Proceedings of the World Congress on Engineering 2014 Vol II,
WCE 2014, July 2 - 4, 2014, London, U.K.

Non-Contact Measurement of Surface Roughness by Conoscopic Holography Systems

Sabino Mateos, Gonzalo Valiño, Pablo Zapico, Pedro Fernández and José Carlos Rico

Abstract—**Roughness measurement is particularly important in the precision industry where requirements of surface finishing are more demanding every day. In order to avoid the common disadvantages of contact profilometers, non-contact methods for roughness measurement are currently sought which be faster and more precise. In the present work, a roughness measuring system based on commercial Conoscopic Holography (CH) sensor is proposed. Tests have been performed on roughness specimens corresponding to four different machining processes: face milling, turning, surface grinding and cylindrical grinding. The experimental results demonstrate the capability of the CH technique for roughness measurement within the ranges N4–N10.**

Index Terms—**Conoscopic holography, non-contact measurement, surface roughness**

I. Introduction

ROUGHNESS measurement is particularly important in the precision industry where requirements of surface finishing are more demanding every day.

The measurement of roughness can be performed by means of contact or non-contact methods. Contact methods use a touch probe which is slipped on the surface to be measured. The waviness are captured by an electronic transducer which is able to calculate the parameters of surface roughness, such as average roughness *Ra*, root mean square roughness *Rq*, maximum peak-to-valley height *Rt*, etc. Precision stands out among the advantages of these methods, which are commonly used as reference of measurements when other methods are employed. Nevertheless, the main drawbacks of contact methods are the low inspection speed and the feasible damage caused to the measured surface, especially in soft materials. In addition, stylus wear may cause a lack of precision in the measurement carried out.

In order to avoid these disadvantages, non-contact methods for roughness measurement are sought which additionally have to be non-destructive, faster and more precise, if possible, than contact methods. Numerous publications refer to the application of different measurement tools based on optical techniques [1]–[3]. An optical method based on laser scattering and optical triangulation for measurement of surface roughness and micro-displacement measurement was proposed by Wang et al. [4]. The method and the basic instrumentation design were described and the validity of the principle demonstrated by experimental evaluations. Another non-contact roughness measurement method based on laser speckle was reported in [5] and [6]. The experimental results showed that the proposed method was valid in a certain range in contrast with results measured by means of a profilometer.

In some cases, the measuring system has been integrated in a production machine. Such are the cases of a confocal microscope, installed by Minioni and Cavalli [7] onto a machining centre to measure roughness of high precision automotive components, or a computer vision system used by Shahabi and Ratnam to appreciate roughness of rotational workpieces on a lathe [8].

In the present work, a roughness measuring system based on commercial Conoscopic Holography (CH) sensor is proposed. Tests have been performed on roughness standard specimens corresponding to four different machining processes: face milling, turning, surface grinding and cylindrical grinding. Comparison carried out between the experimental results and the theoretical values certified for the specimens demonstrates the capability of the CH technique for roughness measurement within the ranges N1–N10.

II. Conoscopic Holography Systems

A. *Conoscopic Holography Equipment*

Conoscopic Holography (CH) is an interferometric technique based on the double refractive property of birefringent crystals. It was first described by Sirat and Psaltis [9] and patented by Optimet Optical Metrology LTD. When a polarized monochromatic light ray crosses the crystal, it is divided into two orthogonal polarizations, the ordinary and extraordinary rays, which travel at different speeds through the crystal. The speed of the ordinary ray is constant. However, the speed of the extraordinary ray depends on the angle of incidence. In order to make both rays interfere in the detector plane, two circular polarizers are placed before and after the crystal. The interference pattern obtained in the detector has a radial symmetry, so all the information is contained in one radius. Therefore, given an appropriate calibration, it is possible to calculate the original distance to the light emitting point from the fundamental frequency of one of the signal rays.

Manuscript received March 14, 2014; revised March 25, 2014. This work is part of a research supported by the Spanish Ministry of Economy and Competitiveness and FEDER (DPI2012-30987) and the Regional Ministry of Economy and Employment of the Principality of Asturias (Spain) (SV-PA-13-ECOEMP-15).

