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A Proposition for New Quality 3D Indexes to Measure Surface Roughness

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Abstract

The average absolute roughness S_a presented in ISO 25178, commonly used in the industry, is not a reliable discriminator of different surface texture types. This paper presents new quality indexes for a 3D characterization of surface texture of diamond cut die inserts used for injected plastic optics in lighting applications. The proposed surface quality indexes, namely floor and ceiling surface quality index ($FSQI, CSQI$) were tested on nineteen different die insert samples. The results of the analysis demonstrate that $FSQI$ and $CSQI$ provide a better understanding and improved discriminator of the texture of different high precision diamond cutting processes than S_a .

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1. Introduction

Surfaces are not perfectly smooth and always contain certain irregularities. From a tribological point of view, typically there is an optimal roughness which ensures the best application of the principles of friction, lubrication and wear between interacting surfaces in relative motion. When characterizing surface quality, one must distinguish between form, waviness and roughness. The form represents the shape of the surface (long wavelength) while the roughness represents small irregularities on top of that shape (small wavelength; micrometer scale). The roughness is an indication of the extent asperities can penetrate the opposite surface. It also influences the surface stress conditions, the lubrication regime, the friction and the wear. There are also other reasons to measure surface roughness. For example, in surface finishing, it is important to define the appearance of a surface, how smooth it is and how smooth it needs to be for different engineering applications.

Despite the breadth of available three dimensional (3D) surface topography measurement parameters, professionals continue to evaluate and characterize surface finish solely on the value of the average absolute roughness (S_a). One of the major problems with this approach is that, different profiles can still have close to S_a values [1]. Specifically, a surface with sharp spikes, deep pits, or general isotropy may all yield the same S_a. Therefore, there is a clear need for a list of significant parameters to distinguish the surface texture characteristics created by every individual machining process which also take into account the workpiece's material. The problem becomes even crucial when high precision components need to be machined for high tech applications. In 2010, Petropoulos *et al.* [2] provided an overview of the current knowledge on the association of surface texture with machining, along with recent advances in surface characterization and evaluation. In their study, various texture parameters, adopted or not by ISO standards and their distinctive impacts, were considered for their distinctive power. In 2013, Deltombe *et al.* [3] proposed a multiscale surface topography decomposition method as a new methodology to select, without preconceived notions, the 3D roughness parameters relevant for discriminating different topographies. The material used in the above study was a rolled stainless steel and machined using electrical discharge tool. In 2015, a study of variations of areal parameters on machined surfaces were reported by Pawlus *et al.* [4]. They studied tendencies of parameter variations for various types of

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measured surfaces and selected 3D parameters that were stable for surfaces, but sensitive to surface irregularities.

In the present paper, two surface quality indexes ($SQIs$) are proposed as an alternative to S_a for 3D characterization of surface texture of diamond cut die inserts used for injected plastic optics in lighting applications. The remainder of this paper is organized as follows: The proposed surface quality indexes, namely floor and ceiling surface quality index ($FSQI, CSQI$) are presented in Section 2. Section 3 describes an experimental surface analysis carried out on nineteen different manufactured die inserts followed by a comparison between S_a and the proposed $SQIs$ and a discussion of the results. Finally, a summary is provided in Section 4.

2. The proposed surface quality index

Two surface quality indexes, named Floor Surface Quality Index ($FSQI$) and Ceiling Surface Quality Index ($CSQI$), are proposed as an alternative to S_a. $FSQI$ is a 3D parameter expanded from the roughness (2D) parameter *e* proposed by Kandlikar et al. [6]. In their work, they proposed three roughness (2D) parameters for characterizing the surface roughness feature effect on fluid flow:

- Two parameters from the ASME B46.1-2002 standard [7]: The maximum profile peak height (R_p) and the mean spacing of profile irregularities (R_{sm}).
- A new 2D parameter $e = R_p + F_p$; where F_p is the floor distance to mean line as shown in Fig. 1.

