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Relevance of Roughness Parameters of Surface Finish in Precision Hard Turning

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Summary: Precision hard turning is a process to improve the surface integrity of functional surfaces. Machining experiments are carried out on hardened AISI 52100 bearing steel under dry condition using c-BN cutting tools. A full factorial experimental design is used to characterize the effect of cutting parameters. As surface topography is characterized by numerous roughness parameters, their relative relevance is investigated by statistical indices of performance computed by combining the analysis of variance, discriminant analysis and the bootstrap method. The analysis shows that the profile Length ratio (Lr) and the Roughness average (Ra) are the relevant pair of roughness parameters which best discriminates the effect of cutting parameters and enable the classification of surfaces which cannot be distinguished by one parameter: low profile length ratio Lr (Lr = 100.23%) is clearly distinguished from an irregular surface corresponding to a profile length ratio Lr (Lr = 100.42%), whereas the roughness average Ra values are nearly identical. SCANNING 9999:1–9, 2013. © 2013 Wiley Periodicals, Inc.

Key words: precision hard turning, roughness, cutting parameters, experimental design

Introduction

Precision hard turning (PHT), defined as single-point cutting of part pieces with hardness of material in excess of 45 HRC under small feed rate and fine depth of cut conditions, has become an attractive alternative to conventional grinding in many industrial applications. It offers very substantial benefits such as environmentally friendly and capability to manufacture complex workpiece geometry (Koenig *et al.*, '93). Through the low surface roughness amplitude and compressive residual stresses (Tonshoff *et al.*, 2000; Klocke *et al.*, 2005), PHT can improve the functional performance of workpieces such as increasing the fatigue life (Koenig *et al.*, '93; Jouini *et al.*, 2013). In PHT, the achievable values of the Ra parameter is 0.1–0.3 μm (Byrne *et al.*, 2003).

Surface quality obtained by PHT is one criterion for the surface integrity (Schwach and Guo, 2005) and plays an important role in term of surface functionalities. Numerous investigations have quantified the impact of cutting parameters on surface quality in hard turning using CBN cutting tools. Klocke *et al.* (2005); and Grzesik and Wanat (2005) and Waikar and Guo (2008) established multi-parameter 2D and 3D characterization of the surface finish produced by hard turning. Sahin and Motorcu (2008) developed a predictive model of surface roughness Ra, Rz, and Rmax using response surface methodology when machining hardened AISI 1050 steel. They reported that feed rate was the most powerful factor on surface roughness for different tools. Benga and Abrao (2003) investigated the effect of speed and feed rate on surface roughness and tool life using three-level factorial design (3^2) on machining of hardened 100Cr6 bearing steel (62–64) HRC. Ozel and Karpat (2005) developed predictive model of surface roughness Ra and tool wear in hard turning using regression and neural network for AISI H13 steel using CBN tools. However, to characterize the surface roughness, a high number of roughness parameters (amplitude, frequency, and hybrid parameters) may be used (Whitehouse, '94; Bigerelle *et al.*, 2003). Thus, the question is: which parameter is the most relevant to characterize the morphology of a PHT surface with regard to a specific

application (optical quality, wear, etc.). The aim of this paper is to determine quantitatively, and without preconception opinion, the most relevant roughness parameters investigated by a powerful statistical computer by combining analysis of variance (ANOVA), discriminant analysis and the bootstrap method (Najjar *et al.*, 2003).

Experimental Procedure

Experimental Set-Up and Machining Tool

The machining tests were conducted on a CNC high precision turning machine, as shown in Figure 1. This machine is a prototype lathe proposed for the finishing of the AISI 52100 bearing components. The two slides-ways (X- and Z-axis) are guided by hydrostatic-bearings offering low friction, high stiffness and high damping; fixed on a massive granite block (1.5 tons), which rests on four self-leveling pneumatic isolators. The straightness of both slides is better than 0.3 μm over a displacement of 100 mm. The spindle is mounted axially to the Z-axis and an active magnetic bearing is adopted to achieve greater spindle dynamic stiffness. Due to the high demands on X- and Z-axis accuracy, ironless linear motors ILD 24-050 (ETEL Motion Technology, Switzerland) are used for the feed drive system. Each linear axis is operated by a position control system controlled using an incremental linear encoders LIP 401R (Heidenhain, Germany) of 4 nm resolution. Displacements are controlled by an accurate Computer Numerical Control system with a powerful numerical card (Programmable Multi-Axis Controller, PMAC, Delta Tau Data Systems, Inc).

In this work, AISI 52100 bearing steel rings thermally treated to an average hardness of 61 ± 1 HRC were used as workpiece material. The length of the ring was 14 mm with an outer diameter of 70 mm and an inner diameter of 19 mm.

