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Multi-parameter analysis and modelling of engineering surface texture

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Materials

ABSTRACT

Purpose: Owing to the complexity of machined surface profiles and the contemporary demands for functional characterization, multi- parameter analysis of roughness is recommended by international surface metrology standards, as well as by recent research studies. This article is aimed at presenting a retrospect of works reported by the author on aspects of machined surfaces along with modelling of various texture parameters.
Design/methodology/approach: Multi-parameter surface analyses according to the international standards ISO 13565-2: 1997, ISO 12085: 1996 and ISO 13565-2:1996, and with the use of non-standardized parameters as well, are performed on turned and EDM' ed surfaces of different metallic materials over a wide range of machining conditions in order to study: conventional and functional parameter characterization, texture variability, anisotropy and the impact of machining factors on texture parameters. The ultimate goal will be a contribution to surface typology and proposals for selecting representative subsets of parameters in each case considered.
Findings: The correlation of each parameter selected is examined with the machining conditions; single and multi-statistical regression models with varying correlation coefficients are developed. New indices to evaluate surface texture anisotropy are proved to be successful. New typology maps for surface control are developed and reduction of roughness parameters in appropriate subsets is achieved.
Research limitations/implications: A systematic study of the variation of the parameters selected is conducted regarding three international standards and some ''non-common'' parameters.
Practical implications: Industrial control will benefit by the formulated parameter models, which possess very high coefficients of correlation and a minimum number of representative texture parameters.
Originality/value: An integrated view of surfaces obtained by machining processes with quite different physical characteristics and chip formation mechanisms is achieved in the present surface typology oriented study.
Keywords: Multi parameter surface analysis; Functional surface characterization; Surface typology; Machining processes

1. Introduction

Surface topography is a characteristic of paramount importance among the surface integriy magnitudes and properties imparted by the tools used in the various machining processes and especially in their finishing versions.

Moreover, various surface texture parameters are introduced in analytical and empirical tribological models concerning contact of surfaces, friction and wear mechanisms, boundary, hydrodynamic and elasto-hydrodynamic lubrication and others [1-3]. And it has to be considered in view of two standpoints i.e. process control and tribological function, in the context that to achieve the proper functionally oriented surface the appropriate manufacturing method must be performed along with the inverse problem of controlling the forms of texture various processes generate related also to the improvement of the latter and of the machine tools, acordingly. This ''dualism'' is encountered in the evolution of surface metrology.

Over the years the characterization and evaluation of engineering surface texture has constituted a challenging metrological problem remained open so far, especially when high precision and/or functional performance requirements exist. This fact is attributed to the usually complicated form of surface textures and the need to obtain a satisfying description globally, as well as at various levels.

Traditionally, surface texture has been considered more as an index of the variation in the process due to tool wear, machine tool vibration, damaged machine elements etc. than as a measure of the performance of the component; a stable process combined with the specification of the arithmetic average, Ra, was considered to be enough in industrial practice. A machined surface possesses, more or less depending on the cutting factors employed, recognizable features imparted by the cutting operation previously performed. Since these characteristics cannot be described with a single parameter, a multi parameter surface roughness analysis is recommended [4,5]. Emerging technological advances put new limits in manufacturing tolerances and better understanding of tribological phenomena on the other hand, implied the need of functional surface characterization, which in turn caused a plethora of parameters.

A great amount of research works towards a concise and proper characterization of surface texture is met in literature with an inevitable emphasis on the association of profile characteristics with the manufacturing process parameters (indicative refs [6-9]).

The present article_is aimed at presenting a retrospect of works reported by the author on aspects of machined surfaces along with modelling of various texture parameters. It is directed to the ultimate goal, that is surface typology, the classification of textures in classes according to their shape followed by an exhaustive investigation on the capability of various manufacturing processes of producing these classes.

The machining processes selected to be performed are Turning, mostly, and Electro-Discharge Machining (EDM), as they produce quite different surface topography and on the other hand are extensively used in industry and representative of conventional and unconventional processes, accordingly.

The paragraphs of this retrospect are:

- **"Conventional" ISO parameter analysis**
  A multi-parameter surface analysis according to ISO 13565-2: 1997 standard [10] (Table 1) is performed on longitudinally and face turned surfaces over a wide range of variation of cutting conditions in order to establish regression models for the parameters regarded, as well as subsets of mutually unrelated roughness parameters. The second step concerns EDM and the modelling of the relevant parameters for a wide variation of machining conditions too.
- **Topological and morphological standards**
  The application of the topological and morphological surface metrology standards namely, motif combination (ISO 12085: 1996) [11] (Table 2) and "Rk" family of bearing curve parameters (ISO 13565) [12] (Table 3) on turned and EDM'ed surfaces is described.