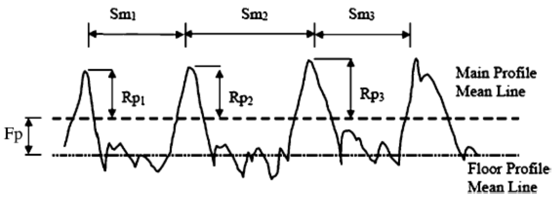


Fig. 1 Illustration of roughness 2D parameters proposed in [6]

The surface can be imagined as a two-dimensional function $Z(x, y)$ defined on the entire $\mathbb{R} \times \mathbb{R}$ domain.

Measurements taken by the confocal microscope sample this function, at discrete points in a finite area. Let Z be a real matrix of heights $Z_{i,j}$ defining the surface where $i = 0, 1, 2, \ldots N-1$ and $j = 0, 1, 2 \ldots M-1$ as presented in Fig. 2.

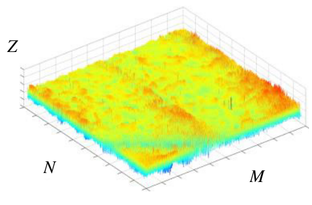


Fig. 2 Surface representation

S_a is a 3D parameter expanded from the roughness (2D) parameter R_a [5] and is presented in equation 1.

$$S_a = \frac{1}{NM}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}|Z_{i,j}| \quad (1)$$

The $Mean\ Plane$ is defined as:

$$Mean\ Plane = \frac{1}{NM}\sum_{i=0}^{N-1}\sum_{j=0}^{M-1}Z_{i,j} \quad (2)$$

Let $z_p \subseteq Z$ be a real matrix of heights $z_{p_{i,j}}$ defining the surface where $i = 0, 1, 2, \ldots n_p - 1$ and $j = 0, 1, 2 \ldots m_p - 1$ such that all $z_{p_{i,j}} = Z_{i,j}$ if and only if $Z_{i,j} < Mean\ Plane$.

The proposed $Floor\ Plane$ is then defined as:

$$Floor\ Plane = F_p = \frac{1}{n_p m_p}\sum_{i=0}^{n_p-1}\sum_{j=0}^{m_p-1} z_{p_{i,j}} \quad (3)$$

The proposed $FSQI$ parameter is defined as the distance between the $Floor\ Plane$ (F_p) and the maximum peak height (S_p) values of the surface as shown in Fig. 3.

$$S_p = \max_{i,j} Z_{i,j} - Mean\ Plane \quad (4)$$

$$FSQI = S_p + F_p \quad (5)$$

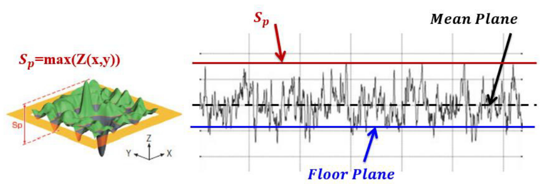


Fig. 3 Floor Surface Quality Index ($FSQI$)

Let $z_c \subseteq Z$ be a real matrix of heights $z_{c_{i,j}}$ defining the surface where $i = 0, 1, 2, \ldots n_c - 1$ and $j = 0, 1, 2 \ldots m_c - 1$ such that all $z_{c_{i,j}} = Z_{i,j}$ if and only if $Z_{i,j} > Mean\ Plane$.

The Ceiling Plane (C_p) is then defined as:

$$Ceiling\ Plane = C_p = \frac{1}{n_c m_c}\sum_{i=1}^{n_c-1}\sum_{j=1}^{m_c-1} z_{c_{i,j}} \quad (6)$$

The proposed $CSQI$ parameter represents the distance between the $Ceiling\ Plane$ (C_p) and the maximum valley depth (S_v) of the same surface as shown in Fig. 4.

$$S_v = \min_{i,j} Z_{i,j} - Mean\ Plane \quad (7)$$

$$CSQI = S_v + C_p \quad (8)$$

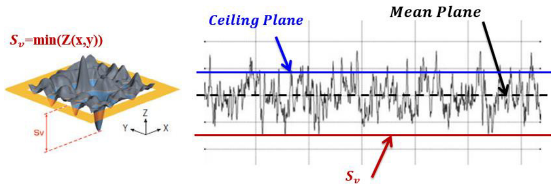


Fig. 4 Ceiling Surface Quality Index ($CSQI$)

3. Experimental procedure

An experimental procedure to validate the proposed methodology is performed in this section. A total of nineteen different die inserts surface for optical applications were manufactured for examination. The samples (X_i) represent a combination of four different materials with four different manufacturing processes. Table 1 summarizes the samples and their overall dimensions.

