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Decomposition of a tribological system by chaos theory on rough surfaces

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ABSTRACT

The purpose of this paper is to analyze the turning machinability of a martensitic steel, according to the cutting speed, and through signal analyses of the morphology of the machined surface. We initially carried out the classification of a large number of parameters of roughness, on the basis of their relevance with regard to cutting speed. The originality of the proposed method lies in the combination of the classical technique of analysis of variance with the statistical technique of resampling of data, called Bootstrap. Another characteristic of the study consists in the addition to the traditional categories of roughness parameters (Amplitude, Frequency, Morphological and Hybrid parameters) to analyze multi-scale aspect of surface topography through fractal analysis. According to the analysis carried out, the fractal dimension and the slope of the signal (*dz/dx*) of the topographical signal of the studied surface appear much more relevant than all the other Euclidian parameters. The fractal dimension and the slope of profile allow us to estimate a critical transition speed between the cutting states by generalized strain hardening and those by localized strain hardening. This parameter is also more relevant than the others, because it allows a good analysis of the influence of cutting speed, within each of the two machining modes. The obtained result is relevant because it provides a practical and inexpensive method for the quality control of the machined surface, to manufacturers and engineering companies, without removing some mechanical part, but only through a direct analysis of the slopes of the profile, with, in particular, the help of a portable instrument. We establish later that the transition between disorder and order of the aspect of the observed profiles is essentially due to an instability, which we analyze by the chaos theory. For that purpose, we propose an original construction of an attractor that presents a fixed point for low cutting speeds. This attractor characterizes, beyond the critical cutting speed, an instability described by a phenomenon of successions of states on the attractor between work hardening by localized shear plastic deformation and softening due to the rise in temperature.

1. Introduction

The improvement of the processes of quantification of the state of machined surfaces is always one of the major concerns for many researchers and industrialists. However, quality control of these surfaces generally requires an analysis of their roughness (signal of the surface), whose choice of parameters has often been the object of many controversies because of multiple possibilities of collection and interpretation of data, in general related to statistical analysis, and in particular to roughness profiles (roughness signal). We point out that certain parameters of roughness usually used, such as the average deviation of roughness R_a (*arithmetic mean of all the ordinates of the profile over a basic length*), have appeared in the international standards (*ISO 4287*) only since roughly fifteen years. Previously, each country had its own parameters, and in addition, had its own methods of calculation. The question of choosing the most relevant parameter of roughness thus remains particularly delicate, especially if we take into account the conditions of measure as well as the characteristics of the measuring device. Thus in this study, we consider the various evolutions in the relation between the tool, the matter and the process, in order to ensure an optimal use of the machined surfaces, as well as possible productivity gains. We thereafter use the chaos theory to explain the transition between generalized strain hardening and localized strain hardening. This transition is, in particular, described through the analysis of the evolution of the average

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Nomenclature

$\overrightarrow{A}_i$	vector of physical parameters in the space phase i
$B(x)$	Uniform noise in the range 0 and 1
D	Euclidian dimension of the space phase
$M_1, M_2, \ldots, M_D$	mechanisms creating the space phase
R_a	mean of signal amplitude $R_a = 1/L\int_L \lvert z(x)\rvert dx$
R_t	range of signal amplitude
T	cutting temperature
$U(x)$	Modeled signal of tooled surface
V_c	cutting speed
x	scanning length of signal roughness
$z(x)$	signal amplitude of the surface
β	a factor lying between 0 and 100
Δ_a	mean slope of profile $\Delta_a = (1/L)\int_L \lvert\partial z(x)/dx\rvert dx$
$\partial\tau/\partial\gamma$	strain hardening
γ	shear strain
τ	shear stress

slope of the estimated profiles (dz/dx, where z is the amplitude of the topography and x the sampling length of the surface). Two types of behavior are likely to cause a change in the machined surface: chatter and machinability. Whereas the first concerns primarily the vibratory aspect of the tool, appearing, except in the event of instability, through a topography of the machined surface with relatively periodic patterns, the second is dependent on the stakes of balance between strain hardening, which tends to harden the material, and thermal softening, due to the heat that is released at the cutting time. A localized shear plastic deformation will thus tend to support the machinability of the surface, while a prevalence of strain hardening would block it. The cutting process is then carried out through a wrenching of material. The instability of the structure observed for high speeds that we propose to model by the means of the chaos theory would thus be explained by the alternation of a strain hardening state and a thermal softening of material. The studied surfaces come from a stainless steel martensite of type Z210CW12. The tests were carried out under the following conditions:

