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Conformity analysis in the measurement of machined metal surfaces with Optoelectronic profilometer

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Abstract

The objective of this work is to analyse the conformity of the roughness parameters measured with an optoelectronic profilometer in order to make equivalent the measurement results with those obtained with traditional contact devices. The working parameters of the optoelectronic profilometer are based on computational filters which are controlled by software working with a 3D stratified colour map (chromatic fragmentation of the white light). However, these parameters substantially differ from the usual contact profilometers that work with 2D roughness profiles (cut-off, evaluation length, contact stylus radii). This work pursues to find the optical profilometer parameters, and its values, that ensure the best quality measurement for a wide range of machining process.

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Keywords: Optoelectronic profilometer, surface quality, roughness measurement

1. Introduction

Optoelectronic profilometers employing white light have considerable potential and measuring capabilities, allowing to create real 3D surface maps of a relatively large areas. Depending on the lens used on the profilometer,

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an area up to a few squared centimetres can be processed with a sub-micrometric scale. Thanks to these maps, surface quality parameters such us amplitude, spacing and hybrid parameters on the roughness and waviness profiles can be measured without any contact with the part. In addition this technology allows for an elevated data acquiring speed, around thousand points per second, what enable a significant reduction in the operation time and consequently in the cost of the inspection task.

In spite of the above advantages, there are still some drawbacks that need to be overcome in order to face up to the conventional methods for roughness measurement. Apart from differences in price and other commercial trades, comparison between technologies was previously studied for specific metallic materials (Durakbasa et al. (2011), Viotti et al. (2008), and Yiin-Kuen et al. (2012)) and non-metallic surfaces, Vorburger et al. (2012), but a deeper comparison for covering the most common machining processes is needed. (Demircioglu et al. (2011), and Kumar et al. (2005)), especially when a wide range of machining processes are considered. There are many parameters that have influence on the measurement; apart from the parameters related with the sensor, other optical parameters must be considered such as the light wavelength, interference phenomena, diffraction, reflection, surface optic characteristics, orientation and machining patterns, colour or brightness, similar to what happens with other optic inspection processes like laser triangulation sensors, Cuesta et al. (2009).

The objective of this work is to analyse the conformity of the roughness parameters measured with an optoelectronic profilometer in order to make equivalent the measurement results with those obtained with traditional contact devices. The working parameters of the optoelectronic profilometer are controlled by software and based on filters which are modified depending on the measurement basis, chromatic fragmentation of the white light in this case. However, these parameters substantially differ from the usual contact profilometers (cut-off, evaluation length, contact stylus radii) that work with 2D roughness profiles. Therefore, the equivalence between both optic and contact methods needs to be analysed by measuring a wide range of test parts with different surface finishes and from different machining processes. This work pursues to find the parameters, and its values, that ensure the most accurate measurement for each machining process.

Nomenclature

Ra	arithmetic average roughness parameter, in μm
LCT	cut-off length, in mm
NCT	number of cut-offs
D	scanning density, in μm
EDM	Electro-Discharge Machining

2. Methodology and Experimental Procedure

The available equipment has a singular relevance in this study because it somehow restricts or defines the methodology and the experimental design scope. The profilometer under study is a Solarius Viking that uses chromatic probes based on white light confocal technology (Fig. 1). The use of chromatic "splitting" allows for sub-division of the white light spectrum to correspond to unique Z-axis displacement levels. Each wavelength will be perfectly focused at a different Z height using the confocal principle, all out of focus light is rejected resulting in only the in-focus point been registered.