S. Mateos is a Professor (e-mail: sabino@uniovi.es).
G. Valiño is a Professor (e-mail: gvr@uniovi.es).
P. Zapico is a Research fellow (e-mail: pablozapicog@gmail.com).
P. Fernández is a Lecturer (e-mail: pedrofa@uniovi.es).
J. C. Rico is a Full Professor (e-mail: jcarlosr@uniovi.es).
The corresponding address for all authors is: Department of Manufacturing Engineering, University of Oviedo, Campus de Gijón, 33203 Gijón, SPAIN.

Malet and Sirat [10] stated that the performance of a conoscopic system can be described by the quartet of precision, depth of field, speed and transverse resolution. Furthermore, many advantages of CH compared to laser triangulation have been reported by Sirat et al. [11] such as better accuracy and repeatability (up to 10 times for a given depth of field), good behaviour for a wide variety of materials (even for translucent materials) and suitability of digitizing sloped surfaces up to 85º. Another practical characteristic is that a single conoscopic sensor can be combined with different lenses to be adapted to various depths of field (0.6 mm up to 120 mm) with accuracy from less than 1 µm up to 60 µm, respectively. Finally, being a collinear system allows for accessing to complex geometries such as holes or narrow cavities, by using simple devices for light redirection.

These characteristics have led CH to be considered in a wide variety of fields, including quality assessment, reverse engineering and in-process inspection.

B. *Configuration Parameters of CH Systems*

There are two main setting parameters in a CH sensor:

1) *Working Frequency* (*F*) represents the data acquisition rate and, depending on the type of sensor, it can be set up to a maximum of 9000 Hz. The manufacturer of the sensor recommends using the highest possible *F*, since measurement error can be minimized by better use of averaging filters.
2) *Power Level* (*P*) represents the value for the laser beam energy and can be set up in a range from 0 to 4096.

For a given frequency *F*, the value of power *P* has to be adjusted so that a proper amount of energy reaches the sensor. For a low level of *P*, the amount of light reflected off the surface that reaches the CCD may be insufficient and the quality of the measurement will drop. On the other hand, high values of *P* may yield a saturated signal and the CH sensor will send an out-of-range message, which indicates that the measurement values are not reliable.

Apart from these parameters, the CH systems commonly use the Signal-to-Noise Ratio (SNR) as an indicator for describing the quality of a digitized point-cloud. It is calculated by comparison of the peak power value used for the measurement with the whole signal power, which includes signal noise. SNR may range from 0% to 100% and it is commonly assumed that the highest the SNR, the highest the accuracy of measurement. SNR values below 30% indicate non-reliable measurements, whereas values above 50% yield accurate measurement results.

Additionally, the indicator *Total* is provided by the sensor control software. According to the manufacturer, *Total* is proportional to the area limited by the signal envelope and it increases as signal intensity does [12]. Acceptable values for *Total* should be between 2000 and 16000.

III. Experimental Design

A. *Scanner and CH Sensor*

The tests described in this study have been performed using a conoscopic sensor Optimet Conoprobe Mark 10 with a distortion free aspheric lens of 25 mm focal length and 1.8 mm of working range (WR). This is a point-type sensor, thus each reading provides the value of distance between the transmitter and the projection of the laser beam onto a material surface. The visible light source is a 655 nm laser diode. This sensor is provided with an auto-exposure feature enabling real time adjustment to various surface colours and reflection levels (black, white, shiny or absorbent). Table I shows the main sensor characteristics.