- cutting speeds V_C in m min^{-1} ($65 \le V_C \le 200$),
- feed rate: 0.15 mm tr^{-1} and
- cutting depth: 0.5 mm.

The measurement of surface roughness is carried out perpendicularly to the machining grooves using a mechanical profilometer (KLA Tencor P10™) with an evaluation length of 15 mm and a sampling length of 0.4 μm.

The paper is organized as follows: in Section 2, the method of statistical treatment used to analyze the relevance of conventional roughness parameters is presented. Section 3 is devoted to the results of this conventional analysis of roughness. In Section 4, we analyzed the topography via the chaos theory. Section 5 deals with the results' interpretation of the machinability analysis via the same highlighted theory.

2. The conventional analysis of roughness

The studied surfaces are machined at the 10 following cutting speeds: 65, 80, 95, 110, 125, 140, 155, 170, 185 and 200 m/min. For each of these 10 samples, 30 profiles are implemented by means of the software Mesrug™ that is conceived by our research teams [1,2]. Besides, for each of the profiles, 95 roughness parameters are measured and distributed according to 10 classes (Fig. 1) containing amplitude parameters (R_a, R_t,…), frequency parameters (*number of peaks, spectral moments, length of autocorrelation*), hybrid parameters (*slopes of the profiles, area ratio of surface*), and parameters resulting from the fractal analysis (*fractal dimension, slope of the spectral density*).

However, for the determination of the most relevant parameters, we propose in this paper an original technique of variance analysis: *ANOVA by bootstrap* [3,4]. This technique is of such great importance that the statistical approach used in this study requires a large number of parameters. Besides, similar to the classic *ANOVA*, this technique allows the determination of the parameter containing maximum information on a given class. It allows later an estimation of the influence of this class, through the definition of a Fischer variable F, as well as of a critical probability below which we could wrongly assert the aforementioned influence. However, unlike the traditional *ANOVA*, the variable F is considered as a random variable according to *ANOVA by bootstrap*. This random behavior is essentially due to data variation which, besides, implies a variation of the critical probability. Let us note too that the more the value observed by the variable F corresponding to a given cutting parameter is large, the more this last one will be considered as a discriminant parameter according to the cutting speed (Fig. 2).

3. Results of the conventional analysis of roughness

According to the conventional analysis described in the previous paragraph, the three most relevant parameters (Table 1) were examined:

Although the average deviation of roughness R_a is one of the roughness parameters that is most usually used in the traditional analysis of machined surfaces, it is not, in this study, the most relevant parameter for the characterization of cutting speed effect on machinability. In order to illustrate these results, Figs. 3 and 4 present the comparison of the histograms of the Fischer variable for the three selected parameters, as well as the comparative studies of the box-plot for these last ones, according to cutting speed. These results are also confirmed on the basis of 8000 discretization points obtained using a portable profilometer Perthometer™ M4Pi, with a probe tip radius of 5 μm. One of the major consequences of this study is the possibility of quantifying the machinability in situ without taking off the machined part from the tool machine (Table 1).

3.1. Analysis of the relevance of parameter Δ_a

Mathematically, the mean value Δ_a of the profile slopes over a profile evaluation length L is described by a numerical function z, generally unknown, and defined by

$$\Delta_a = \frac{1}{L}\int_L \left|\frac{\partial z(x)}{\partial x}\right| dx \quad (1)$$

- The experimental results analysis shows a great decrease of the profile slopes Δ_a around a critical cutting speed V_C of 125 m/min. Indeed, for speeds lower than V_C, the profile presents a disordered aspect, whereas beyond this value a periodic component with weak noise appears. However, it is