Table 1 Experimental matrix

Surface samples	MACHINED SAMPLES						
	Turning		Fly-cutting	Ruling		Milling	
Tool radius (μm)	40	150	100	40	150	150	500
Maximum cutting speed (m/min)	142	145	375	1.8	1.8	30	137
Pitch (μm)	4.2	8.3	6.8	4.2	8.3	8.4	15
Feed per tooth (μm)	-	-	236	-	-	8.4	15
MATERIAL: Toughmet (3AT110)	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**
MATERIAL: Nickel Phosphor	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**
MATERIAL: Acrylic (PMMA)	**A1**	**A2**		**A3**	**A4**		
MATERIAL: Aluminium (Al 1100)	**A5**						
	Example of insert (Ø10 mm, height=16 mm)						

The materials used in these experiments were: Toughmet, Nickel-Phosphor, Aluminum and Acrylic (PMMA). The different machining processes were: turning, fly-cutting, ruling and milling by a diamond cutter. Extensive details about theses processes could be found in [8]. The manufacturing process was adapted in terms of feed rate, cuter diameter and cutting speed, in order to ensure a theoretical roughness value S_a equal to 20 nm. The samples have been stored in a personalized vacuum chamber to avoid the possible oxidation in the air. The surface roughness samples were collected for analysis using a Confocal Digital Microscope Olympus LEXT OLS4100 unit provided at the École de Technologie Superieure's Products, Processes, and Systems Engineering Laboratory (ÉTS-P²SEL) in Montréal (QC), Canada. The unit is a laser scanning microscope that performs non-contact 3D observations and measurements of surface features [9]. The microscope has been checked for repeatability using the standard KNT 4070/03 ultrafine roughness measurement profile provided by HALLE Präzisions-Kalibriernormale GmbH inc [10]. In order to characterize the surface of each insert, 3D images of 400 $\mu m \times$ 400 μm were captured using an objective lens with 50× magnification. These dimensions are selected based on the recommendation for the evaluation length provided in [7]. The Olympus microscope software uses a Gaussian probability function in order to separate the waviness from the roughness (filtering). This was done using a cut-off value λ_c of 0.08 mm as recommended by the standards [7, 11].

Table 2 Repeatability test results

Repeatability of the measurement system (25 measures)				
	Standard KNT 4070/03		Measured (LEXT)	
	R_a [nm]	R_z [nm]	R_a [nm]	R_z [nm]
Max.	29.2	164.0	31.0	165.0
Mean	26.5	146.4	26.8	141.0
Min.	23.9	128.8	25.0	125.0
Repeatability of the measures taken on T1 sample (25 measures)				
	R_a [nm]	R_q [nm]		
Mean	16.0	20.0		
Standard deviation	1.7	2.2		

R_a: Arithmetical mean deviation of the roughness profile [7]
R_q: Root mean square deviation of the roughness profile [7]
R_z: Maximum height of the roughness profile [7]

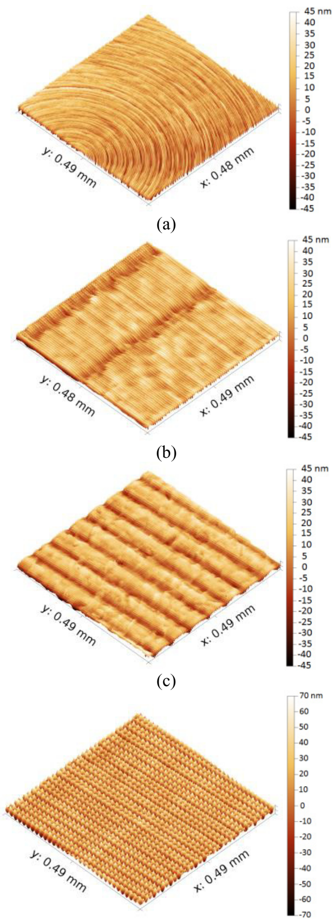


Fig. 5 3D views of the surface topography for some inserts: (a) Turning A1 (b) Fly-cutting N3 (c) Ruling T4 (d) Milling N7