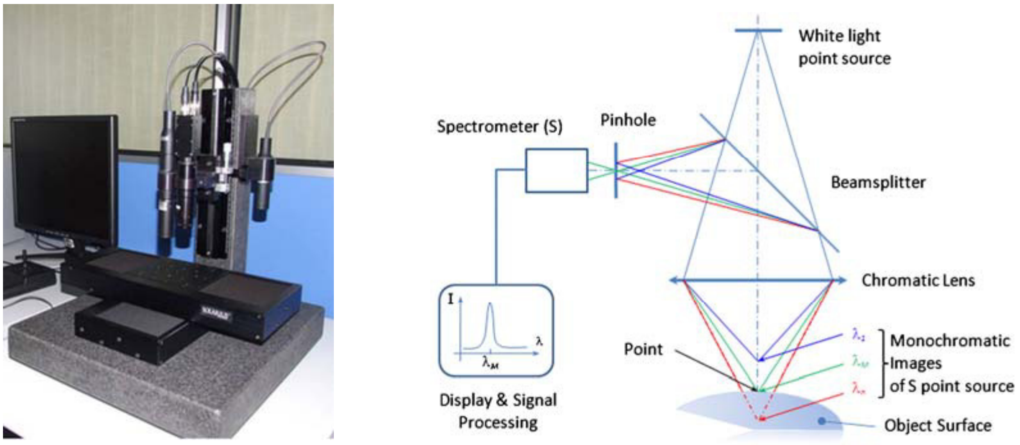

Figure 1. Image and principle of measurement of the Solarius Viking profilometer. Source: Stil S.A., Aix-en-Provence, France.

Table 1. Chromatic confocal parameters of the two sensors

Features	WLC2	WLC4
Range	300 µm	2.5 mm
Working distance	11 mm	16.4 mm
Resolution	0.012 µm	0.075 µm
Accuracy	0.06 µm	0.4 µm
Angle	± 28°	± 22°
Spot	2.6 µm	8 µm

This type of profilometers has several colour sensors with capture ranges between 110 µm and 20 mm, resolution between 0.005 µm and 0.6 µm respectively. In this case only two white light chromatic probes were available, although sufficient for the current study. These models are WLC4 and WLC2, whose main characteristics are shown in Table 1. The probe signal is initially processed by the chromatic confocal sensor CHR150 and then, the software (CHR setup utility®, STIL S.A.) calibrates and performs a previous analysis of the signal, thus obtaining a 3D chromatic map. Thereafter, the signal is filtered and finally analysed be the 3D SolarMap software.

Before comparing the measurement results of optoelectronic profilometers and contact roughness testers, a criterion for determining what is the best quality or best fit measurement must be defined. The purpose is to establish the manufacturing processes and the range of surface roughness where the best fit measurement is reached (conformance zone). In order to analyse the influence of the parameters of roughness measurement on an optoelectronic profilometer, the following methodology was carried out:

- Previous study of the optoelectronic profilometer parameters, proper optical probe selection, design of experiments for pre-classifying the parameters under study.
- Selection of roughness gauges or standards that represent significantly the majority of surface finishes that may be found in machined parts (manufacturing processes based on chip removal).
- Development of a two-step procedure: 1st) preliminary probing of the specimens in order to approximate to the optimal solution and, 2nd) in-depth search within the conformance zone of the parameters.
- Analysis of the results, establishing a complete map of the parameters and their conformance zones.

- Generation of working guidelines for measuring surface roughness with high accuracy and estimation of the measurement uncertainty associated with every surface finish, comparing it with the uncertainty of the profilometer assured by the manufacturer.

In the first and second stages optimum filter values were established for the profilometer parameters by taking into account guidelines from the equipment manufacturer as well as standards about surface quality and later by performing tests with different filter types. Thereafter, in order to extend the study to a wider range of machining processes and to a wider range of surface quality, roughness gauges of Rugotest type (TESA©) were tested, classified into roughness grades from N3 to N9 (ISO/R468 and ISO2632-1.2) and related to different machining processes, mainly metal removal processes. The different processes and range of surface finishes analysed in this work are shown in Table 2.