Table 1.
The "conventional" ISO I13565-2: 1997 parameters

Parameter	Description
Ra	Profile average height
Rt	Maximum profile height
Rq	Standard deviation of the profile height distribution
Rp	Maximum profile peak height
Rv	Maximum profile valley depth
RDelA	Average slope of the profile
Rsk	Skewness of the profile height distribution
Rku	Kurtosis of the profile height distribution
Rsm	Mean spacing of the profile
RDelQ	Root mean square slope of the profile
Rz	Average maximum height of the profile
Rtp	Bearing length ratio of the profile

Table 2.
The motif (R & W) parameters

Parameter	Description
R	Average depth of roughness motifs
R_x	Maximum depth of roughness motifs
A_r	Average spacing of roughness motifs
W	Average depth of waviness motifs
W_x	Maximum depth of waviness motifs
W_{te}	Maximum depth of the waviness profile
A_w	Average spacing of waviness motifs
K_r	Average slope of roughness motifs
K_w	Average slope of waviness motifs
P_t	Maximum depth of the raw profile

Table 3.
The "R_k" family of parameters

Parameter	Description
R_k	Depth of the roughness core profile
R_{pk}	Top portion of the surface to be worn away
R_{vk}	Lowest part of the surface retaining
MR1	Upper limit of the core roughness
MR2	Lowest limit of the core roughness

- **Fractal geometry analysis**
  Fractal geometry analysis has been introduced to render the micro roughness of surfaces generated by fracture, and machined surfaces are as such [13]. The association of fractal parameters with cutting conditions and roughness parameters is studied herein, also considering the bearing capability of the surface.
- **Profile classification in turning -New surface typology charts**
  Representative surface patterns are obtained by proper selection of cutting factors to carry out a thorough investigation aimed at control and classification of the differing profile forms. New typology charts are formed and compared to older ones.

- **Surface texture anisotropy**
  New proposed indices to evaluate surface texture anisotropy together with others used in view of literature are examined herein. The surfaces studied may be characterized alternatively towards the desired tribological function or machining process control.

In each of the aforementioned studies the experimental conditions and procedure will be given in brief.

2."Conventional" ISO parameter analysis

2.1. Multi-parameter analysis of turned surfaces

Worth mentioning that amplitude roughness parameters in general are associated with feed and cutting speed in turning, as well as in other cutting processes. Worth noting that turning, besides its widespread use in industry, is considered as a reference cutting process with tool of defined geometry and studies on machinability parameters are initially evaluated by testing turning operations [14-16].

The results that will be presented next are collected from an extensive work [17] on postulating predictive statistical models of various surface texture parameters adopted in the ISO13565-2: 1997 standard for two different turning operations in view of kinematics: longitudinal (conventional) and face turning.

Three kinematic modes of turning were performed, namely, longitudinal turning (LT), in-feed turning (IFT) and out-feed face turning (OFT) with constant spindle rotational frequency. Note that facing exhibits different kinematics than longitudinal turning, since cutting speed varies linearly with the workpiece instant diameter for constant spindle rotational frequency for either of its modes [19]. Surface roughness is influenced by this cutting speed effect and obtains a certain degree of inhomogeneity; therefore, more roughness parameters show closer correlation to cutting conditions in LT than in the two FT modes

An uncoated sintered carbide insert P10 was employed as the cutting tool, properly clamped on a suitable tool holder with the following combined geometry: rake angle: $\gamma = +6^0$, relief angle: $\alpha = 11^0$, inclination angle: $\lambda_s = 0^0$, tool side cutting angle: $\kappa = 75^0$, tool approach angle: $\kappa_1 = 15^0$, cutting edge radius: $r_e = 0.8$ mm. Special attention was paid to keep the cutting tool negligibly worn during the experiments. The workpiece material was a plain medium carbon steel Ck60

The cutting conditions applied were: Cutting speed, **v** from 100up to 185 [m/min],
Feed, s from 0.05 up to 0.60 [mm/rev] and Depth of cut, a: 0.5 mm.

For facing modes (IFT) and (OFT) with constant spindle rotational frequency the above cutting speed values are considered as the maximum ones. Of course, in both cases of facing the cutting speed will diminish at the inner rings of the specimens and a severe built-up edge will influence roughness systematically.
The models developed in refs. [17, 18] for R_a, R_{sk}, R_{ku}, and R_{DelQ} with respect to feed are presented in Tables 4 to 6. These parameters are not generally interrelated; for comparison purposes R_a values were also included in these Tables.