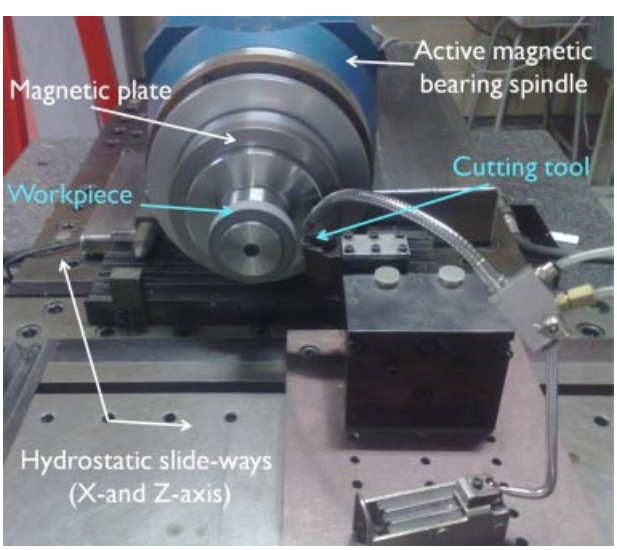

Fig. 1. Focus on the high precision turning machine used in this study.

The machining tests were performed under dry cutting conditions using c-BN cutting tool inserts (ISO code CNGA 120408 S01030 7025) manufactured by Sandvik™ Coromant, Sweden. The inserts were mounted using a Coro torn RC rigid clamp system in the tool holder DCLN 2525M12 (ISO), providing the following angles: rake angle $\gamma_0 = -6^\circ$, inclination angle $\lambda_s = -6^\circ$, cutting edge angle $\chi_r = 95^\circ$, clearance angle $\alpha = 6^\circ$, and nose radius r = 0.8 mm.

Experimental Design

A full factorial experimental design (2^3) was performed to analyze the effect of cutting parameters (cutting speed, feed rate, and depth of cut). The cutting speed, noted Vc (m/mn), is the relative velocity between the cutting edge and the removed material. The feed rate, noted f (μm/rev), is the axial displacement of the tool during one rotation of the part. The depth of cut, noted ap (μm), is the depth to which the tool penetrates the material. The levels of cutting parameters were determined by a preliminary study and according to the characteristics of the CNC prototype lathe for machine hardened steel. Table I shows the different levels of the cutting parameters. The full set of eight experiments is shown in Table II.

Surface roughness measurements were carried out by stylus profilometer (Tencor P-10, KLA Tencor Corporation, USA) with a 2 μm tip radius, loaded with

TABLE I Assignment of the factors levels

Cutting parameters	Low level	High level
Cutting speed, Vc (m/mn)	210	260
Feed rate, f (μm/rev)	50	100
Depth of cut, ap (μm)	5	10

TABLE II Experimental design matrix

Experiments no.	Depth of cut, ap (μm)	Cutting speed, Vc (m/mn)	Feed rate, f (μm/rev)
1	5	210	50
2	5	210	100
3	5	260	50
4	5	260	100
5	10	210	50
6	10	210	100
7	10	260	50
8	10	260	100

50 mN. For each experiment, 25 roughness profiles were recorded perpendicular to the grooves. The scanning length and the sampling length were, respectively, 8 mm and 0.1 μm (80,000 data points along the profile length). Each profile was rectified by a third degree polynomial suitable to remove from consideration the form of the surface.

Roughness Characterization

Classical Analysis of Experimental Design

The classical statistical analysis was conducted to investigate which design parameters significantly affect Roughness average (Ra), defined as the average absolute deviation of the roughness irregularities from the mean line over one sampling length (the most-often employed roughness parameter). The experimental results were investigated with the ANOVA.

Table III represents the calculated values of Fisher variate (F). This analysis was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. It may be observed that all factors (Vc, f, and ap) and their mutual interactions present significant influences on the roughness average Ra. The interaction Vc × f and f have the highest *F* values, whereas f × ap, Vc × f × ap, and Vc × ap the lowest *F* values.

In Figure 2, the interaction effects were plotted. The feed rate strongly affects roughness average Ra. It has an increasing effect (from Ra = 0.15 to 0.25 μm). Indeed, it is well know that the theoretical geometrical roughness average Ra is primarily a function of feed rate for a given nose radius. Moreover, a significant variation was observed on Ra due to cutting speed that has a decreasing effect (Ra = 0.24 to 0.16 μm). Depth of cut has an important increasing effect (Ra = 0.16 to 0.24 μm). The interaction Vc × f is the most significant effect whatever ap value. More precisely, for low cutting speed (210 m/mn) the Ra value increases with increasing feed rate and it is constant for high cutting speed (260 m/mn).

A multiple linear regression analysis was carried out to model the relationship between the factors (cutting speed, feed rate, and depth of cut) and the roughness average Ra by fitting a linear equation. The prediction model is:

$$\begin{aligned} Ra = & -0.36 + 0.0017\ Vc + 0.0036\ f \\ & -0.1047\ ap + 0.00044\ Vc.ap \\ & -0.000014\ Vc.f + 0.0026\ f.ap \\ & +0.00001\ Vc.f.ap \end{aligned} \quad (1)$$

TABLE III ANOVA table for roughness average Ra

Effect	df	MS	F
Vc × f	1	0.610	24,112
f	1	0.514	20,343
Vc	1	0.355	14,034
ap	1	0.336	13,275
Vc × ap	1	0.077	3,043
Vc × f × ap	1	0.048	1,906
f × ap	1	0.040	1,573

Note. DF, degrees of freedom; SS, sum of squares; MS, mean squares; *F*, *F*-test.

