterize surface finish. We will discuss the relevancy of the roughness parameters with regards to the machining process and the workpiece material.

2. Manufacturing process parameters

A series of experiments has been achieved to investigate waterjet machining influence on surface finish using a Flow™ Mach3 waterjet machine with the following parameters :

- Water orifice diameter : 0.76 mm
- Stand-off distance : 20 mm
- Abrasive mass flow rate : 2218,4 g/min
- Abrasive material grain size : 120 mesh
- Abrasive material type : garnet
- Angle of impact : 0 rad (normal to the sample surface)
- Zig-zag machining strategy
- Pressure inside the pumping system : 35 MPa
- Traverse speed : 750 ; 1500 ; 3000 ; 4000 mm/min corresponding to samples 4 ; 3 ; 2 ; 1 respectively

Pockets of 90 mm width, 110 mm length and various depth have been machined on $110 \times 130 \times 7\ mm^3$ Planilux™ glass samples. This material is characterized by a Vickers hardness Hv of 1,500 GPa, and a fracture toughness K_{IC} of 0.71 MPa.m$^{1/2}$.

3. Topography analysis

Glass samples pocket bottom surfaces topography has been acquired using an Alicona InfiniteFocus 3-D contactless measuring system. The measured area has been restricted to the pocket center to observe the surface finish resulting of a stabilized machining process. Aspect of surface finish is characterized by damages at different scales :

- form defect : at the largest scale, a slightly convex form defect
- textured waviness : an alternation of mounts and craters
- roughness : high R_{vk}, low R_{pk} typical of machined brittle material
- SSD : sub surface damage is commonly observed on brittle material. They can induce cracking when the workpiece is loaded [1].

This study focuses on the roughness and waviness scales. Two methods have been used to identify the different scales of damages : a standard gaussian filter based approach and a modal approach.

4. Gaussian filter based approach

The complexity of the surface finish lead us to investigate the relevancy of the cut-off value to separate the damages scale. Figure 1 shows a surface finish profile waviness for two standard cut-off values: $\lambda_c = 2.5$ mm ; $\lambda_c = 0.8$ mm. The 2.5 mm cut-off roughness profile shows some waviness that still need to be filtered. A 0.8 mm cut-off gives better results where roughness and waviness are well separated without reducing significantly the roughness amplitude in one hand. In the other hand, the topographies of waviness and roughness is close to the observed macro-craters (waviness) and individual impact (roughness) shapes.

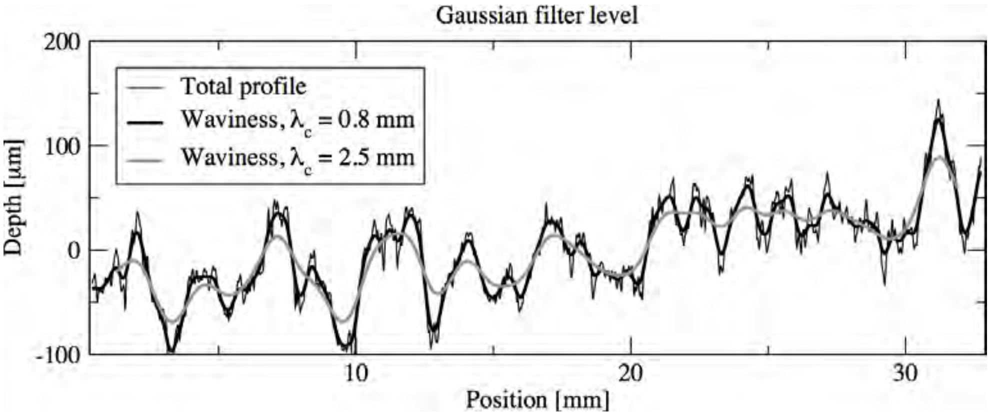


Figure 1. Roughness filtered for two different cut-off on a profile of sample 2.

Additionally, depth distribution for different samples acquired with a Taylor Hobson mechanical profilometer has been plotted for $\lambda_c = 2.5$ mm and $\lambda_c = 0.8$ mm (c.f. figure 2). Depth distribution obtained after 0.8 mm cut-off high-pass filtering have a better correlation coefficient with a Gaussian fit. All results based on a Gaussian filter presented afterwards have been filtered with this value.

Surface finish characterization protocol is described on figure 3.