Table 4.
Statistical regression models for LT

Parameter	v [m/min]	Exponential model			
		b_0	b_1	r	F
R_a	100	1.8	2.9	0.87	25.9
	130	0.88	4.4	0.97	116.2
	185	0.52	5.7	0.98	254.7
R_{DelQ}	100	12.41	0.5	0.44	1.9
	130	8.89	1.1	0.67	6.6
	185	7.67	1	0.79	13
R_{sk}	100	low correlation			
	130				
	185				
R_{ku}	100	0.93	-0.45	0.61	5
	130	2.73	-0.21	0.23	0
	185	2.29	0.09	0.19	0

Note: The exponentional model is $Y=b_0\exp(b_1X)$;
r: the correlation coefficient; F: *F-test* parameter

Table 5.
Statistical regression models for t OFT facing

Parameter	v [m/min]	Exponential model			
		b_0	b_1	r	F
R_a	100	2.86	2.09	0.62	17.6
	130	2.06	2.89	0.8	50.7
	185	1.19	3.96	0.8	51.2
R_{DelQ}	100	17.23	-0.54	0.49	9.1
	130	15.09	-0.27	0.24	1.6
	185	12	0.11	0.09	0.24
R_{sk}	100	low correlation			
	130				
	185				
R_{ku}	100	3.13	-0.54	0.63	18.8
	130	3.65	-0.9	0.67	22.7
	185	3.52	-1.05	0.59	14.7

Note: The exponentional model is $Y=b_0\exp(b_1X)$;
r: the correlation coefficient; F: *F-test* parameter.

The fact of low correlation of the parameters revealed for the FT modes may be attributed to the great amount of scatter in their values owing to built-up-edge and discontinuous chip formation, due to the cutting speed variation up to very low values, at the inner diameters of the specimens.

Hence, a combination of any one of the uncorrelated parameters or all together considered with R_a, the most popular correlated to cutting conditions amplitude parameter, may provide a more detailed description of the profile. Certainly, the number of parameters that could constitute an appropriate set depends upon industrial and/or research requirements varying from standard control to fundamental investigations on engineering surfaces, concerning always their tribological function.

Table 6.
Statistical regression models for IFT facing

Parameter	v [m/min]	Exponential model			
		b_0	b_1	r	F
R_a	100	2.83	2.13	0.7	27.3
	130	1.55	3.33	0.76	37.4
	185	1.23	3.72	0.78	42.5
R_{DelQ}	100	16.42	-0.22	0.21	1.24
	130	12.42	0.25	0.18	0.99
	185	11.05	0.34	0.28	2.5
R_{sk}	100	low correlation			
	130				
	185				
R_{ku}	100	3.14	-0.41	0.37	4.5
	130	3.47	-0.77	0.53	11
	185	3.2	-0.52	0.54	11.8

Note: The exponentional model is $Y=b_0\exp(b_1X)$;
r: the correlation coefficient; F: *F-test* parameter

2.2. Multi-parameter evaluation of EDM'ed surfaces

Typical topographies generated by EDM are presented in Fig. 1. As far as surface topography is concerned, the configuration of an EDMed surface clearly reflects the nature of the process by which it has been created. The mean chordal diameter of the craters, formed due to melting and evaporation of the metal heated from the discharges, increases with increasing pulse current and/or pulse-on time.

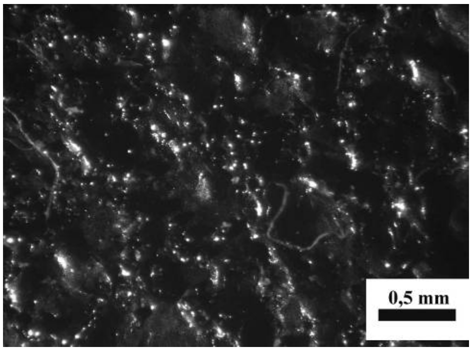

Fig. 1. Topographic characteristics of an EDM' ed surface; W_e= 180 mJ, R_a= 14,7 μm

In [19,20] the pulse current, i_e and the pulse-on time, t_p considered being the main operational parameters varied over a range from roughing to finishing, namely: i_e: 5, 10, 20, 30 A, - t_e: 100, 300, 500 μsec, thus resulting in 12 discrete pulse energies.
The test materials [20] were three grades of quality tool steel, namely: a modified AISI P20 type prehardened mould steel (Impax Supreme®), an AISI D2 type cold work tool steel (Sverker 21®) and a premium AISI H13 type hot work tool steel (Orvar Supreme®) produced by Uddeholm s.a.

Statistical regression models were developed, when possible, to express the correlation of the machining conditions with the imparted surface finish characteristics.

Models characterized by varying degree of fitness are presented below.

Table 7.
Power function models for EDM of AISI D2 steel

$R_a = 0,29523\ I_e^{0,445}\ t_e^{0,394}$	r = 0.952
$R_t = 2,466993\ I_e^{0,442}\ t_e^{0,34}$	r = 0.954
$R_{sk} = 0,932394\ I_e^{0,452}\ t_e^{-0,486}$	r = 0.641
$R_{ku} = 4,854956\ I_e^{0,0159}\ t_e^{-0,0990}$	r = 0.567
$R_{DelA} = 0.482\ I_e^{0,392}\ t_e^{0,197}$	r = 0.879
$R_{sm} = 57,97431\ I_e^{0,195}\ t_e^{0,175}$	r =0.742

The best correlation is exhibited by R_a and R_t parameters and can be characterized satisfactorily high. The parameters R_{delA} and R_{sm} show fair correlation, whilst R_{sk} and R_{ku} appear uncorrelated.

