Validation of in-line surface characterization by light scattering in Robot Assisted Polishing

Pilny, Lukas; Bissacco, Giuliano; De Chiffre, Leonardo

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L. Pilný, G. Bissacco and L. De Chiffre
Department of Mechanical Engineering, Technical University of Denmark,
Produktionstorvet, Building 427A, 2800 Kgs. Lyngby, Denmark
lupi@mek.dtu.dk

Abstract: The suitability of a commercial scattered light sensor for in-line characterization of fine surfaces in the roughness range Sa $1 - 30$ nm generated by the Robot Assisted Polishing (RAP) was investigated and validated. A number of surfaces were generated and directly measured with the scattered light sensor on the machine in a shop floor environment. Scattered light roughness measurements of the whole surfaces were performed to investigate the measurement method suitability for 100% quality control. For comparison, the surfaces were measured with reference optical instruments in laboratory conditions. Comparison of the scattered light measurements results taken on the machine with the reference optical roughness measurements taken in laboratory demonstrate the capability of the scattered light sensor for robust in-line surface characterization. This allows for the RAP process control by proper process endpoint detection in a multi-step polishing sequence. The measurements of the whole polished surfaces demonstrate improved reliability of the measurements with fast measurement rate, well suitable for cost- efficient 100% quality assurance.
Keywords: Surface roughness, in-line measurement, light scattering, robot assisted polishing

1. INTRODUCTION

Robot Assisted Polishing (RAP), a system developed and patented by the company Strecon A/S, provides for automated, robust and repetitive generation of polished surfaces down to mirror like surfaces (Hansen et al. 2011). The system is currently semi-automatic, with the process control based on offline roughness measurements, which sometimes necessitate removal of the part from the machine tool, and decision of a skilled operator. The ambition is to develop a fully automated RAP system by implementation of intelligent process monitoring and control. In-process sensing techniques will indicate the polishing step completion (Pilný et al. 2013) and in-line characterization of the surface texture will enable to control the process. Combination of both in-process sensing techniques and robust in-line characterization of the polished surfaces will provide for proper definition of the process endpoint (optimal time for changing to finer abrasive media) in a multi-step polishing sequence. The current paper describes efforts on the latter matter.

In-line characterization of polished surfaces of nanometer roughness level poses challenges in terms of robustness, reliability and cost of a measurement technique to be implemented in the machine. The choice of traceable measurement technique must take into account the presence of vibrations, which cannot be entirely avoided in shop floor environment, and the reflectivity of polished surfaces with high gloss. The majority of the traditional coordinate based measurement systems (i.e. line profiling and areal topography), comprehensively described in (Leach 2011; Lonardo, Lucca, and De Chiffre 2002), lack robustness when applied in a production environment with vibrations. An angle resolved scattered light sensor was shown in (Brodmann, Gast, and Thurn 1984) to provide fast measurement insensitive to variations in distance and tilting of the measured surface. Scattered light sensors can also be used in an oil-vapor environment close to the manufacturing process (Leach 2011, p. 299), making the scattered light instruments potentially the best suitable for implementation in the RAP.

The purpose of this work is to validate the applicability of a commercial angle resolved scattered light sensor for in-line characterization of fine surfaces generated by RAP. The objective is to provide for robust process endpoint detection (proper time to change the polishing abrasive medium), thereby allowing for the RAP process control.

1.1. Robot Assisted Polishing (RAP)

The RAP machine tool is intended for polishing inner and outer functional surfaces on axisymmetric rotational, flat and simplified free-form part geometries. The main machine elements are a part holding spindle, a polishing module holding a polishing tool, mounted on a small industrial robot providing for spatial movements in the machine workspace (see figure 1). The polishing module with air-pressure controlled contact force provides either oscillating (reciprocating) or rotating polishing movement to the tool. The programmable process parameters, such as spindle speed, oscillating frequency and stroke length for oscillating tool, tool rotational speed and angle of approach for rotating tool as well as robot feed rate, determine the main polishing process movements. All the standard polishing abrasive media ranging from coarse stones down to fine diamond grit pastes on various carriers made of brass, wood or felt can be used as polishing tools in RAP (Hansen et al. 2011; Eriksen et al. 2012).

Figure 1; STRECON's Robot Assisted Polishing (RAP®) machine tool (left) and polishing module with oscillating tool motion close up (right) (Pilný et al. 2013).