Characterization of the surface finish needs to be based on appropriate parameters to give relevant results. At roughness scale, machining of glass usually induces surface finishes characterized by a low amount of peaks broken by the cutting forces and the presence of cracks at roughness scale. Abbott-Firestone derived parameters S_{pk}, S_k and S_{vk} provide a good evaluation of these aspects [1]. Morevover, valleys depth is linked to SSD, so S_{vk} parameter gives a good assumption of the SSD size [6].

Waterjet machined pocket bottom of the first series of experiments have been measured. 0.8 mm cut-off high-pass filtered surfaces roughness parameters S_k, S_{pk} and S_{vk} values are plotted on Figure 5. All parameters show a slight increase with regards to the transverse speed.

A watershed analysis of roughness has also been carried out. The valleys mean diameter is close to the size of damage area of an elementary impact (c.f. figure 4). This result support our hypothesis of a cut-off value set at 0.8 mm.

At waviness scale, surface finish of the waterjet machined pockets shows an alternation of craters and mounts. We propose to evaluate the waviness surface obtained with a 0.8 mm cut-off low-pass filter with material and void volumes parameters obtained from the Abbott-Firestone curve V_{mp}, V_{mc}, V_{vc}, V_{vv} [8]. Figure 5 shows the evolution of these parameters with regards to transverse speed. When speed increases, material volumes of peaks and core roughness as well as void volumes of valleys and core roughness tend to decrease. Interestingly, the decrease of the four parameters is very similar, and the ratio between material and void stays roughly the same. Waviness amplitude is assessed by summing S_{pk}, S_k and S_{vk} to filter outlier. It also

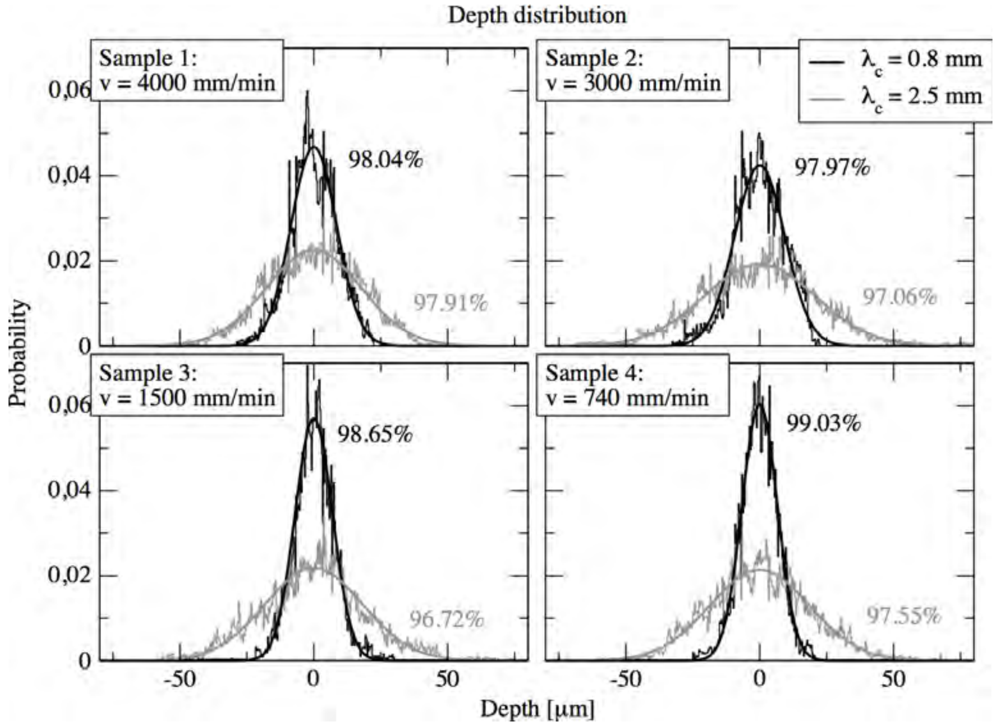


Figure 2. Depth distribution for several profilometric data and for two different cut-off. The corelation coefficient with a Gaussian fit is given.

tends to decrease with transverse speed. Overall this shows that the surface waviness amplitude decreases with transverse speed while keeping its "craters and mounts" aspect.