Summing up EDMed surfaces are revealed to be in view of topography "empty", "open'', "steep'' and random in shape, whilst the parameters selected express quantitatively in a satisfying manner these features.; see also [21,22] for further description of EDM' ed surface topography.

Observed characteristics become more profound, when intensifying the machining conditions. Indicative behaviour is shown in Fig. 2.

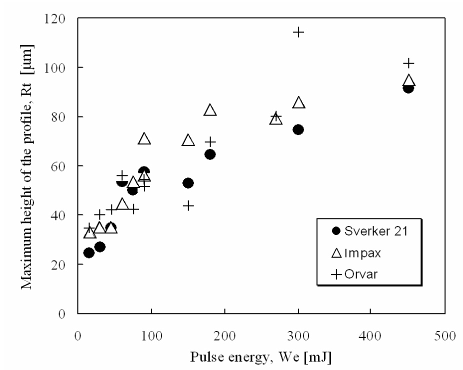

Fig. 2. Variation of the Rt parameter against pulse energy

3. Topological and morphological standards

Surface motif combination, ISO 12085:1996, is a method of analyzing surface texture alternatively to the central line system 'M'. It gives a graphical evaluation of surface profile using mainly six parameters without filtering waviness from roughness. Another functional roughness characterization is introduced by the DIN 4776 and ISO 13565-2 standards through the ''Rk'' parameters, which describe the shape of the relevant Abbott curves.

3.1. Surface texture in turning using motif and Rk parameters

The application of both the aforementioned methods in the analysis of turned textures carrying out turning tests for cutting conditions varied over a representative range will be presented now [23]. The workpiece material was a 304 stainless steel turned by a P30 cemented carbide tool. with a nose radius of 0.8 mm. The cutting conditions: were selected in order to correspond to a practically applicable range. The feed was set from 0.034 up to 0.60 mm/rev and the cutting speed was varied from 5 to 180 m/min.

Table 8.
Models for motif parameters with respect to feed

Parameter	Regression models	r^2
R	$y=135.51x^2+14.003x+1.9605$	0.987
R_x	$y=105.76x^2+20.689x+5.1613$	0.950
A_r	$y=276.72x^2+803.57x+37.99$	0.977
W_x	$y=385.42x^2-60.82x+16.526$	0.850

Concerning the variation of ’’Rk’s’’, the R_k and R_{pk} parameters are related to feed and the MR1 and MR2 appear less correlated On the other hand, the R_{vk} seems uncorrelated. Rk and Rpk clearly increase with increase in feed, indicating that the core and the upper portions of the surface are strengthened.

Certainly, the ‘’Rk’s’’ provide information about the profiles essentially different than single amplitude or spacing parameters and their significance in both functional and morphological features of turned surfaces needs further research.

Table 9.
Models for ‘’Rk’’parameters with respect to feed

Parameter	Regression models	r^2
R_k	$y = 0.1009x^2 - 0.6226x + 3.6024$	0.968
R_{pk}	$y = 0.1059x^2 - 1.2386x + 4.4862$	0.877
MR1	$y = 0.0004x^5 - 0.0268x^4 + 0.6226x^3 - 6.2146x^2 + 25.269x - 15.56$	0.872
MR2	$y = 0.0003x^5 - 0.0168x^4 + 0.371x^3 - 3.733x^2 + 17x + 67.705$	0.884
Note: y, stands for the relevant parameter; x, for cutting speed; R^2, coefficient of determination		

Using the postulated models, the appropriate conditions for successful finish can be selected, as well as functional surface characteristics are quantified.

3.2. Surface texture in EDM using motif and Rk parameters

The machining conditions were varied over a representative range from roughing to semi-finishing of Ck60 carbon steel parts [24]. Close correlation was detected between the motif parameters and some ‘’R_k’s’’ and the machining conditions, and by applying analysis of variance and response surface methodology to the experimental data, predictive models possessing high coefficients of determination were developed.

The relevant response surface graphs that illustrate the aforementioned models are presented In Figures 3 and 4. It is evident that all three parameters show increasing trends, when I_e and t_p increase.

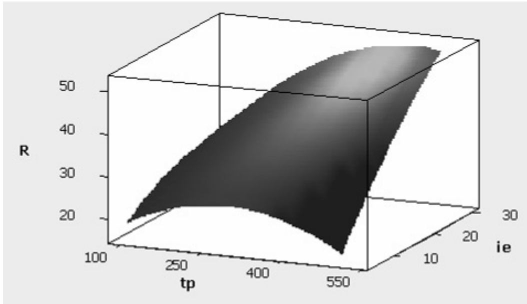

Fig. 3. Estimated response surface of R variation

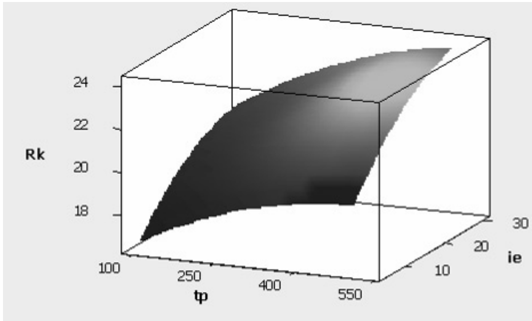

Fig. 4. Estimated response surface of R_k variation

The motif parameters increase monotonously, when pulse current and/or pulse-on time increase. This behaviour implies that roughness amplitude, steepness and spacing are pronounced, when increasing the machining conditions.