All these 54 gauges were measured in a controlled room, in temperature (20 °C ± 0.5 °C) and relative humidity, using an optimum sampling frequency of 300 Hz with a discrete variation of the scanning density (D) between 0.1 and 30 or 45 micrometers (depending on the process). The density is a crucial parameter directly related with the scanning speed (mm/s) and the frequency. With a few exceptions, the more accurate sensor, WLC-2, was adequate for most of the gauges of ISO roughness lower than N8 grade (Ra < 1.6 μm) whereas the gauges of ISO grades N8 and N9 required the use of WLC-4 sensor. With regard to the third stage and in order to find the parameters values that ensure the best quality measurement for all the machining process available, a definition about the best "quality of measurement" is needed. Obviously, the best quality measurements will be those that best fit (statistically) to the measurement results obtained with a contact profilometer.

Table 2. Processes and roughness gauges available

Processes	"ISO N" grade available	*Ra* (μm)
Electro-Discharge Machining (EDM)	N5-N6-N7-N8-N9	0.4 ~ 6.3
Shot-blasting (spherical grain)	N6-N7-N8-N9	0.8 ~ 6.3
Shot-blasting (sharp grain)	N6-N7-N8-N9	0.8 ~ 6.3
Free hand Grinding (flat specimen)	N6-N7-N8-N9	0.8 ~ 6.3
Shaping hand filling (straight& crossed pattern)	N6-N7-N8	0.8 ~ 3.2
Vertical face milling (frontal)	N5-N6-N7-N8-N9	0.4 ~ 6.3
Turning	N5-N6-N7-N8-N9	0.4 ~ 6.3
Horizontal face milling	N7-N8	1.6 ~ 3.2
Planing	N6-N7-N8-N9	0.8 ~ 6.3
Flat Grinding	N3-N4-N5-N6-N7-N8	0.1 ~ 3.2
Cylindrical grinding	N3-N4-N5-N6-N7-N8	0.1 ~ 3.2
Lapping	N3-N4-N5	0.1 ~ 0.4
Superfinishing (cylindrical surface)	N3-N4-N5	0.1 ~ 0.4

On the other hand, roughness gauges are classified according ISO grades that do not specify a single value for the arithmetic mean roughness (Ra) but an interval of values. For example, ISO N4 corresponds to an interval of [0.1 ~ 0.2 μm], ISO N5 corresponds to [0.2 ~ 0.4 μm], etc. This fact implies a double check; in first place, measurement results may vary quite within the interval of the ISO grade of the roughness gauge and in second place, the deviation between a series of measurements (even sampling on adjacent regions) must be low enough to consider the measurement as "best quality". The parameter values that lead to a minimum deviation will be taken as the optimum parameter values for the process. This idea that constitutes the third phase of the experimentation is subdivided in two stages (Fig. 2).

2.1. Test Design - part 1: Profilometer parameters and Conformance zone establishment

This first step starts from the previous study, so that the optimal working distances, lighting conditions, filter type depending on the process and optical sensor have been already set. In this step (Fig. 2 left), all the roughness gauges have been scanned varying the sampling density from the minimum recommended value (0.1 µm) up to a value close to the lowest possible density (45 µm). However, as only few roughness gauges allow for testing sampling densities larger than 30 µm, a final upper limit for sampling density of 30 µm was selected.

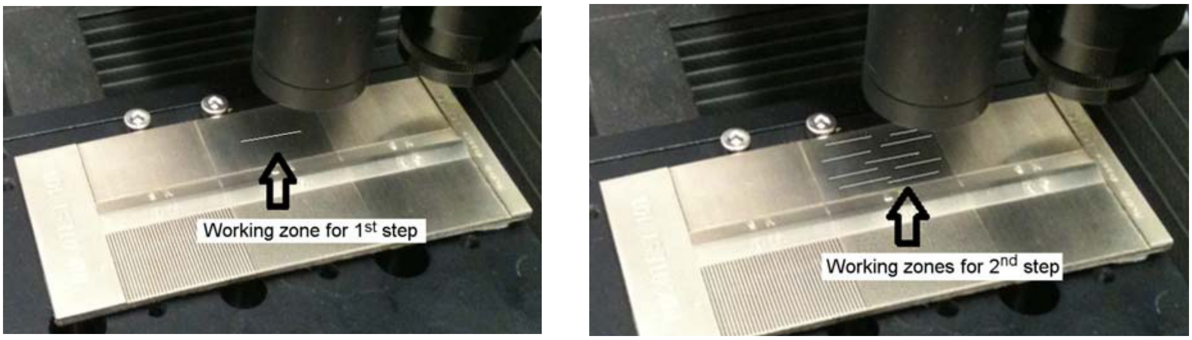

Figure 2. Roughness gauge on 1st step measurement (left) and 2nd iterations sampling (right)