5. Modal filter based approach

The modal method [7], is a 3D topographic filtering method based on the dynamic modal shapes (natural eigen shapes) of surfaces. Here, we have used the modal shapes of a square surface. The modal eigen shapes of any structural object define a set of shapes that have very interesting properties applied to topography:

- First of all, this geometric basis of shapes is built automatically.
- All modal shapes are independant from each other.
- Globally, their shape complexity is sorted by their number (i.e. modal coefficients decrease acording to the their number/order generally quickly in the same way than Fourier methods).
- All possible measured surface is fully decomposable in its corresponding modal basis.
- The initial surface is an addition of all filtered surfaces. Thus, non filtered (initial) surface is the addition of form, waviness and roughness surfaces.

In fig 6, the filtering process begins with the creation of a modal basis of the ideal (square here) surface. This preliminary operation is made only one time (modal database creation).Then we calculate the projection of the topography deviations in the modal basis (vectorial operation in a non orthonormal basis). The results are modal coordinates. The later can be observed as a list of values (coordinates in a n modal dimension space) or as a spectrum (Fourier like representation).

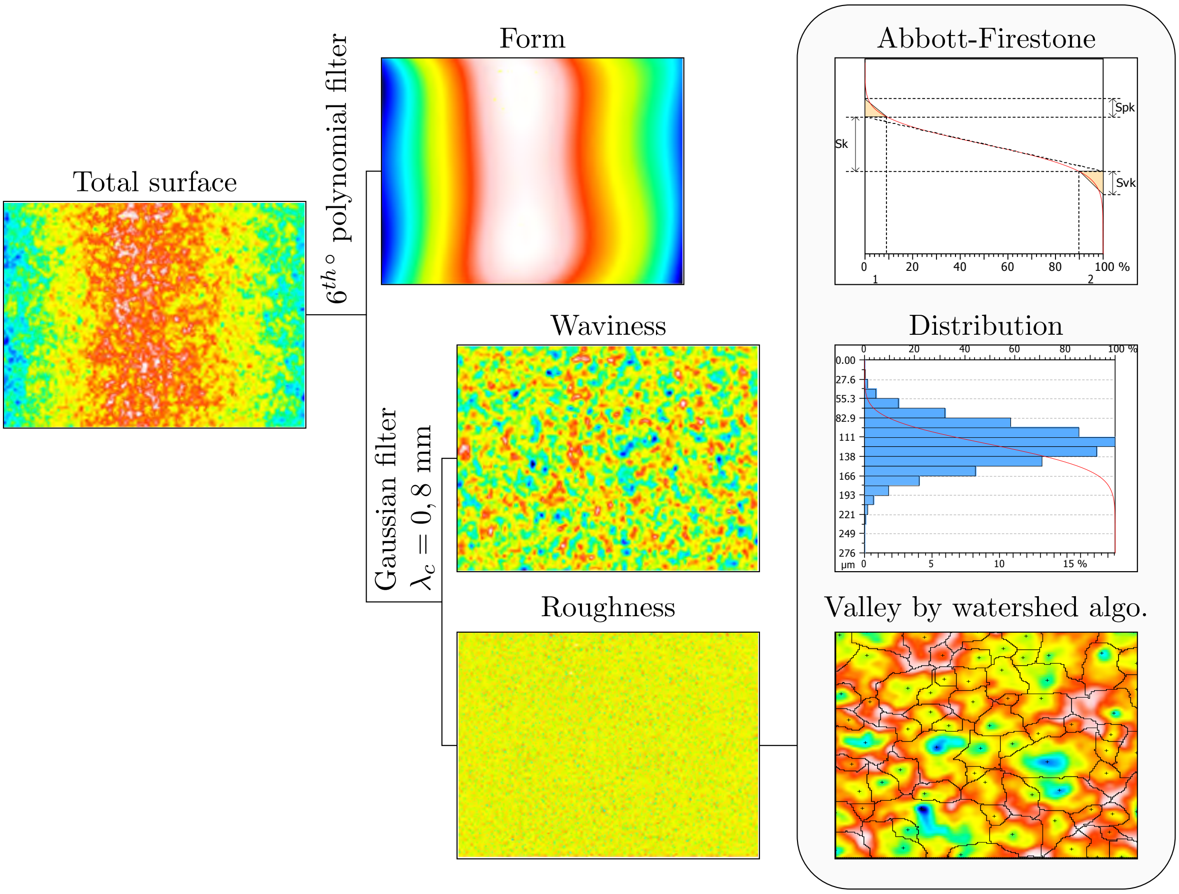


Figure 3. Analysis approach of Gaussian filtered surfaces of sample 1.