The Choice of Roughness Parameter

There is an increasing interest in developing reliable methodologies suitable for quality control stage processes of surface products in a manufacturing environment. Because of the various industrial and scientific interests in topography analysis, a proliferation of roughness parameters, possibly running into the hundreds, has been triggered to describe different kinds of surface morphology with regard to specific functions, properties, or applications. In spite of this proliferation, termed by Whitehouse the "Parameter rash," there is still no complete comprehensive account for the relevance of these roughness parameters. This probably comes from a lack of global methodology combined with the limits of the software presently on the market (whose function is) to characterize a surface morphology. The main objective of such a global methodology should be to determine quantitatively, and without preconception, the most relevant roughness parameter that can characterize the surface morphology of a manufactured product with regard to a correlation with a particular function, property, or application. Then, the question that arises is: which parameter is the most relevant one to characterize the morphology of a machined surface with regard to a specific application, an optical quality control for example? The main purpose of the present study is to answer this previous question without any preconceived opinion regarding the surface roughness parameters.

In order to answer this question, a status surface analysis system called "MesRug" was designed (Najjar *et al.*, 2006; Gilgean *et al.*, 2008). The interest of this system is to build a robust statistical analysis to create a probabilistic index, independent of the number of parameters, which characterize the relevance of each roughness parameter. For these reasons, a recent data analysis tool called the bootstrap was used.

Fifty five roughness parameters were under investigation including: (i) amplitude parameters (Ra, Rq, Rz, Rp, Rv, Rt, Rsk, Rku, etc.); (ii) spacing parameters (Sm, m, g, etc.); (iii) hybrid parameters (L0, Lr, Δa, Δq, λa, λq, Ro, M0, etc.) and frequency parameters (F1, F2, F3, F4, etc.). For each roughness parameter q induced by i ($i \in [1, p]$), the Fisher variates F_i can be computed for all effects and their interactions. However, a small variation in any score induces simultaneously a variation in F_i. This is why the bootstrap theory was

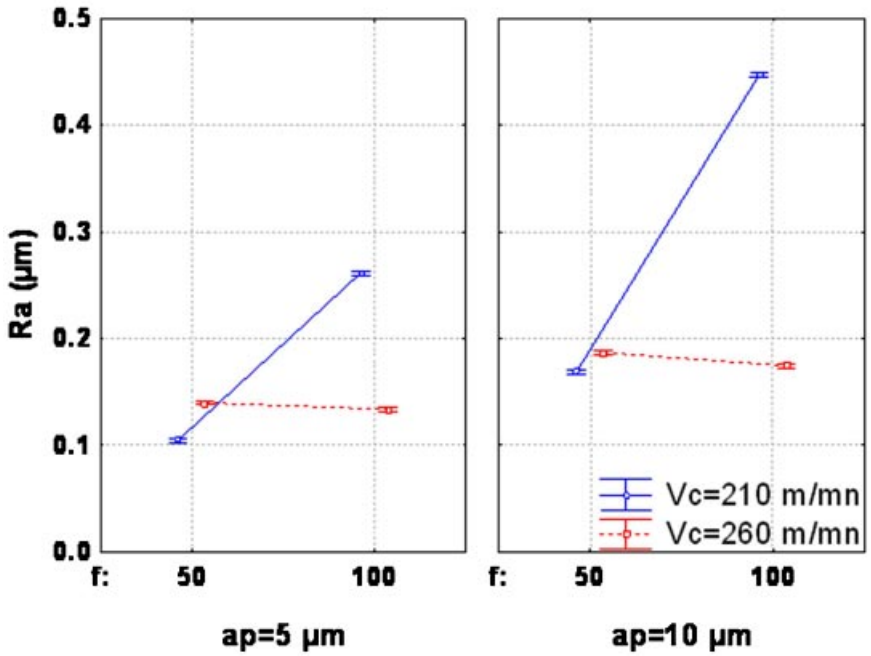

Fig. 2. Interaction effects for roughness average Ra.

used in this study to generate, from data of only one experimental design, the calculation of one value F_i^*, a set of N (N = 100) equivalent computational designs. Thus, a set of N values of F_i^* can be calculated from which it is possible for a given surface roughness parameter q_i

1. To extract an average value F_i.
2. To build a 95% confidence interval.

A parameter q_i will be more relevant than a parameter q_j when $F_i > F_j$ in a statistical sense.

Figure 3 represents the relevant roughness parameters according to cutting parameters and their associated interactions. Best roughness parameters were then extracted in Table IV. Moreover, the position of Ra in the roughness parameters relevancy was added. As it can be observed, Table IV shows that the 0th (m_0) and the 2nd (m_2) spectral moments well characterized the cutting parameters. The 0th and 2nd moments are the variance of height distribution and the variance of distribution of slopes, respectively (Thomas, '99). It is well known that spectrum analyses can be helpful to analyze the effect of the cutting parameters (Cheung and Lee, 2000).