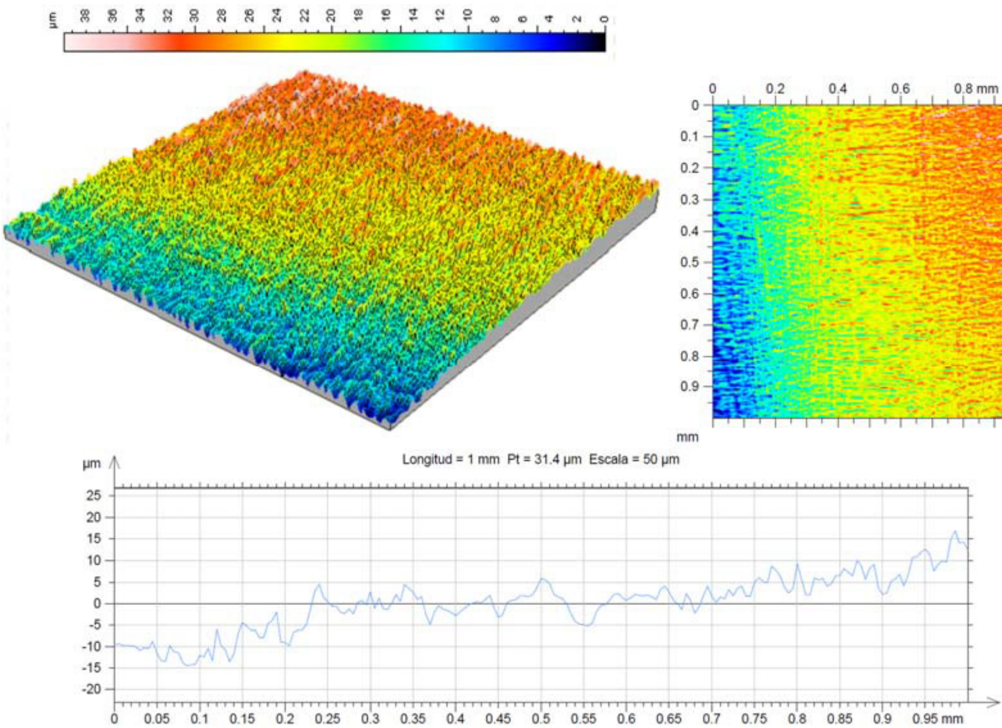

Figure 3. Chromatic 3D map and extracted 2D profile obtained from "turning rugotest" gauge

Fig. 3 shows an example of measurement of a roughness gauge that correspond to a turning process and an ISO grade N4. Measurement was carried out employing the WLC-2 sensor, applying a Gaussian filter over a sampling length of 12.5 mm, with a cut-off length (LCT) of 2,5 mm, so the number of cut-offs (NCT) were 5. At the left of

Fig. 3 the unfiltered profile can be seen whereas the figure at the right shows the profile after leveling and filtering simulating the probe ball radius. Finally, the resulting value for Ra was 0.175 µm.

2.2. Test Design - part 2: Measurement iterations and refining conformance zone

After performing the first group of tests, it is possible to set a conformance zone, that is, to establish those values of sampling density (sampling density range) that make coincide the Ra measured value with the defined interval by the ISO grade of each roughness gauge. A second iteration (Fig. 2 right), that consisted on performing more tests for each value of sampling density within the conformance zone, allowed for determining the sampling quality, i.e., the dispersion between the measured values for an specific sampling density.

It must be noted that it is impossible to scan exactly the same region with both methods, contact scanning and white light scanning. Therefore a statistical sampling is needed. In this case 10 scans were carried out for each roughness gauge, taking care that each scan were performed over an adjacent region different than the previous scanned region (Fig.2 left).