In the RAP, a generic part is polished in a number of process steps using increasingly finer abrasives, as depicted in figure 2 (left). Determination of the optimal time for change of the abrasive media between the polishing steps (process endpoint detection) is a key and time consuming issue. Currently, this requires interruption of the process (based on operator decision), proper surface cleaning and roughness measurements for verification, that sometimes necessitate removal of the part from the machine tool. If one abrasive media is used for too short time, residual surface marks from the previous operation are not entirely removed and subsequent finer abrasive in the following polishing steps will not remove these marks. On the other hand, if one process step is continued beyond the moment when the finest surface, for the abrasive used, is reached, this will only result in an unnecessary increase of the process time and associated costs. Moreover, it can lead to an excessive material removal beyond the required tolerance limits and pose a risk of generating defects due to local overheating (orange peel, etc.).

1.2. Scattered light sensor

A commercial angle resolved scattered light sensor OS500-32 from OptoSurf GmbH was used in this investigation. The sensor is intended for roughness and form measurements of fine machined surfaces, with measurement range approximately 0.05 μm < Rz < 3 μm in transverse and 3 μm < Rz < 30 μm in longitudinal direction (Optosurf Gmbh 2014). The instrument working principle is based on a non-coherent light beam of 0.9 mm in diameter illuminating the measured surface, reflection of the incident light from the surface slopes in spatial directions, and its acquisition within $\pm$ 16º angular range with a linear detector array consisting of 32 photodiodes. From the acquired scattered light intensity distribution, a number of statistical parameters describing the surface texture are calculated, where the *Aq* parameter (variance of the scattered light distribution), is used to characterize the surface roughness. A description of the sensor working principle, statistical parameters used, and indications on drawing specifications can be found in (*VDA 2009*).

2. METHODOLOGY, EXPERIMENTAL SETUP AND PROCEDURE

To validate the applicability of the scattered light sensor for in-line characterization of fine surfaces generated by RAP, the RAP polishing module with oscillating tool movement and the scattered light sensor were mounted on a CNC milling machine, resembling the RAP setup (see figure 2 right). A number of surfaces with different surface roughness were generated using a well-defined procedure and characterized directly on the machine, in a shop floor environment, with the scattered light sensor. For comparison, the generated surfaces were measured in laboratory conditions using reference optical instruments. To investigate the suitability of the scattered light measurement for 100% quality control, roughness measurements of the whole polished surfaces were performed on a dedicated setup allowing automatic triggering of the measurement.
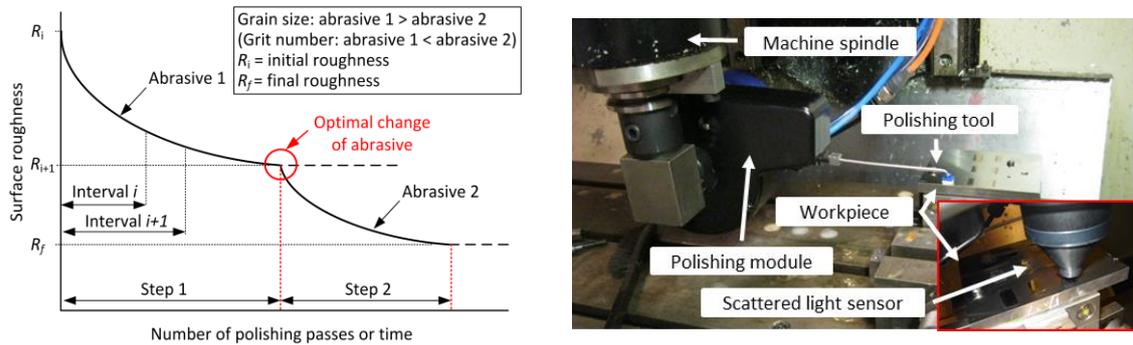
Figure 2; Schematic of surface generation in sequential RAP process depicting the optimal time for change of the abrasive media (left) and experimental setup (right).

2.1. Polishing procedure

Five flat work pieces in hardened martensitic stainless steel Stavax ESR (56 ± 2 HRC) were ground to a roughness of approximately *Sa* 200 nm. On each work piece, 7 surfaces of 20 mm x 10 mm were pre-polished to approximately *Sa* 30 nm using a #600 grit size polishing stone pad. The pre-polished surfaces were further fine polished with increasing polishing time as reported in table 1. The polishing intervals were determined by means of preliminary tests to ensure reaching stabilization of the surface roughness with the longest time interval, representing 100% of process completion. The polishing procedure was repeated on the 5 work pieces, resulting in 5 repetitions for each polishing interval. Diamond paste of 8 μm grain size and soft polishing pads were used. Fixed polishing process parameters of 15 N contact polishing force, pulsation of 3 000 pulses/min with stroke length of 1 mm, feed rate of 1 mm/s were used for the tests.