TABLE I
Characteristics of Mark 10 Conoscopic Sensor

Property (Lens 25 mm)	Value
Dimensions (L × W × H) (mm)	164 × 79 × 57
Weight (g)	740
Measuring frequency, F (Hz)	50/9000
Working range, WR (mm)	1.8
Stand-off (mm)	18
Static resolution (µm)	<0.1
Precision (µm)	<3
Reproducibility 1σ (µm)	<0.4
Angular coverage (º)	170

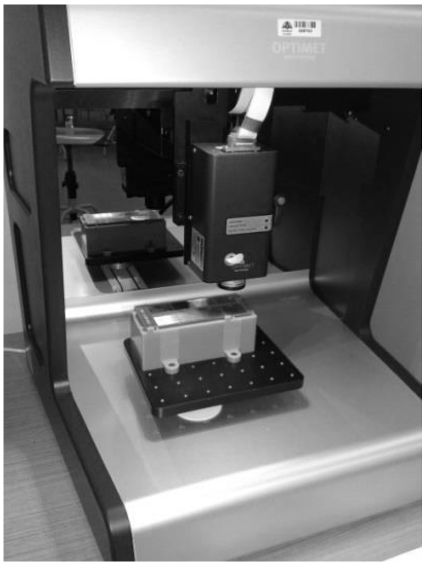

Fig. 1. General view of Conoscan 4000 3D measurement scanner. Maximum travel speed: 50 mm/s; minimum XY step size: 3 µm; scanning area: 160 mm × 150 mm.

A complete digitized surface requires a relative displacement between the sensor and the roughness specimens. A 3D high precision measurement scanner named Optimet Conoscan 4000 was used for this purpose (Fig. 1). The equipment is controlled by means of a software application which allows for adjusting the measurement parameters of the sensor as well as selecting the digitizing area on the roughness specimen and to visualize the results.

B. *Roughness Specimens*

Four roughness specimens of Rugotest type (TESA©) were tested, classified into roughness grades from N1 to N10 (ISO/R468 and ISO2632-1.2) and related to the processes of turning (N5 to N10), face milling (N5 to N10), surface grinding (N1 to N8) and cylindrical grinding (N1 to N8). For each grade, the manufacturer provides parameters *Ra*, *Rmax* and *Rz* measured with a mechanical profilometer using an analog type 2RC filtering process. The parameter *Rmax* is designated in current standards as *Rt*.