Relevant models were formulated via response surface methodology characterized by high degrees of determination with the machining conditions I_e and t_p ($0.90<R^2<0.98$).

As far as the description of bearing curves by the set of R_k parameters is concerned, it is indicated that the R, R_{vk} and MR1 parameters increase with increase in the machining conditions. The meaning of this is that the core roughness amplitude and the portion of the surface for oil retention enlarge when intensifying the machining conditions. Of course, this fact appears favourable but the maximum roughness height must be considered as a constraint.

4. Fractal geometry analysis

An alternative approach developed in the recent years is the fractal theory which was applied to machined surfaces and aimed at characterizing texture independently from the measuring instrument and the evaluation length [25-27].

The main fractal parameters are fractal dimension D and topothesy L. To give a physical definition of these parameters, the fractal dimension D is an intrinsic property of the surface, which is scale independent and reflects the ‘’complexity’’ of the profile structure. The topothesy L is a characteristic length representing the horizontal separation of profile heights corresponding to an average slope of one radian; it takes very small values.

An approach is reported in the following upon the effect of the main cutting conditions on the fractal geometry of turned surfaces [28]. The potential correlation with other roughness parameters has been studied considering the surface bearing capacity. Also, the use of fractal parameters to distinguish chip formation modes is discussed.

The cutting factors implemented are tabulated below (Table 10) The materials used were: Ck60 carbon steel, 6061 Aluminum alloy, 304 stainless steel and brass.

Table 10.
Cutting factors

Turning operations	Cutting parameters: Feed f(mm/rev)	Cutting speed V_c(m/min)	Depth of cut a(mm)	Tool geometry: Insert: cemented carbide P20 (uncoated)
Finish	0.05-0.12	5-200	0.5	Rake angle: $\gamma = 0^0$
Medium	0.12-0.28	5-200	0.5	Clearance angle: $\alpha = 11^0$; Inclination angle: $\lambda_s = 0^0$; Side cutting edge angle $\kappa_1 = 15^0$
Rough	0.32-0.60	5-200	0.5	Nose radius: $r_e = 0.8$ mm

Turned profiles are suggested to be represented at small length scales by a two dimensional self-affined fractal and its parameters are calculated through the profile structure function, as proposed by Russ [29]:

4.1. Influence of cutting conditions on fractal

Only fractal dimension is considered in the following, as topothesy appeared quite unrelated to the cutting factors. It is revealed that at medium and higher feeds the profiles obtain a simpler fine structure. Of course, these feed values are not applied for finishing (Fig. 5).

The effect of the cutting speed on the fractal dimension is irregular and consequently D is proved to be rather uncorrelated to V_c. Although a dropping trend is detected towards the high speeds (Fig. 6).

Since D reflects the "complexity" of the profile, it is expectable that simple periodic forms would have very small fractal dimension; this is confirmed by the resulting turned profiles at the medium to high range of feed values (Fig. 5). As speed increases, the profile takes the regular form and D reduces.

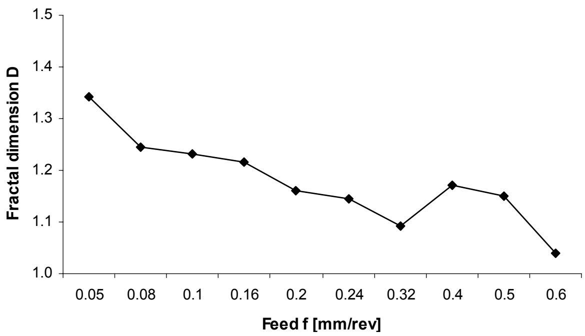

Fig. 5. Variation of fractal dimension against feed (Ck60, V_c=185m/min)

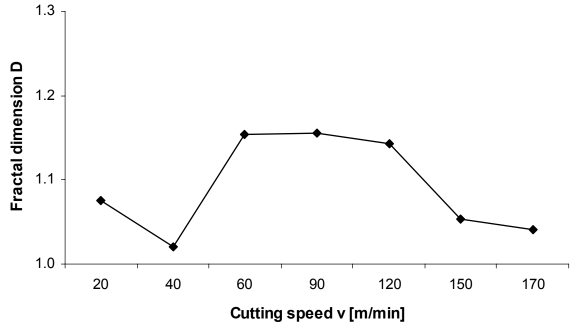

Fig. 6. Variation of fractal dimension with cutting speed (Ck60, f = 0.20mm/rev)

4.2. Surface bearing capacity

The connection of fractal to the load bearing capacity of the surface is of a great importance and the dependence of D on R_{sk} is presented in Fig. 7. As the fractal dimension was assumed to indicate the bearing capacity of a surface [30], it is compared to Abbott curve and its relevant parameters. The results confirm the suggestions made by He and Zhou [31] for shaped textures.