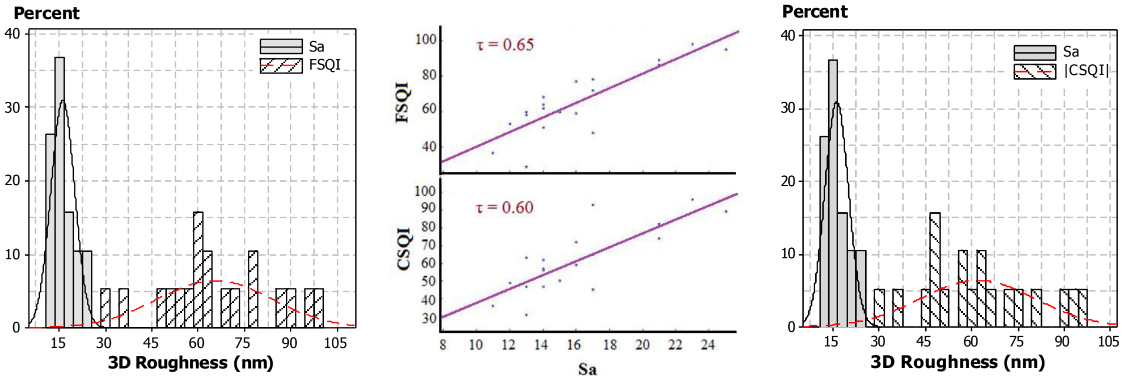
For each sample, a total of five different positions were measured; twenty five different surface profile measurement (for repeatability study) were extracted from the 3D images. Table 2 presents the repeatability study results and Fig. 5 presents 3D views of the surface topography of some samples.

The statistical comparison between S_a and both SQIs is presented in Table 3 and Fig. 6. The quartile coefficient of dispersion of both $SQIs$ is 1.5 times as high as that of S_a. In addition, the index of dispersion (VMR) shows that the distribution of Sa is under dispersed (less then 1) while that of both $SQIs$ is over dispersed (bigger than 1). On the other hand, Kendall's correlation coefficient (τ) results show that S_a is not highly correlated with both $SQIs$. All these results confirm that both $SQIs$ could be employed as improved discriminators to distinguish between different surfaces produced by different machining processes.

Table 3 Statistical comparaison between S_a and both $SQIs$

	Quartile coefficient of dispersion	Index of dispersion
	$(Q_3 - Q_1)/(Q_3 + Q_1)$	$VMR = \sigma^2/\mu$ $[nm]$
Sa	0.13	0.92
$FSQI$	0.19	5.28
$\|CSQI\|$	0.22	5.63

Q_1, Q_3: First and third quartiles respectively
σ: Standard deviation
μ: mean



(a) (b) (c)

Fig. 6 (a) Distribution plot of: S_a vs $FSQI$ (b) Kendall's corerelation plot (c) Distribution plot of: S_a vs $|CSQI|$

4. Conclusion

Two new 3D surface quality indexes (SQIs) for measuring surface roughness are proposed in this paper. An experimental surface analysis carried out on nineteen manufactured die inserts used for injected plastic optics in lighting applications was performed in order to compare the proposed SQIs related to the conventional S_a. Results confirm that S_a can be a poor discriminator of surface profile generated by different machining processes and more variability is detected and proven with both proposed SQIs. Further work will focus on quantifying the influence of the various surface texture and areal parameters generated from the experimental surface analysis, in order to develop a better understanding of the influence of the manufacturing process and their correlations on the optical performance of the injected plastic lens. Considering the resultant cost saving and better quality control, results of this study, and the upcoming ones, could have a profit influence on increasing the competitiveness of the process. The findings of the project can also be directly applied to other industries that use a diamond turning process such as aerospace and satellite application.

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