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

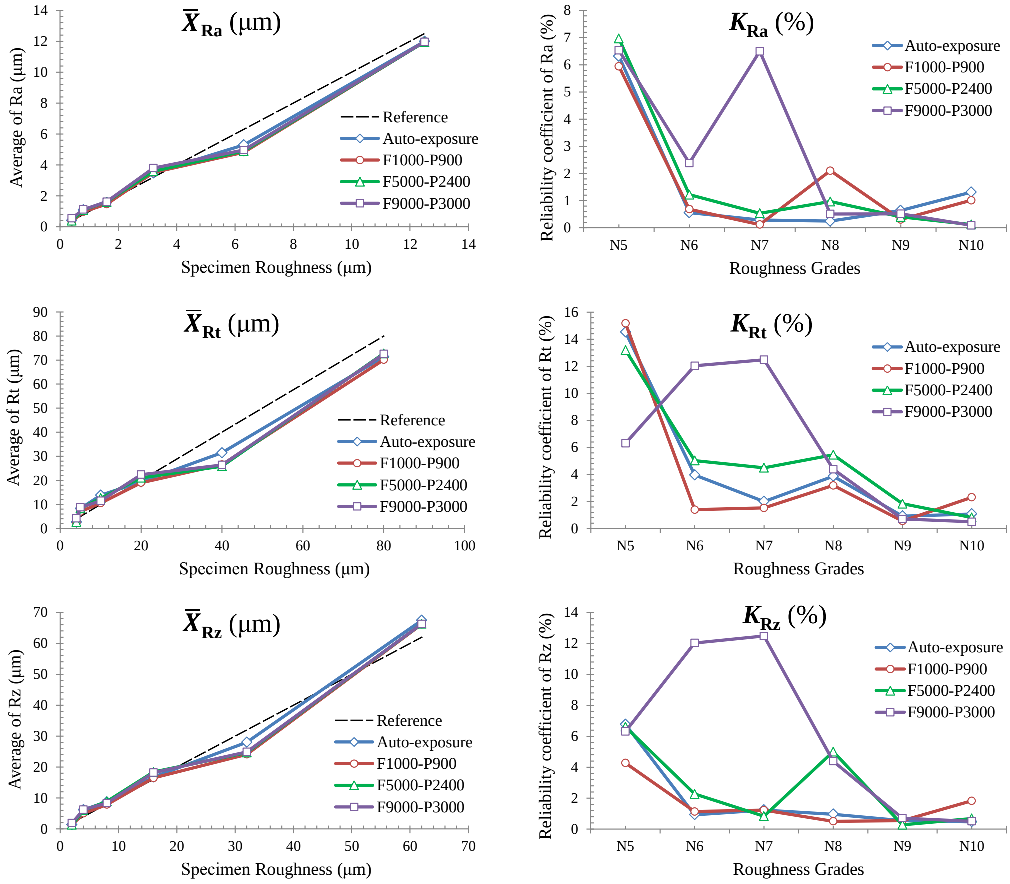

Fig. 2. Values of indicators $\bar{X}$ and K obtained for *Ra*, *Rt* y *Rz* corresponding to the face milling roughness specimen

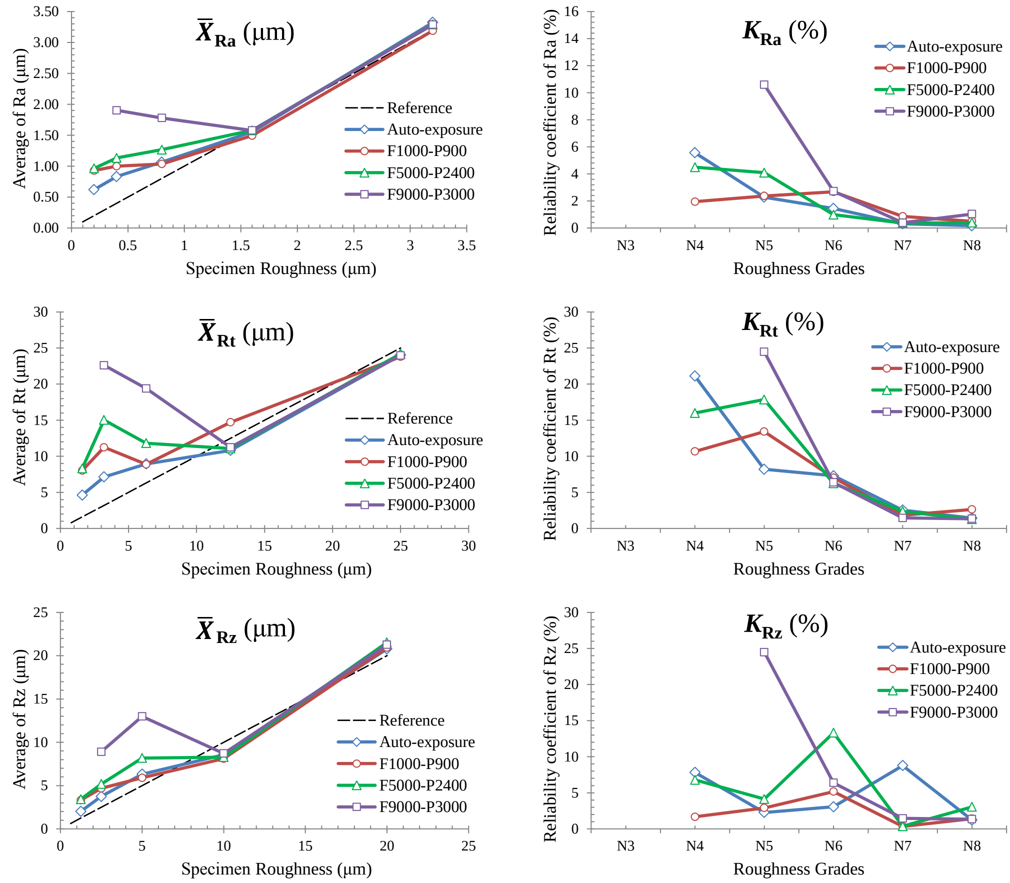

Fig. 3. Values of indicators $\bar{X}$ and K obtained for *Ra*, *Rt* y *Rz* corresponding to the surface grinding roughness specimen

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

C. Measurement Procedure with the CH Sensor

As an optic technique, CH is affected by factors such as surface slope and its position within the working range. In order to avoid these factors of influence, the roughness specimens were located on a test bench taking care that the test surfaces stayed parallel to the XY plane of the Conoscan 4000 scanner at distance equal to the sensor stand-off. The main directions of the test specimens were also aligned with the machine X-Y axes.