Table 3 shows a summary of the test stages performed over a Lapping ISO N5 gauge. As can be seen in the table, first group of tests include all the sampling densities possible, from 0.1 µm up to 30 µm, whereas for the second group of tests, only those densities that provided Ra values within the "conformance zone" (i.e., in concordance with the ISO grade of roughness gauge) were analysed. For this range of selected sampling densities, 10 new scans were carried out in order to obtain the standard deviation, range and mean value of Ra over the whole surface of the roughness gauge (that is, scanning different zones). Finally, it can be appreciated that the optimal scanning parameters for this process and this surface finish are sampling densities of 2, 3 or 5 µm. Among these values, the densities of 2 and 3 µm are preferred because the standard deviation of their measurement is lower (0.026µm).

Table 3. Results for 1st and 2nd test groups on ISO N5 lapping gauge (NCT = 5 mm, LCT = 0.8 mm)

	1st test		2nd test												
Scanning density *D* [µm]	*Ra* [µm] primary profile	*Ra* [µm] level & filtered	1	2	3	4	5	6	7	8	9	10	Ra Mean	Ra Std.Dev.	Ra Range
0,1	1,650	0,525													
0,2	1,490	0,514													
0,3	1,510	0,514													
0,4	1,510	0,516													
0,5	1,520	0,505													
0,7	1,330	0,478													
1	1,320	0,472	0,582	0,495	0,553	0,492	0,559	0,470	0,497	0,540	0,528	0,491	0,521	0,03681	0,112
2	**1,360**	**0,364**	**0,413**	**0,414**	**0,424**	**0,381**	**0,418**	**0,427**	**0,446**	**0,377**	**0,399**	**0,358**	**0,406**	**0,02675**	**0,088**
3	**0,913**	**0,295**	**0,380**	**0,312**	**0,357**	**0,346**	**0,351**	**0,341**	**0,385**	**0,358**	**0,331**	**0,288**	**0,345**	**0,02930**	**0,097**
5	**0,252**	**0,236**	**0,284**	**0,324**	**0,335**	**0,237**	**0,310**	**0,249**	**0,302**	**0,254**	**0,273**	**0,247**	**0,282**	**0,03490**	**0,098**
10	0,310	0,196	0,202	0,212	0,238	0,212	0,210	0,189	0,265	0,207	0,188	0,218	0,214	0,03288	0,077
15	0,170	0,154													
20	0,221	0,135													
25	0,182	0,179													
30	0,216	0,161													

3. Results and Conclusions

The methodology explained above was applied to the measurement of the 54 roughness gauges shown in table 2 that correspond to 13 different machining processes (most of them are chip removal processes) and 7 different surface finish grades (from ISO N3 to ISO N9). The test results were represented graphically (Fig. 4 and 5) for each process, for all of the sampling densities and for every surface finish available. In this type of graphs every curve represents, for the same roughness gauge, the measured Ra value obtained for the different sampling densities.

A first conclusion that can be deduced from these graphs is that a plain curve (more or less horizontal) indicates that the profilometer is able to measure the Ra value independently of the sampling density. Therefore, faster scans may be carried out with low sampling densities for the same level of accuracy. Even more, for those processes where the optimal scanning density is low (D > 15 µm, as it occurs for the ISO N8 and N9 grades of EDM gauges of Fig. 4) there is no need to test the lower values of sampling density, avoiding the typical trial&error tests that imply elevated measurement times and costs.