In analyzing more statistical results, the bootstrap method allows us to prove that m_2 is not statistically more relevant that m_0, so m_0 is the best roughness parameters to characterize the cutting parameters. However, by analyzing the correlation between roughness parameters (Fig. 4: the diagonal of the matrix is a histogram of the roughness parameter value. The scatter plots are the correlation between two roughness parameters), Ra and m_0 are highly correlated ($R^2 = 0.99$). So, even if m_0 better described the cutting parameters, it does not affect the result found in the first analyses based on the Ra. It can be noticed that the Ra parameter is always well classified, meaning that Ra is a good roughness parameters to analyze all the effects and their mutual interactions of cutting parameters.

A very interesting fact is the high correlation between Ra and mean space between asperities S_m (Fig. 5) which is equal to:

$$Ra = 0.04 + 0.0072 \times S_m \quad (2)$$

In fact, as these parameters are dimensionally independent, no dimensional correlation is expected. This correlation can be explained only by the cutting process. In fact, basically two groups would emerge with two different S_m: If cutting conditions are optimal, the S_m must be equal to the feed rate. But cutting conditions are not (so) optimal and so some peaks and valleys appear in the profile, which leads to minimizing the mean distance between asperities. This structure is in fact fractal because a self-affine fractal profile presents a perfect relation between Ra and S_m. This relation is of major interest: the distance between asperities and amplitude roughness varies linearly in the same relation whatever the cutting conditions. This property is one particularity of high precision turning (Bigerelle *et al.*, 2007).

Multi-Parameter Estimation

Figure 2 shows that Ra seems to be constant for different feed rates if the cutting speed is equal to

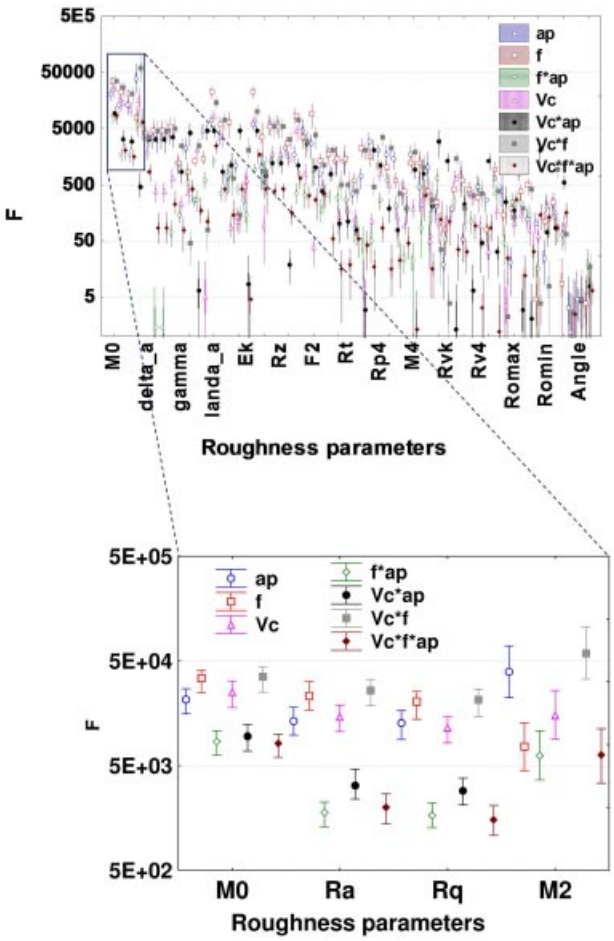

Fig. 3. Relevant roughness parameters according to cutting parameters and zoom of the best relevant roughness parameters.

260 m/mn and thus whatever the cutting depths. Does it mean that these profiles are similar? It is certain that two similar profiles will have a similar Ra but this does not mean that similar Ra values result from similar profiles. So what are the morphological differences and how to characterize them? Another tool must be used to answer to this question. In fact, two roughness parameters were required to characterize all profiles. This pair of roughness parameters must satisfy the two following conditions:

1. Accurately describe cutting conditions.
2. Be statistically lower correlated.

An original analysis is therefore proposed. The relevant pair of roughness parameters is the parameters that best discriminate each of the eight experiments from the experimental design and get low correlation. As a consequence, two statistical tools must be employed. To find to the best group discrimination, the discriminant analysis will be used. The statistical indicator is the percentage of badly classified data or more precisely, the probability that data are badly classified. This probability is computed using a Bayesian approach. This indicator is noticed as $Pr_{bad}(q_1, q_2)$ where (q_1, q_2) is a pair of roughness parameters. To find to the lower correlation, the statistical indicator used is noted $Pr_{cor}(q_1, q_2)$. The lower $Pr_{cor}(q_1, q_2)$ is, the higher the correlation, and inversely if $Pr_{cor}(q_1, q_2)$ values converges to unity, no correlations are found.