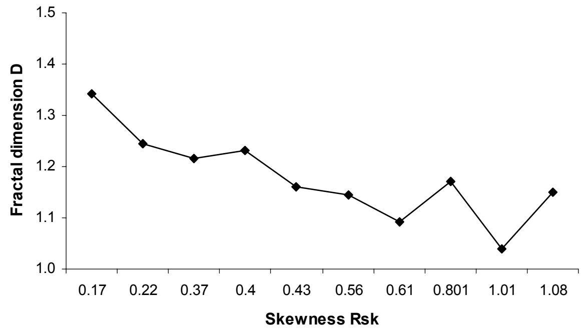

Fig. 7. Fractal dimension variation with Rsk (Ck60)

4.3. Fractal laws

An uni- fractal behaviour is shown in view of the structure function for the regularly turned profiles (possessing the arc chain form) at higher feed rates and cutting speeds, whereas the

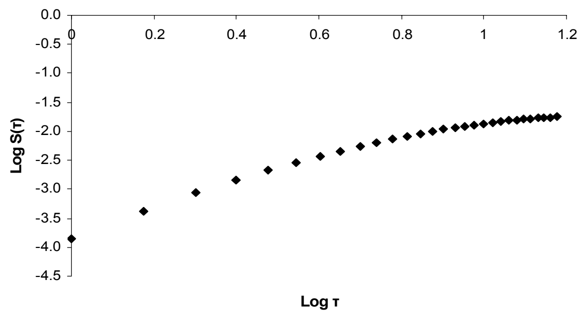

Fig. 8. Bi- fractal behaviour of turned profile corresponding to a very small feed (f=0.05mm/rev)

irregular surfaces appear to possess a bi- fractal structure, as illustrated in Figs 8 and 9, accordingly; This result was confirmed for all of the materials tested.

A chart comprising the parameters of the beta statistical function is also illustrated in Fig. 10. The values are less scattered now and compared to the Whitehouse beta function typology [35] the range is wider due to the fact explained before. The diagram for the log-normal distribution parameters is presented too, where the points are almost uniformly distributed and the whole regime looks expanded compared to a previous approach [36].

An approach through the Fisher- Pearson parameters is proposed and the corresponding chart is shown in Fig. 11. It has a resemblance to the beta function as expected but it may distinguish more explicitly between different texture shapes; so it could be considered as a satisfactory method towards the desired process identification.

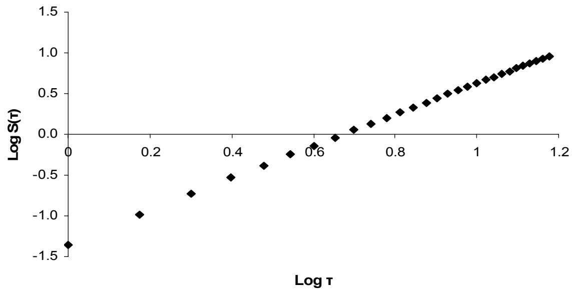

Fig. 9. Uni- fractal behaviour of turned profile at a high feed (f=0.60mm/rev)

As a general conclusion fractal analysis gives insight to aspects of turned surfaces. and is mainly related to the chip formation procedure.

5. Profile classification in turning - New surface typology charts

The aim is to investigate into the topography of turned surfaces processed under cutting factors leading to differing profile forms for practical reasons of control and classification or for developing simulation models and surface functioning. Specimens of Ck60 steel were turned for cutting factors properly selected to achieve representative surface patterns at each case considered [32].

Two axes are followed in the analysis of the experimental results: firstly, the comparison between the irregular types and secondly, the distinction between them and the regular surface texture [33, 34].

5.1. Development of new typology charts

In Fig.10 the kurtosis and skewness of the measured surfaces are shown. A cluster of points appears, as kurtosis and skewness are not interrelated but can fix the boundaries of surface textures in view of shape for a wide range of cutting conditions employed. The area of high concentration of values located at the down-right side of the diagram corresponds to regular chip formation. For the shake of comparison a relevant chart taken from [32] is presented in Fig. 10.