Finally mention that in the conformance zone, where the Ra obtained with the profilometer clearly lies within ISO grade of roughness, Fig. 4 and 5 show the standard deviation as vertical bars error. This standard deviation is calculated from the 10 iterations of the second step, performed on 10 different regions of the gauge. Again, these error bars also provide information on the scan quality; if the error bar is very small or negligible for a specific surface finish, it is likely to be measured with an optimum density and with very high accuracy (that is, with less uncertainty in the determination of Ra). On the other hand, larger values of the vertical error bar within the conformance zone indicate that the profilometer is not capable of measuring accurately the gauge roughness. In Figures 4 and 5, note that logarithmic scales both in the X axis (density) and Y axis (Ra) have been used in order to facilitate the representation. Therefore, a large error bar or a large slope indicates that the profilometer may make an unacceptable mistake, even overlap another ISO grade, as it happens with N3, N4 and N5 gauges from Superfinishing by Honing process (Fig. 5).

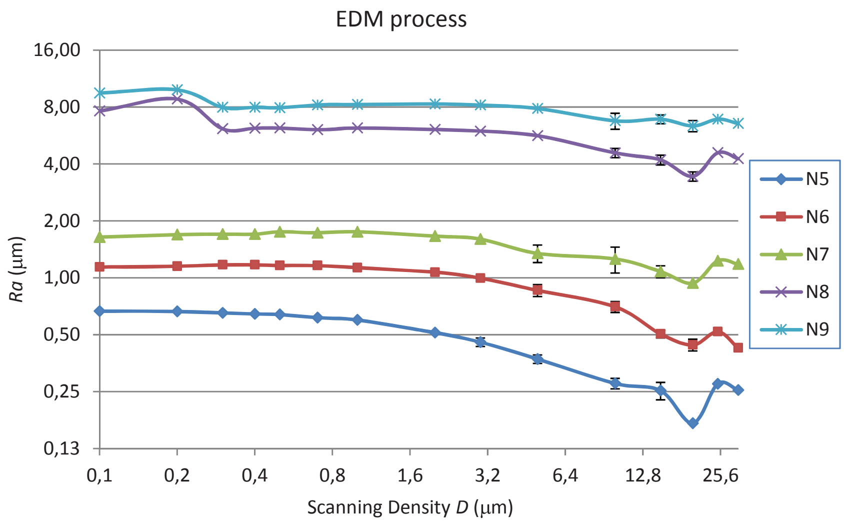

Figure 4. Measured values of Ra for different scanning density measurements over the EDM roughness gauge

The aim of these tests is to propose working guidelines for measurement of roughness with "high accuracy". With these guidelines, metrologists can take advantage of the high potential of optical profilometer as an alternative to the contact one, and with high reliability. In order to achieve this objective, a complete map with the optimum densities for each machining process and for all tested gauges was developed. Table 4 summarizes this map, which shows the density values needed for each process and surface finish, i.e., where the measured values of Ra match on both profilometers. Numbers in bold display the value of preferred scan density, meaning that they had lower density deviation. Processes that correspond to smaller ranges of optimum density, even a single value, are those with fairly flat performance curves where the standard deviations of the Ra (obtained in the second group of tests) are relatively large (Std Dev = 0.1~0.8 μm). Such is the case of specimens EDM processes, Vertical Face Milling, Planing, Shaping hand filing and, to a lesser extent, the Shot-Blasting process. On the other hand, processes with a wide range of optimum density that generate large conformance zones, correspond to decreasing curves and with lower standard deviations (Std Dev = 0.01~0.05 μm). This is the case of the finishing processes like Lapping, Grinding and Superfinishing (Honing).

4. Summary and future works

Extensive tests were carried out over parts with a wide range of surface finish (roughness). An in-depth study of the test results allowed for finding the main parameters that relates the contact profilometer measurement and the optoelectronic profilometer measurement. Operation time savings, avoiding "trial&error" tests for finding the optimum setup of a particular measurement, justifies the importance of this study.

The following survey will be to compare the values of the standard deviations between processes and between surface finishes, so the study can be extend to answer the question about what is the best process, and its best finish, that allows for the best fit with minimum error.