Figure 6 represents a selection of pairs of roughness parameters according to their discrimination and correlation indicators: (i) high discrimination with low correlation ((Lr, λa) and (Lr, Ra)); (ii) high discrimination with high correlation ($(m_0, \lambda q)$, (m_0, Ra), and (m_2, Ra)); and (iii) low discrimination with low correlation ((Rk, Ro_{min}) and (Angle, Ro)). Therefore, a new original indicator of classification is defined including these two conditions, noted $I(q_1, q_2)$.

$$I(q_1, q_2) = \frac{Pr_{bad}(q_1, q_2)}{Pr_{cor}(q_1, q_2)} \tag{3}$$

The lower $I(q_1, q_2)$, the relevant pair of roughness parameters (q_1, q_2). Thus, the pair (q_1, q_2) is the retained parameters. Table V shows that the pair of roughness parameters (Lr, λa) and (Lr, Ra) are the best classified. Indeed, there is lower correlation between Lr and λa, and also Lr and Ra. Moreover, these two pairs of roughness parameters discriminate the experiments of the experimental design. Using bootstrap simulation obtained by 100 runs, it is shown that the 95% CI for the two pairs of roughness parameters (Lr, λa) and (Lr, Ra) are, respectively, $(3.7 \times 10^{-10}, 2.5 \times 10^{-20})$ and $(3.2 \times 10^{-08}, 4.15 \times 10^{-19})$.

As overlap occurs between these intervals, it can be stated that these two pairs get the same relevance. As a consequence, the second pair of roughness parameters (Lr, Ra) is retained as relevant parameters because Ra is firstly used in the classical analysis. The second relevant roughness parameter Lr of the pair will be analyzed by ANOVA.

Table VI shows the ANOVA for Lr. It may be observed that all factors (Vc, f, and ap) and their interactions present significant influence on the Lr. Feed

TABLE IV Position classification of R_a, m_0, and m_2 roughness parameters

Effect	Roughness	F	Ra	m_0	m_2
Vc	m_0	23,300	3	1	2
f	m_0	31,700	2	1	8
ap	m_2	36,980	3	2	1
Vc × f	m_2	55,197	3	2	1
Vc × ap	m_0	8,880	8	1	17
f × ap	m_0	7,780	3	1	2
Vc × f × ap	m_0	7,538	4	1	2