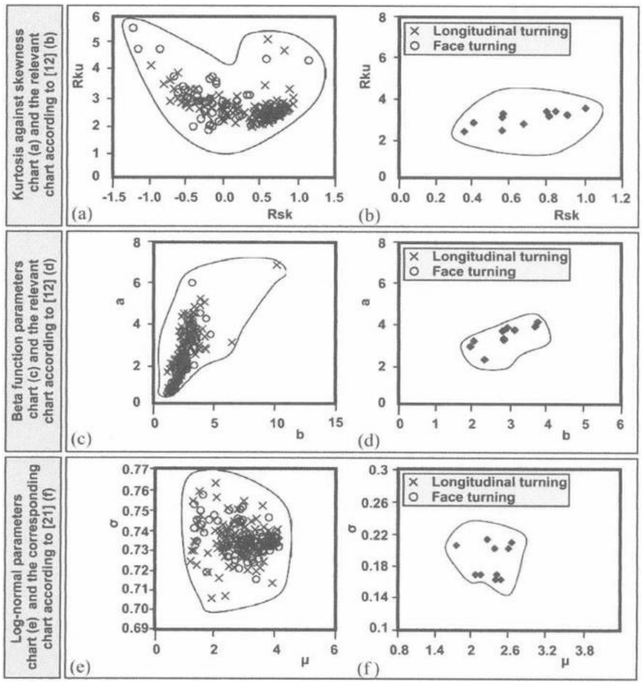

Fig. 10. New developed surface typology charts and older ones

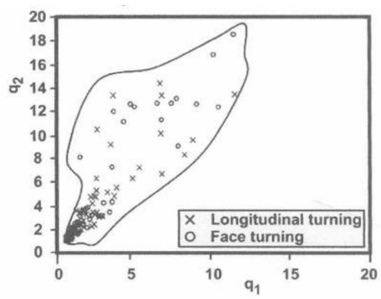

Fig.11. A Fisher- Pearson typology chart

5.2. Variability of the profile parameters over turned surfaces

It is well known that roughness possesses a stochastic character concerning both the shape of individual profiles and their repeatability over the surface. The amount of scatter proposed surface texture parameters exhibit, when measurements are undertaken on different locations of the surface is not only related to the experimental error but also to the degree of homogeneity of the texture, which in turn depends on the machining conditions [37-38].

With a small exception, all the parameters exhibit lesser dispersion and the relevant distributions are closer to the normal for the "regular" surface (VI). Where the parameters show a large scatter in their values they apparently need a larger sample size for their determination or even appear essentially "non-measurable". Fig. 12 [32] presents an example of the variability of R_{sk}, a parameter by definition sensitive to inordinate surface features, is illustrated for the cases of the very small feed and the regular chip formation.

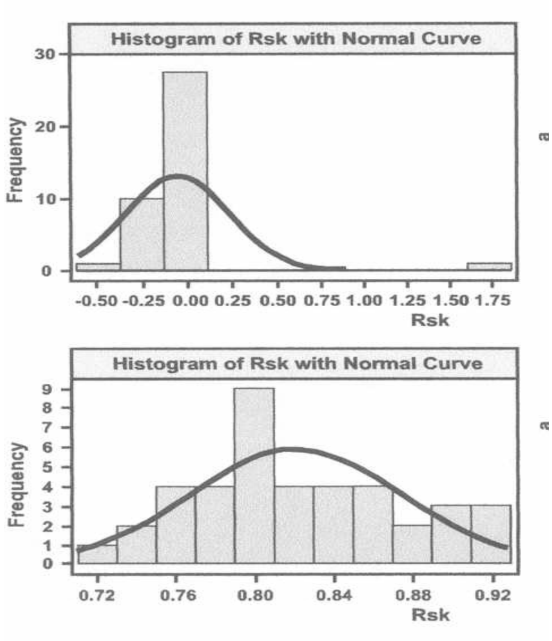

Fig. 12. Histogramme of the Rsk parameter distribution for very low feed and normal feed (regular chip formation)

6. Surface texture anisotropy

6.1. Existing and proposed indices of anisotropy

The wide variety of surface textures obtained in engineering manufacture can be further divided into isotropic or anisotropic. A texture is characterized as isotropic, if its topographic properties are statistically independent from the measuring direction over the surface.

Most of the machined surfaces are topographically anisotropic; they possess a "lay" [39-41]. Machining processes with tools of defined geometry viz. turning, shaping and milling usually generate severe anisotropic patterns, whilst others like EDM create isotropic texture. The directional properties affect the tribological function of the surface (frictional behaviour, wear, lubricant retention etc.), as well as the state of anisotropy can change during function [42].

Considering the existence of isotropy or anisotropy on a surface and these magnitudes several criteria have been manifested in literature. Most of them are based on an "anisotropy index", a ratio combining topographic parameters, usually along two directions on the surface. Usually, values of these indices near unity characterize a surface as isotropic, whereas lower or higher values correspond to anisotropy.

Some of the existing methods for evaluating surface texture anisotropy in view of literature are:

a) The ratio γ of the auto correlation lengths of two representative profiles along the principal axes of the surface, called anisotropy index $\gamma = \frac{\lambda_{0.5yy}}{\lambda_{0.5xx}}$
b) The ratio of the unfiltered or raw profile of the minimum and maximum RMS slope values over the profile $\gamma = \frac{\Delta_{qyy}}{\Delta_{qxx}}$.
c) The long crestedness $\Lambda = \frac{2\sqrt{m_{20}m_{02} - m_{11}^2}}{m_{20} + m_{02}}$ considers seven independent combinations of moments of the surface power spectral density function.
d) Fractal dimension and topothesy appear sensitive to the existence of anisotropy [43].
e) A parameter Str defined as the ratio between the axes of an ellipse fitted to a "rose plot" of Hurst coefficients can characterize anisotropy.