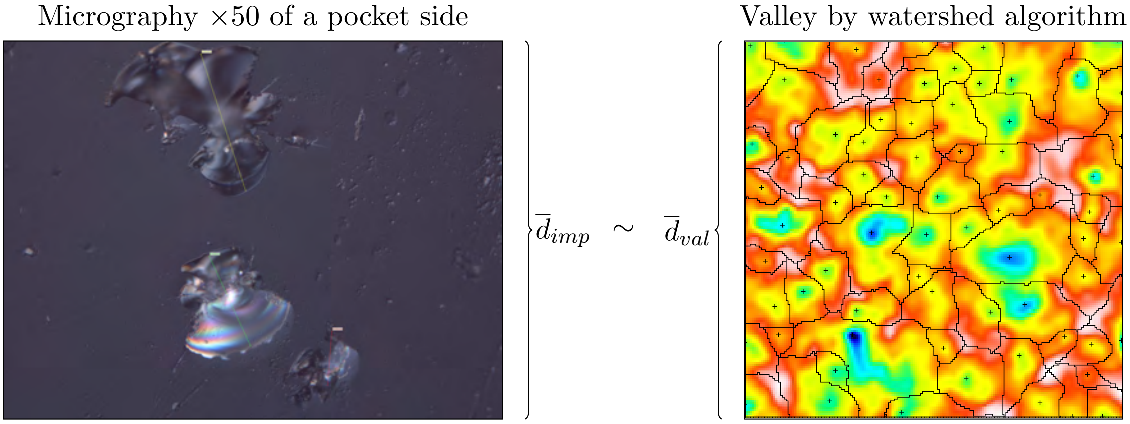


Figure 4. Comparison of averaged width of valley $\overline{d}_{val} \simeq 160$ μm and size of damage area of elementary impact $\overline{d}_{imp} \simeq 100$ μm.

We usually use the modal filtering to filer three surfaces, form, waviness and roughness, but it can be used to filter more or less levels. The separated shapes are subtracted to each other. Their addition give the initial surface. Thus the filtered process of surfaces are not dependents.

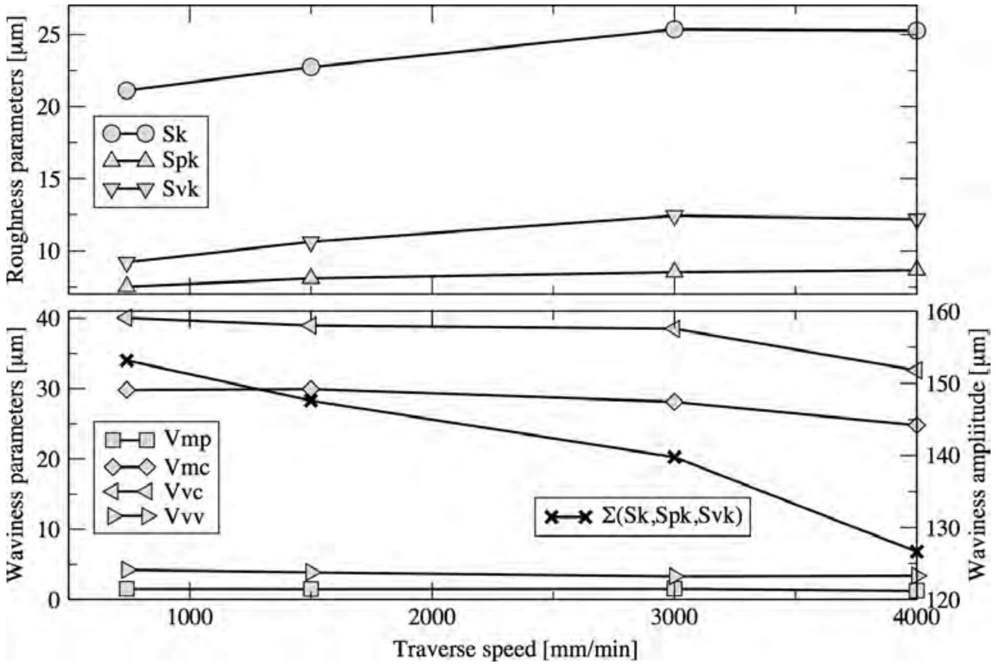


Figure 5. Evolution of roughness parameters S_k, S_{pk}, S_{vk} and waviness parameters V_{mp}, V_{mc}, V_{vc}, V_{vv}, Amplitude $= \sum(S_k, S_{pk}, S_{vk})$, according to traverse speed. Those results are extracted from two different Abbott-Firestone curve of the filtered roughness and waviness surfaces respectively.