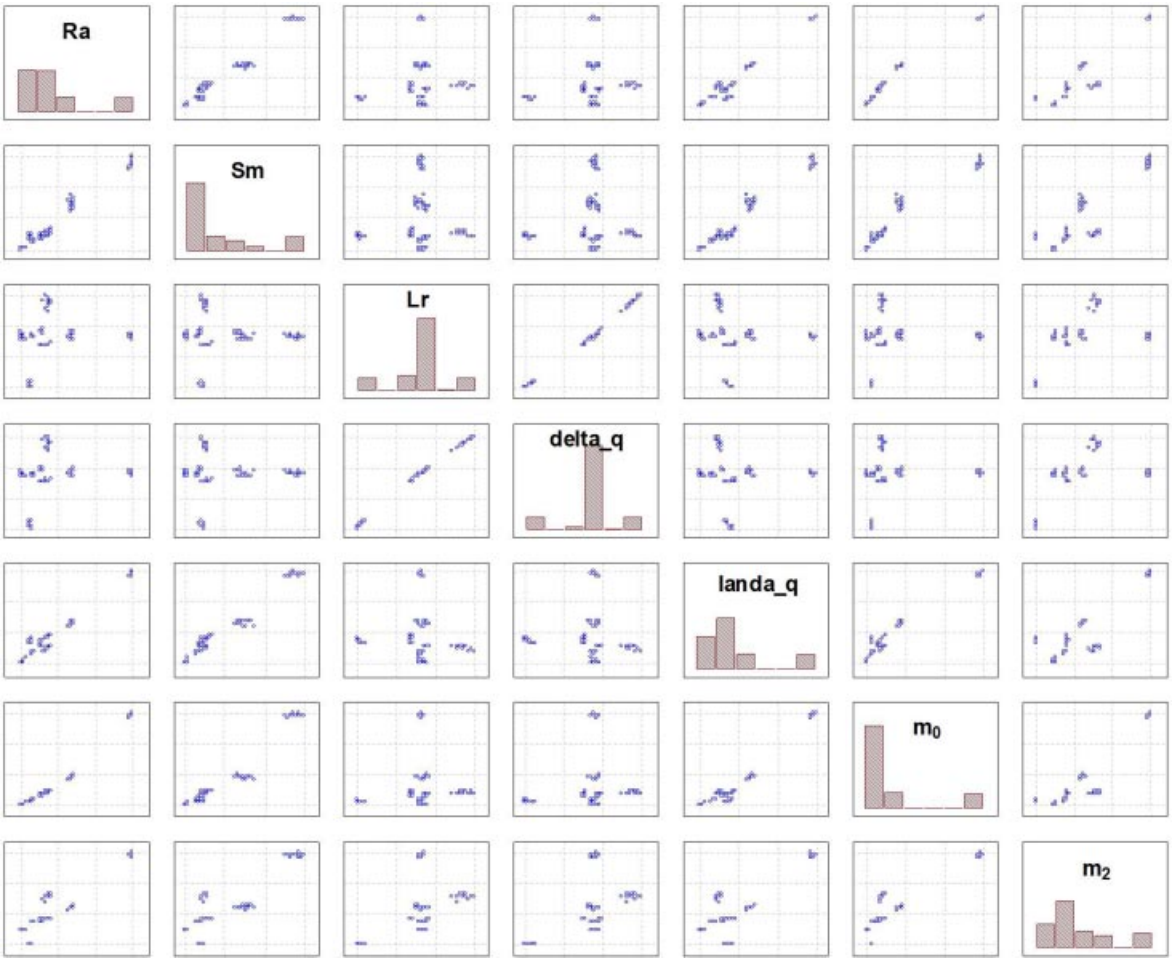

Fig. 4. Correlation between roughness parameters.

rate, the interaction Vc × f, depth of cut, the interaction Vc × ap and cutting speed get an important effects. In Figure 7, the interaction effects were plotted. It shows that at high-level cutting speed (260 m/mn), the feed rate has an important and decreasing effect whatever the cutting depth.

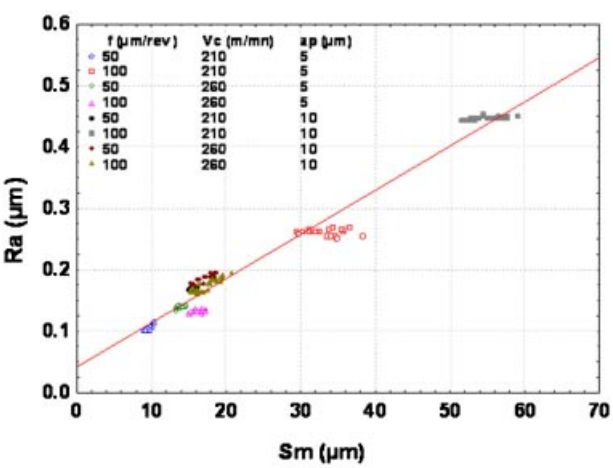

Fig. 5. Plot Ra versus Sm.

A multiple linear regression analysis was carried out to model the relationship between the cutting parameters and Lr by fitting a linear equation. The prediction model is:

$$\begin{aligned} \mathrm{Lr} = {} & 99.85 + 0.0025\ \mathrm{Vc} + 0.0204\ \mathrm{f} - 0.0508\ \mathrm{ap} \\ & +0.00028\ \mathrm{Vc.ap} \\ & -0.000095\ \mathrm{Vc.f} - 0.00084\ \mathrm{f.ap} \\ & +0.0000036\ \mathrm{Vc.f.ap} \end{aligned} \tag{4}$$

The roughness parameters Ra and Lr show their relevancy for characterizing the effect of cutting parameters. Indeed, Figures 2 and 7 show that at low-cutting speed (210 m/mn) the Ra value increases with increasing feed rate while Lr value is constant. At high-cutting speed (260 m/mn), Ra value is constant while Lr value decreases with increasing feed rate. High surface finish is then obtained at low average roughness Ra and low profile length ratio Lr. The complementarity of roughness parameters Ra and Lr allows us to quantify the effect of cutting parameters.