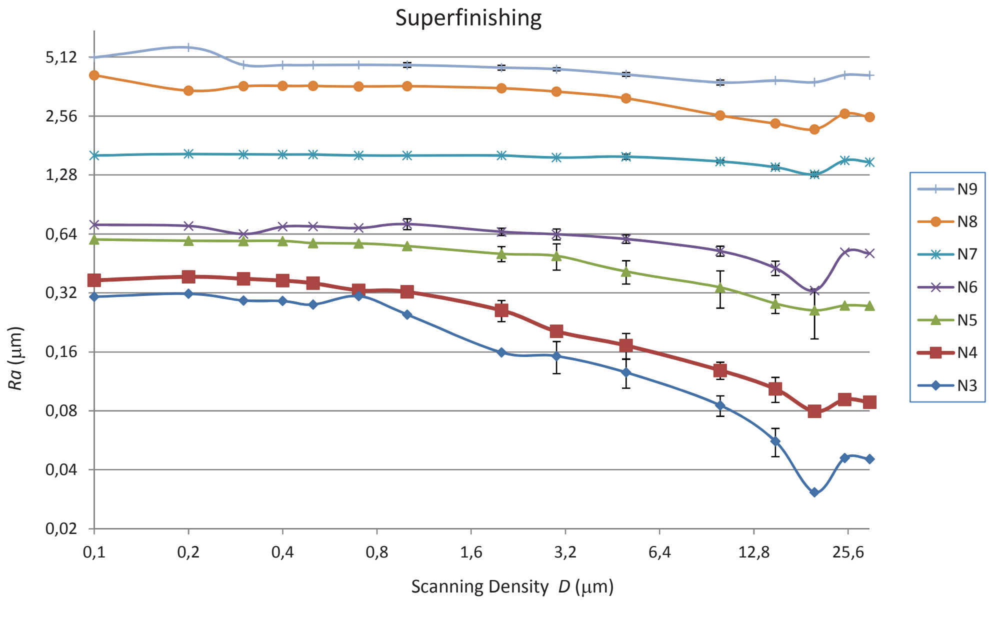

Figure 5. Measured values of Ra for different scanning density measurements over the Superfinishing (N9 to N6) and Honing (N5 to N3) roughness gauges

The ultimate objective of this knowledge is to identify the best process and surface finish to manufacture certain geometries that can be used as standard gauges for optical measurement devices like those based on laser triangulation, structured white light, or interferometers. The geometry of these standard gauges must cover not only spheres, but also (and especially) cylinders, cones and planes in order to allow the use of these geometries for calibrating multisensor Coordinate Measuring Machines, both contact and contactless

Table 4. Recommended interval values for optimum scanning density

Processes	"ISO N" grade						
	3	4	5	6	7	8	9
EDM			5-**10**	**15**	**15**	**20**	15-**20**
Shot-blasting (spherical grain)				**5**-10-15	**20**	15-**20**	**15**-20
Shot-blasting (sharp grain)				**10**-15	**25**	10-**15**-20	**15**-20
Shaping hand filing (str.&cross.)				**10**	**15**	**20**	
Vertical Face milling			**3**-5-10	3-**5**-10	5-**10**	10-**15**	10-**15**
Turning			1-**2**-3	5-**10**	5-**10**	1-2-3-**5**	1-2-3-**5**
Horizontal Face milling					5-10-**15**	3-5-10-**15**	
Planing				15-**20**	1-2-3-5-**10**	5-**10**-15	**5**-10
Free hand Grinding				1-2-3-**5**-10	5-**10**-15-20	**5**-10-15	5-**10**-15
Flat Grinding (CNC)	**3**-5-10-15	2-3-5-**10**-15	10-**15**-20	3-5-**10**-15-20	**5**-10-15	5-10-**15**-20	
Cylindrical Grinding	15-20-25-**30**	2-3-5-10-**15**	2-3-**5**-10	3-5-10-**15**	5-**10**-15-20	10-15-**20**	
Lapping	3-5-**10**-**15**	3-5-**10**-**15**	1-**2**-**3**-**5**-10				
Superfinishing	3-5-**10**-**15**	**3**-**5**-10-**15**	**5**-**10**-**15**-20	1-**2**-**3**-**5**-10-15	5-**10**-15-20	5-**10**-15-20	1-2-**3**-**5**-10

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