A rectangular region of 15 × 0.1 mm was digitized on each roughness grade area of the specimen. Measurement was carried out continuously starting from a corner, moving along the larger dimension and repositioning across for performing the following pass. Density of points captured was 1.5 µm in each direction.

Measurement of each roughness specimen was repeated five times under four different combinations of frequency and power. Three of these combinations were (*F*1000, *P*900), (*F*5000, *P*2400), (*F*9000, *P*3000) and the fourth was performed under the *auto-exposure* mode of the sensor [12]. This is an adjustment of exposure time carried out automatically by the sensor, according to the material optical properties, with the aim of assuring that the *Total* indicator is between the appropriate limits.

IV. Analysis of Results

Data collected in the digitizing processes were visualized by means of TrueMap software whereas the roughness profiles were analysed according to the ISO 4287:1997 and ISO 4288:1996 standards by means of TrueSurf application.

Since the objective of this work is to compare the measurements carried out by the CH sensor with the reference values provided by the roughness specimens, similar filtering conditions to those described in Section III.B have been used. Recommendations of the ISO 4287:1997 standard have been followed to determine the appropriate evaluation length of roughness (*ln*) and the profile filters (λc and λs).

The analysis of results has been performed by means of the average value ($\bar{X}$) and the reliability coefficient (K) calculated for the roughness parameters *Ra*, *Rt* and *Rz* corresponding to the five trials and each combination of *F* and *P*. The dispersion coefficient (K) is defined as follows:

$$K = \frac{\sigma}{\bar{X}} \times 100 \qquad (1)$$

Fig. 2 shows the values of $\bar{X}$ and K obtained for roughness parameters *Ra*, *Rt* and *Rz* with respect to the reference values of the milling specimens.

The graphs of $\bar{X}$ show the low influence of the CH adjustment parameters *F* and *P* on the measurement of different roughness parameters, regardless of the roughness grade considered. It is also observed that the values got for the three roughness parameters are very close to those of reference provided by the roughness specimens, especially for the *Rz* parameter.

Furthermore, the graphs of coefficient K for all roughness parameters show that the greatest dispersion of measurements is met at low roughness values, especially for N5 and N6. For the rest of roughness grades, dispersion decreases for all combinations of *F* and *P*, except for (*F*9000, *P*3000). An irregular variation of dispersion takes place in this case even for intermediate roughness grades (N6 and N7). Therefore, the combination (*F*9000, *P*3000) is only recommended for measuring roughness grades between N8 and N10, whereas other combinations can be used to measure roughness in a wider range (N6 to N10), in which low measurement dispersion is met.

Fig. 3 and Fig. 4 show the results obtained for the roughness specimens of surface grinding and cylindrical grinding processes (N1 to N8). It can be observed that the CH sensor was unable of capturing data for grades below N4 in the case of surface grinding, and below N5 in cylindrical grinding. The best results were achieved in both processes for grades N7 and N8. It is also notable a greater influence of parameters *F* and *P* on the results of $\bar{X}$ for the lowest roughness values. The highest measurement dispersion is also met for these low roughness grades.

In the case of surface grinding, the combination (*F*9000, *P*3000) provides the worst values of *Ra*, *Rt* and *Rz* and also offers the greatest dispersion of measurements. Therefore, this combination shall not be suitable for measuring roughness in this process below N7. With reference to cylindrical grinding, the combination (*F*9000, *P*3000) does not offer the worst results for indicator $\bar{X}$ but dispersion in this case is also pronounced, especially for parameters *Rt* and *Rz*. The combination (*F*1000, *P*900) neither yields good results, with unsteady values in grades below N7 and great dispersion in *Rt* measurements.