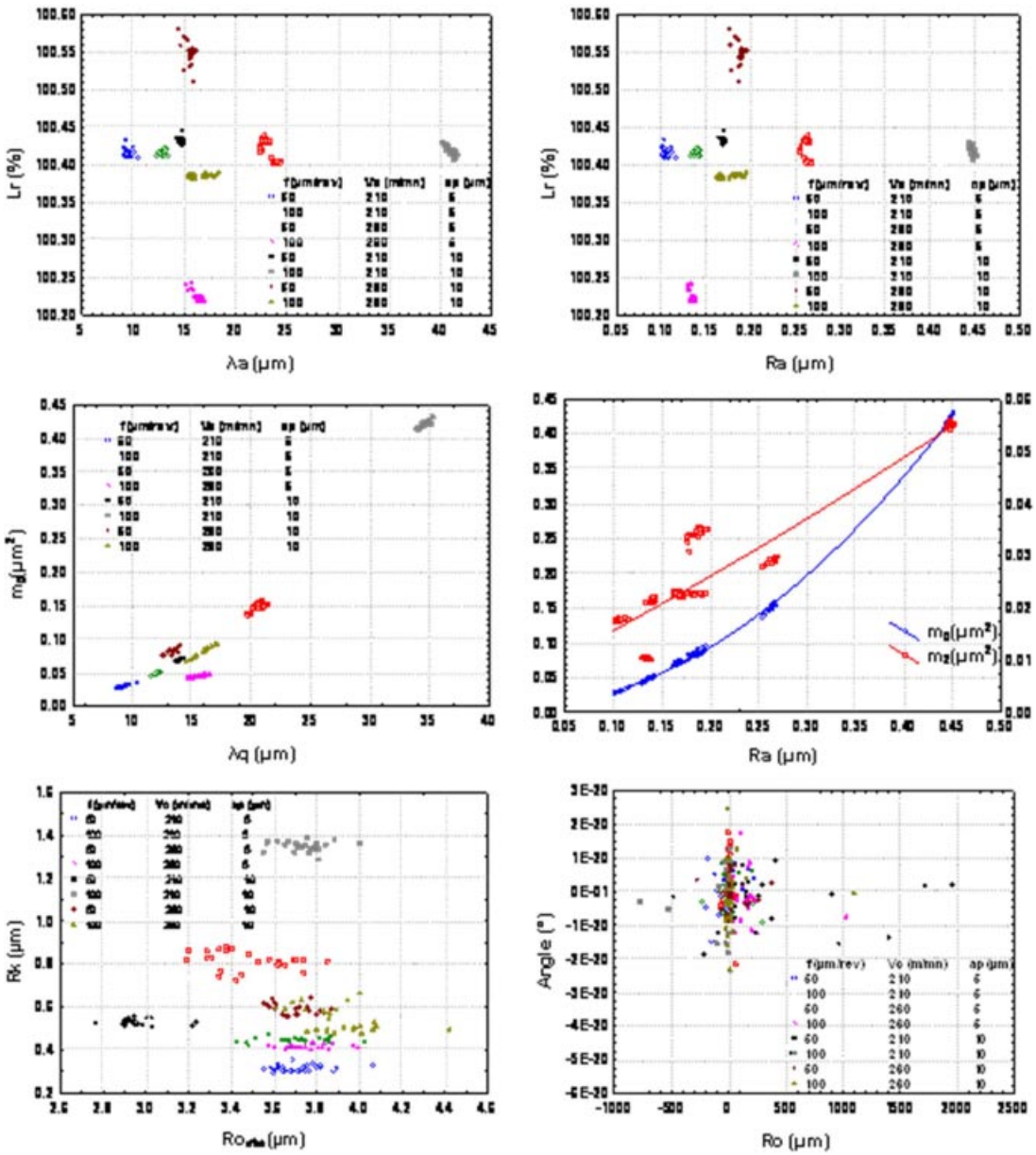

Fig. 6. Selection of pairs of roughness parameters: (Lr, λa), (Lr, Ra), (m_0, λq), (m_0, Ra), (m_2, Ra), (Rk, Ro_{min}), and (Angle, Ro).

The profile length ratio Lr is defined as the degree of irregularity of the profile. Decreasing Lr indicates regular cutting. For example, in some applications particularly where a good adherence is necessary, it can be desirable to have a large Lr value, i.e. greater surface of contact.

TABLE V Classification of pairs of roughness parameters (q_1, q_2)

(q_1, q_2)	$Pr_{bad}(q_1, q_2)$	$Pr_{cor}(q_1, q_2)$	$I(q_1, q_2)$
(Lr, λa)	2.03×10^{-13}	0.93	2.16×10^{-13}
(Lr, Ra)	1.87×10^{-12}	0.03	6.37×10^{-11}
(m_0, λq)	3.7×10^{-13}	2.0×10^{-123}	1.8×10^{110}
(Ro_{min}, Rk)	0.08	0.713	0.11
(Angle, Ro)	0.81	0.18	4.52

TABLE VI ANOVA table for profile length ratio Lr

Effect	df	MS	F
f	1	0.399	5,361
Vc × f	1	0.342	4,601
ap	1	0.280	3,769
Vc × ap	1	0.223	3,005
Vc	1	0.033	440
Vc × f × ap	1	0.006	82
f × ap	1	0.0001	2

Note. DF, degrees of freedom; SS, sum of squares; MS, mean squares; *F*, *F*-test.