As we can obtain the more contributive shapes (and the coefficients) we can use this method in order to extract the geometric signature of the whole shape or of form, waviness and roughness. The modal filtering method is built on a set of computed modal shapes (database). Thus the calculation is very fast (simple vector projections). As the geometric informations usually need less than 250 modes in order to filter form and waviness, we decided to use a 500 modes database. As the surface size is big (35 mm × 45 mm) compare to the cut-off values ($\lambda_c = 0.8$ mm), we should use a large number (more than 500) of modal shapes to obtain the same filtering effect (500 modes on this surface is similar to a cut-off $\lambda_c = 2.5$ mm). It could be justified in the case of a very inhomogeneous surface. In our case, we can analyze a sub-surface (8 mm × 48 mm) on which we make a modal analysis. The 6 first mode shapes gives the form error. The 494 (from #6 to #500) next modes gives the waviness and the residue is the roughness.

6. Influence of manufacturing parameters - filtering methods comparison

Both gaussian and modal filtering methods lend to observe similar results compiled in Table 1. Within the range of study, increase of the transverse speed will decrease waviness amplitude. However the "mounts and craters" characteristic aspect is conserved. Increase in speed will increase roughness amplitude. Roughness is characterized by high core and valley roughness induced by the material brittleness.

7. Conclusions and perspectives

This preliminary study of waterjet pocketing of glass has enlightened part of the influence of the machining parameters on the pocket bottom surface finish. It is characterized by several

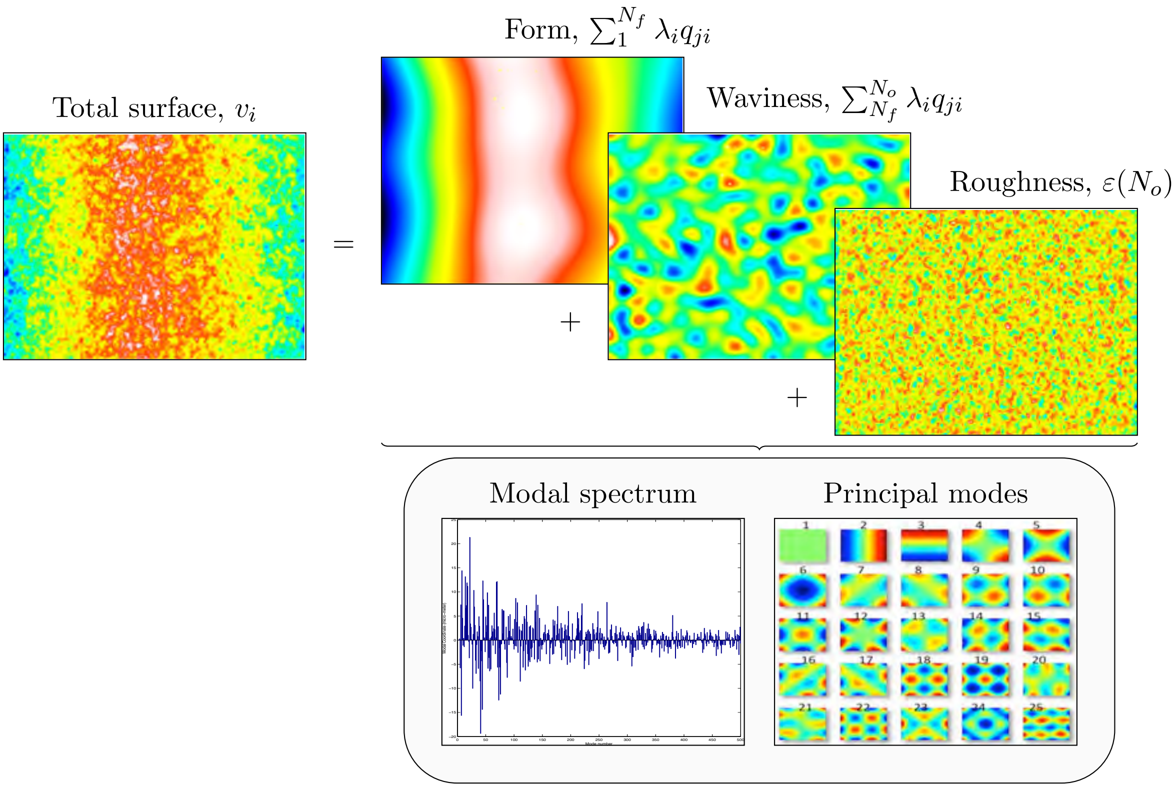
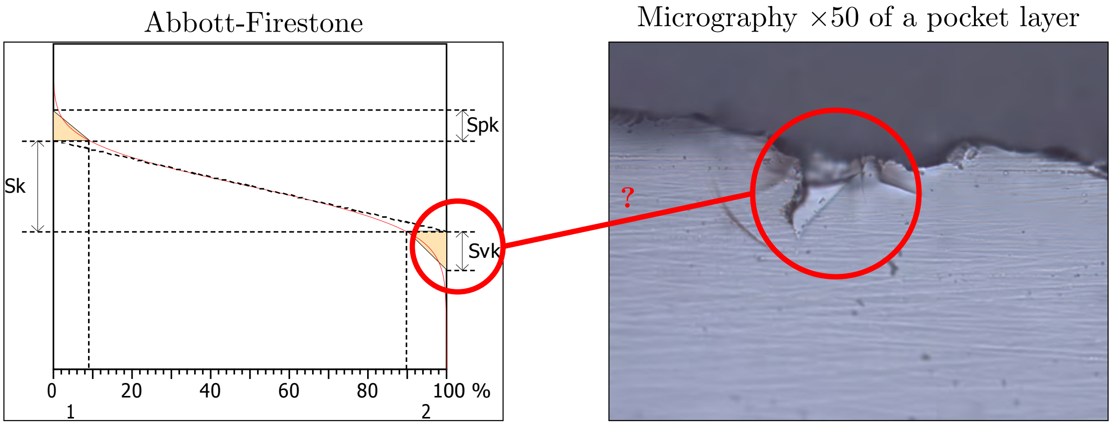