Fig. 5 represents the values of $\bar{X}$ and K for the roughness parameters *Ra*, *Rt* and *Rz* with respect to the reference values of the turning specimens.

The graphs of $\bar{X}$ show the low influence of the CH adjustment parameters *F* and *P* on the measurement of different roughness parameters, regardless of the roughness grade considered. Compared to the reference values provided by the turning specimen, measurements of *Ra* are fairly close whereas the parameters *Rt* and *Rz* have remarkable deviations.

If dispersion coefficients are analysed, it can be noticed the low values of K_{Ra} for roughness grades above N7, especially in the combinations (*F*1000, *P*900) and (*F*5000, *P*2400). Nevertheless, since values of $\bar{X}_{Ra}$ for N7 move away the reference values, only the results for N8 should be acceptable.

In the case of K_{Rt}, irregular values of this indicator are observed concerning all the roughness grades and all the combinations of *F* and *P* tested, which shows the low measurement reliability of parameter *Rt*.

The coefficient K_{Rz} meets low dispersion for all grades, except for N7 measured under the combinations (*F*1000, *P*900) and (*F*5000, *P*2400). This allows for assuring the reliability of the *Rz* parameter measurement, except for those conditions.

V. Conclusions

In this work, the application of a conoscopic holography system has been analysed for roughness measurement.

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

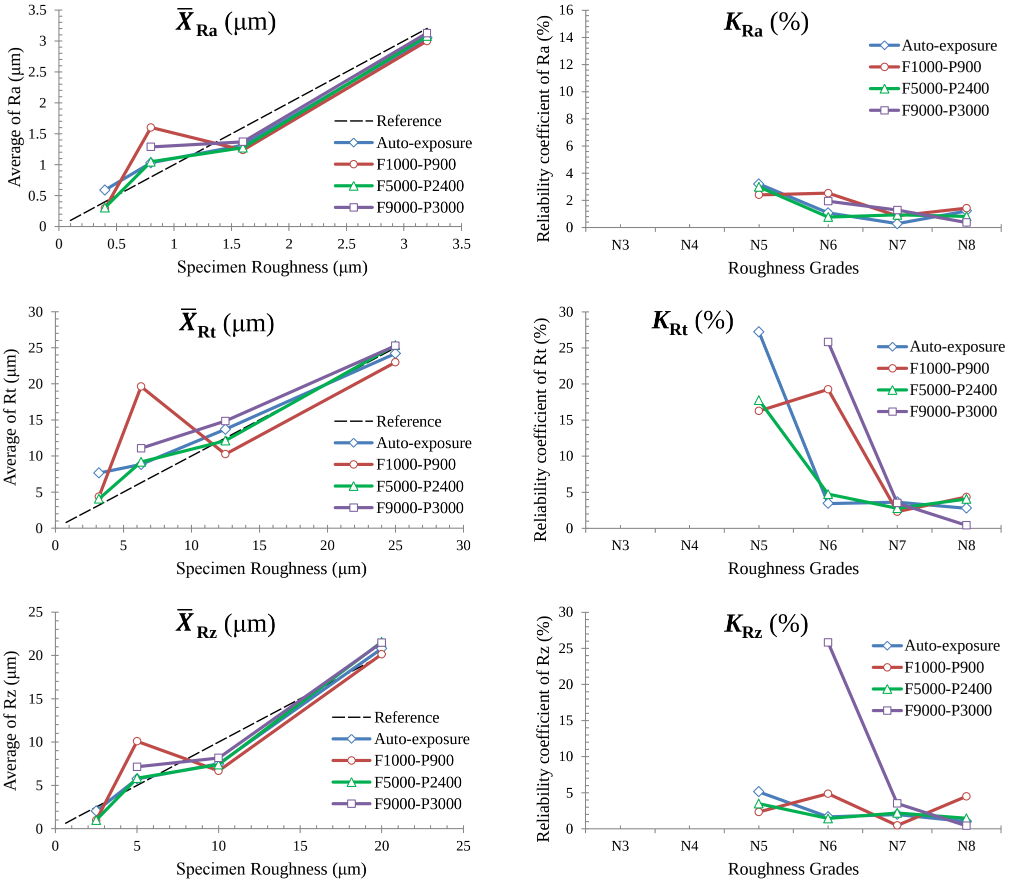

Fig. 4. Values of indicators $\bar{X}$ and K obtained for Ra, Rt y Rz corresponding to the cylindrical grinding roughness specimen