Anisotropy up to now is rendered only to surface roughness, whilst engineering textures incorporate surface waviness that may significantly affect surface functioning [44] and waviness parameters are adopted in the ISO 4287-1997 surface metrology standard. Furthermore, for an integrated description of surface texture unfiltered or raw profile parameters have been introduced in the aforementioned standard.

New suggestions for full scale and morphological evaluation of surface anisotropy are, as follows:

- The waviness component of the surface texture has to be considered in critical and high precision applications, as well as in highly anisotropic textures, where the waviness shows the same directional variations with roughness (not necessarily with the same trend) and an integral texture anisotropy index could be proposed.
- Abbott curves would offer a measure of anisotropy via corresponding parameters, standardized (ISO 13565-2:1996) or not [34].
- Multi- parameter statistical systems like Fisher-Pearson to describe the profile parameters distribution over the surface, would provide a correct evaluation of anisotropy.

In the present study [45] these methods are applied in two extremely different surface textures, one processed by Electro-Discharge Machining (EDM), which is isotropic and the other one, face milled (strongly anisotropic).

For the milled specimen face milling with an one tooth cutter, feed fz=0.14mm/rev and cutting speed v=200m/min. The Electro-Discharge machined specimen was processed at a working voltage 30V with pulse current ie=5A and pulse-on time tp=500μs.

6.2. Differing characterisation

The milled surface is highly anisotropic possessing an annular lay and different topographic components along two crossed directions; very high waviness is located in the tangential direction, as well as the profile is purely periodic in the radial direction, as expected.

On the contrary, the EDM'ed surface patterns are quite similar measured along two mutually perpendicular directions, as they exhibit a multi- directional both profiles are random in shape. The results are listed in Table 10.

The auto correlation length ratio $\lambda_{0.5}$ expresses explicitly the state of anisotropy. The Rq ratio expresses anisotropy in a clear quantitative manner. The asperities mean slope ratio RDelQ is also distinctive along with the Rq ratio. Fractal dimension D reflects the "complexity" of surface profiles and as the anisotropic crossed patterns have unsimilar structures, they exhibit different values but this distinction is not much pronounced in the relevant D ratio value. The corresponding ratios for the Abbott curve parameters can describe more properly the raw profile components and to characterize correctly the roughness anisotropy, especially via the Rk ratio. It must be noted here that the ratios Rtp at 10 per cent and 40 per cent evaluate the existing anisotropy in a different way, which must be taken into account functionally and in this regard the latter can characterize more properly the anisotropy after the running-in stage.

Table 10.
Anisotropy evaluation ratios using various methods

	anisotropic	isotropic
D	0.71	0.94
$\lambda_{0.5}$	0.07	0.65
R_q	7.33	1.26
W_q	0.04	0.72
P_q	1.19	0.97
$P_{tp\,(10\%)}$	0.19	1.77
$R_{tp\,(10\%)}$	0.35	1.16
$P_{tp\,(40\%)}$	0.56	1.51
$R_{tp\,(40\%)}$	1.86	1.25
R_{DelQ}	5.15	1.02
R_k	7.95	1.60
F-P k	-0.002	0.25

Note: The bold symbols stand for ratios of the relevant magnitudes measured along two mutually perpendicular directions on the surface)

Regarding as a criterion the higher difference in the various "anisotropy index" values taken for anisotropic and isotropic surfaces accordingly, the R_q, R_k, and R_{DelQ} are more descriptive.

Certainly, several other machined surfaces must be examined against these aspects and the findings may contribute to an introduction of new criteria in relation to function.

7. Conclusions

Some general remarks and conclusions that may be drawn in view of the aforementioned findings in the area of surface metrology of machining processes are, as follows:

a. A multi-parameter analysis of engineering surface texture is a must owing to the high precision and functional requirements for critical applications existing in the contemporary machining of components.
b. Several ISO 13565-2 arithmetic parameters, especially amplitude, spacing and hybrid, correlate well with machining conditions for both turning and Electro-Discharge Machining. All of the motif parameters and some Rk'' parameters are also in accordance with machining conditions. The single or multiple regression models developed are useful possessing very high correlation coefficients. Certainly, more research is needed on the significance of ''Rk'' characterization.
c. Of functional importance and process control oriented is the investigation into the form of surface roughness under different machining factors. The formulation of surface typology charts will lead to an optimal selection of machining conditions in functionally constrained cases.
d. Regarding topographic anisotropy, the evaluation by surface roughness only is inadequate. More integrated anisotropy indices should be defined.
e. The ''inflation'' of the proposed texture parameters, standardized or not, has a negative influence on industrial and research communications and has to be regarded under the prism of making up subsets for a proper selection of parameters in each case considered.

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