Figure 6. Analysis approach of Modal filtered surfaces of sample 1.

		Waviness parameters [μm]					Roughness parameters [μm]		
Filter	Sample	V_{mp}	V_{mc}	V_{vc}	V_{vv}	Amp.	S_k	S_{pk}	S_{vk}
Gauss	1	1.2649	24.793	32.581	3.4009	126.648	25.262	8.6693	12.2
	2	1.5537	28.108	38.489	3.3192	139.753	25.357	8.5298	12.439
	3	1.5084	29.925	38.949	3.8901	147.587	22.744	8.091	10.627
	4	1.5397	29.798	40.045	4.24	153.166	21.118	7.5195	9.203
Modal	1	0.944	22.3	30.6	2.99	107.4	30.8	9.95	14.7
	2	1.29	23.0	30.3	3.06	116.4	30.2	9.96	15.5
	3	1.19	27.0	35.6	3.25	126.8	27.4	9.37	14.3
	4	1.27	26.8	35.5	3.09	125.3	22.7	7.81	13.0

Table 1. Comparison of waviness and roughness parameters for the Gaussian and the Modal filters.

scale damages. At roughness scale, S_k, S_{vk}, S_{pk} give relevant informations of the surface characteristics. Cracks, peaks and core roughness tend to increase in the same proportions when transverse speed increases. At waviness scale the increase of transverse speed limits the material removal and therefore the amplitude of the waviness. The material and void volume ratio remains the same despite the waviness amplitude decrease. Both modal and Gaussian filtering methods provide relevant results. Influence of the machining parameters coud be combined. A wider analysis based on design of experiments will be carried out in future work. It will also take into account others manufacturing parameters such as stand-off distance. Sub-surface damages scale has not been presented here. However they have been observed (c.f. micrography in figure 7) and a further work will be to investigate the relationship between roughness, SSD, mechanical toughness of machined part.


Abbott-Firestone

Micrography ×50 of a pocket layer

Figure 7. In the case of grind milling process, the S_{vk} parameter from the Abbott-Firestone curve can outcome the presence of sub surface damages. Is it the same in the case of water-jet pocketing ?

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