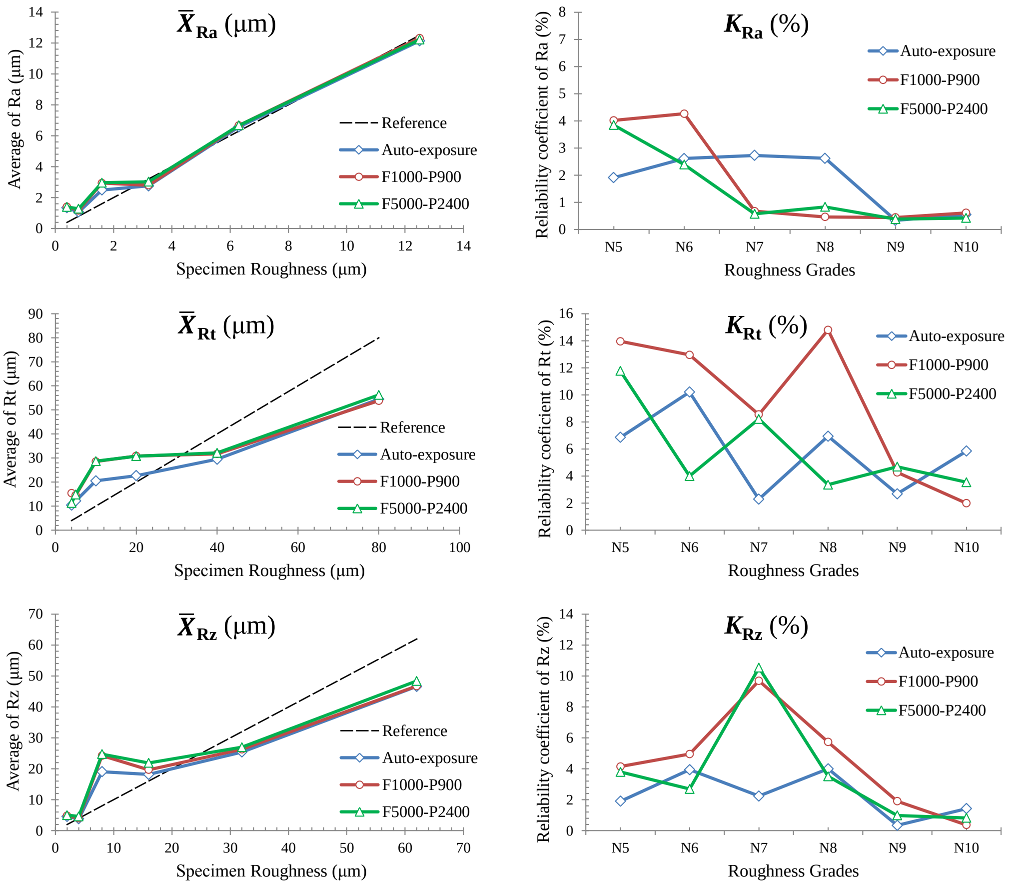

Fig. 5. Values of indicators $\bar{X}$ and K obtained for Ra, Rt y Rz corresponding to the turning roughness specimen

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

For this purpose, various specimens have been tested for roughness grades in the range N1 to N10, concerning four machining processes: face milling, turning, surface grinding and cylindrical grinding.

The tests have been performed by means of a CH Mark 10 sensor installed onto a 3D high precision scanner (Conoscan 4000) under different combinations of the sensor adjustment parameters (F and P). In order to examine the validity of measurements, each test was repeated five times under the same conditions of F and P. The roughness parameters measured have been *Ra*, *Rt* and *Rz*. Two indicators have been used to analyze the behavior of the measuring CH sensor: the average value of roughness parameters ($\bar{X}$) and the respective dispersion coefficient (K).