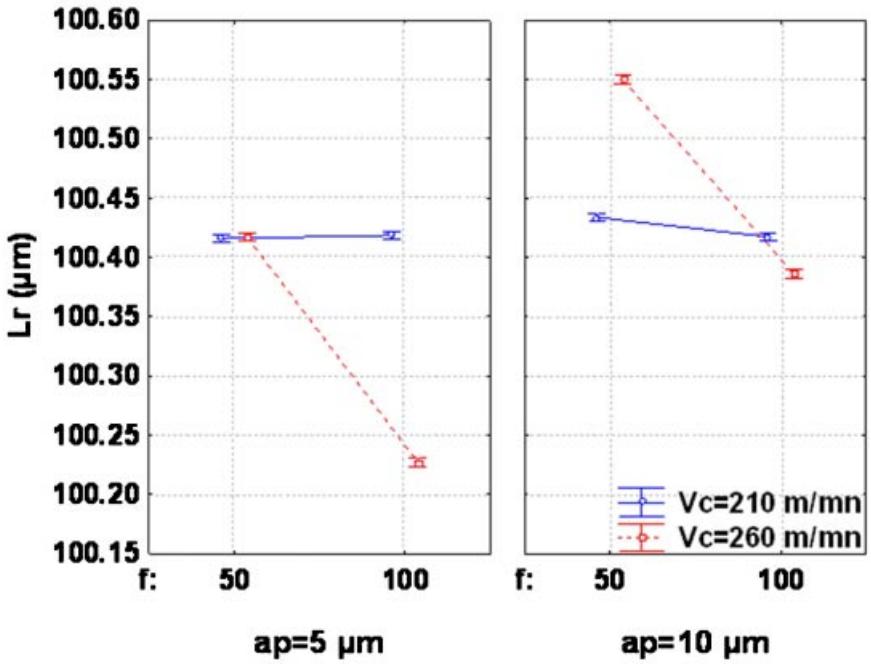

Fig. 7. Interaction effects for profile length ratio Lr.

From Figure 8, a regular surface corresponding to a low profile length ratio Lr (Lr = 100.23%) is clearly distinguished from an irregular surface corresponding to a profile length ratio Lr (Lr = 100.42%), whereas the roughness average Ra values are practically identical. This analysis based on two relevant parameters allows us to qualify different morphologies of quite similar surfaces.

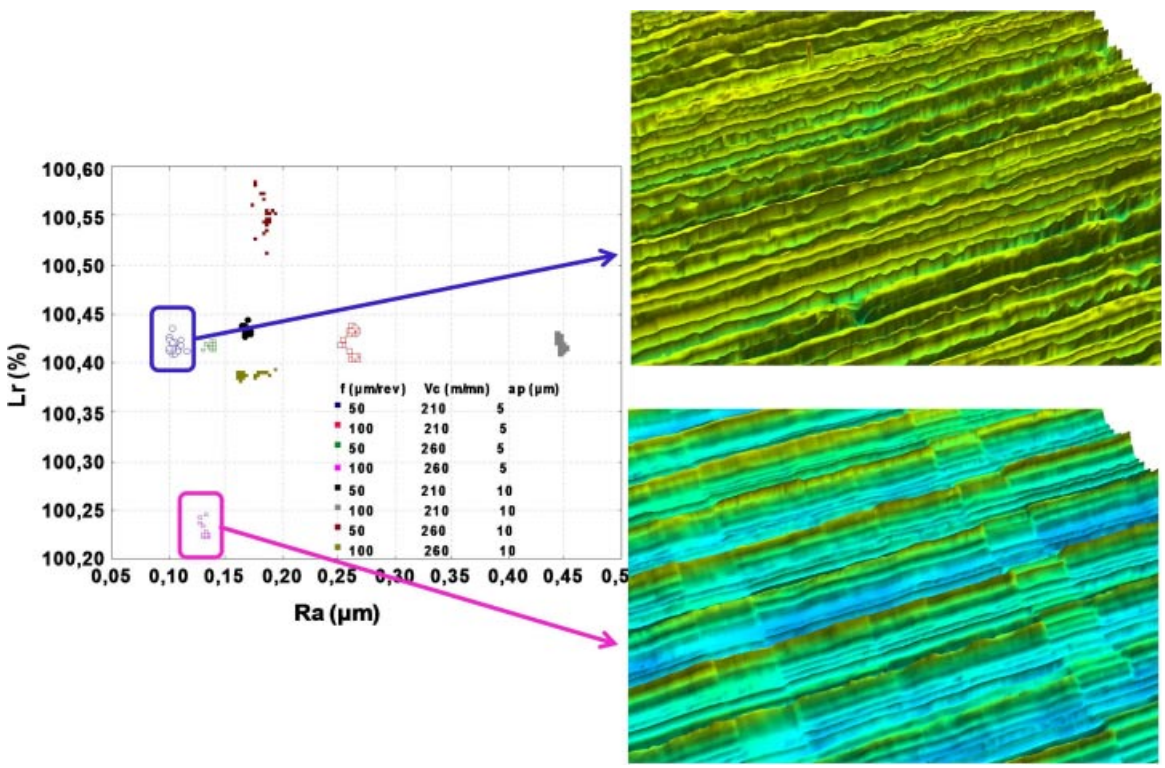

Fig. 8. Morphological analyze of surfaces with a relevant pair of roughness parameters.

Conclusion

An original method was proposed to choose the relevant pair of roughness parameters (Lr, Ra) which best discriminates the effect of cutting parameters (Vc, f, and ap) on surfaces obtained by PHT.

The use of pairs of roughness parameters (Lr, Ra) allows us to classify surfaces which cannot be distinguished by only one parameter: low profile length ratio Lr (Lr = 100.23%) is clearly distinguished from an irregular surface corresponding to a profile length ratio Lr (Lr = 100.42%), whereas the roughness average Ra values are nearly identical.

This methodology can help the researcher to exclude irrelevant roughness parameters and find a set of parameters that are really discriminant to characterize the surface properties from which can be extract those that get a real physical meaning.

Complementary studies on surface integrity with regard to a specific application (optical quality, fatigue, wear, etc.) will be investigated to identify the optimum surface.

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