Indicator $\bar{X}$ is used to compare the values measured by the CH sensor under different combinations of F and P with the reference values related to the roughness specimens. Likewise, indicator K represents the variation of measurements among the different repetitions of the tests and it shows the reliability of results.

The analysis of results confirms the capability of the CH sensor for surface roughness measurement in the processes tested under the following conditions:

1) Face milling process: all the combinations of F and P are feasible for roughness measurement of grades in the range N6 to N10, except for the combination (F9000, P3000), which should only be used for grades above N8.
2) Turning process: under the testing conditions, it has not been possible to meet reliable values for any of the three roughness parameters measured. The lack of results is directly related to the shiny appearance of the roughness specimen, which has a negative influence on the behaviour of any optical measurement system.
3) Surface and cylindrical grinding processes: all the combinations of F and P are feasible for roughness measurement of grades above N7. Below this grade, the difference between the roughness parameters and the reference values increases. Roughness was unfeasible to be measured below N4 in the case of surface grinding and below N5 in cylindrical grinding.

With the aim to improve the results, it is suggested as future work the application of filtering parameters of the roughness profile different of those recommended in the ISO standards for contact profilometers. Moreover, it is also proposed to extend the study by using more sensor adjustment combinations (F, P) as well as lenses with different depth of field.

REFERENCES

[1] R. J. Hocken, N. Chakraborty and C. Brown, "Optical Metrology of Surfaces," *CIRP Annals – Manufacturing Technology*, vol. 54, no. 2, pp. 169–183, 2005.

[2] X. Xu and H. Hu, "Development of Non-contact Surface Roughness Measurement in Last Decades," *International Conference on Measuring Technology and Mechatronics Automation*, vol. 1, pp. 210-213, 2009.

[3] H. Schwenke, U. Neuschaefer-Rube, T. Pfeifer and H. Kunzmann, "Optical Methods for Dimensional Metrology in Production Engineering," *CIRP Annals – Manufacturing Technology*, vol. 51, no. 2, pp. 685-699, 2002.

[4] S. H. Wang, C. J. Tay, C. Quan, H. M. Shang and Z. F. Zhou, "Laser integrated measurement of surface roughness and micro-displacement," *Measurement Science Technology*, vol. 11, no. 5, pp. 454–458, 2000.

[5] X. Xu, "Non-contact Surface Roughness Measurement Based on Laser Technology and Neural Network," in *Proc. of the IEEE International Conference on Mechatronics and Automation*, Changchun, 2009, pp. 4474-4478.

[6] S. L. Toh, C. Quan, K. C. Woo, C. J. Tay and H. M. Shang, "Whole field surface roughness measurement by laser speckle correlation technique," *Optics and Laser Technology*, vol. 33, no. 6, pp. 427–434, 2001.

[7] U. Minoni and F. Cavalli, "Surface quality control device for on-line applications," *Measurement*, vol. 41, no. 7, pp. 774–782, 2008.

[8] H. H. Shahabi and M. M. Ratnam, "Noncontact roughness measurement of turned parts using machine vision," *International Journal of Advanced Manufacturing Technology*, vol. 46, no. 1-4, pp. 275–284, 2010.

[9] G. Sirat and D. Psaltis, "Conoscopic Holography," *Optics Letters*, vol. 10, no. 1, pp. 4-6, 1985.

[10] Y. Malet and G. Y. Sirat, "Conoscopic holography application: multipurpose rangefinders," *Journal of Optics*, vol. 29, no. 3, pp. 183–187, 1998.

[11] G. Y. Sirat, F. Paz, G. Agronik and K. Wilner. Conoscopic systems and conoscopic holography. Laboratory for CAD & Lifecycle Engineering. Faculty of Mechanical Engineering, Technion-Israel Institute of Technology. [Online]. Available: http://mecadserv1.technion.ac.il/public_html/IK05/Sirat_9375.pdf

[12] Optimet Manual P/N 3J06009. (2014, Jan 26). OEM Manual for Optimet's Mark10 (version 1) [Online]. Available: http://www.optimet.com/register_files/Ethernet-Probe-Manual.pdf