Table 1; Single polishing process step divided in 7 polishing intervals.

Polishing interval	1	2	3	4	5	6	7
Process completion [%]	5	10	20	30	50	70	100
No. of polishing passes	8	16	32	48	80	120	160

2.2. In-line scattered light roughness measurements

Surface roughness measurements using the scattered light sensor mounted on the machine were carried out on each generated surface prior and after the polishing. Before the measurements, the surfaces were cleaned with compressed air and non-woven cloth soaked in ethanol. The sensor was positioned in fixed position 5 mm above the work piece surface with the detector perpendicular to the surface lay. The measurements were carried out using a CNC program with 6 measurement locations within the measured area of 5 x 8 mm in the center of each surface with 10 measurement repetitions. The entire measurement cycle took less than 1 minute per work piece (7 measured areas). The measured areas excluded edges and surface areas not receiving equivalent polishing time, thus ensuring consistent conditions.

2.3. Reference surface roughness measurements

The reference roughness measurements of the polished surfaces were performed in laboratory conditions using a white light interferometer (WLI) with 0.1 nm vertical and 0.88 µm lateral measurement resolution. Due to the high surface slopes of the stone pre-polished surfaces resulting in invalid measurements using WLI, the starting surfaces were measured by confocal microscope with 8 nm vertical resolution. The reliability of the measurements was affirmed by measurements on calibrated roughness measurement standard with mean Ra 26.9 nm. The actual measurement strategy consisted of 6 random measurement locations within an area of 5 mm x 8 mm in the center of each measured surface before and after polishing. The areal topography measurements of 180 µm x 135 µm were processed by plane correction (1st order polynomial fit) for removal of form and filtered by λc = 0.08 mm for removal of waviness using the software SPIP^{TM} by Image Metrology. Since the fine polishing with diamond abrasive and flexible carrier affects only surface microstructure (roughness), the longer waves (waviness and form) were suppressed. This is an important aspect for validation of the ability of the scattered light sensor to sense the change in the surface microstructure, while the macrostructure (waviness and form) is constant during the fine polishing. The cut-off length λc was chosen based on sensitivity analysis (see figure 4) and visual assessment of 2D roughness profiles when applying 5 standardized cut-off lengths on 3 finest surfaces resulting from 160 polishing passes (see figure 4 left) and 3 initial pre-polished surfaces (see Figure 4 right). As can be seen from figure 4 and as observed form the 2D roughness profiles, cut-off lengths below 0.025 mm suppress the roughness component itself, causing rapid decrease in Sa value. To ensure that only the longer wavelength component is suppressed while not affecting the roughness, cut-off length of 0.08 mm was used. Subsequently, the surfaces were characterized by means of the roughness amplitude parameter Sa.
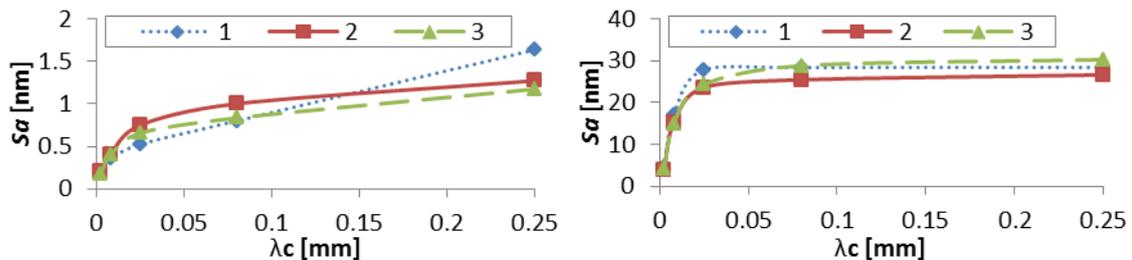

Figure 4; Sensitivity analysis – effect of cut-off length λc on surface roughness Sa on 3 fine surfaces after 160 polishing passes (left) and 3 rough pre-polished surfaces (right); λc = 0.25; 0.08; 0.025; 0.008 and 0.0025 mm.

2.4. 100% quality control by scattered light measurements

The whole polished surfaces of 10 mm x 20 mm were measured using the scattered light sensor on a dedicated X-Y stage allowing automatic triggering of the measurements. To ensure proper location of the measurements by suppressing the effect of acceleration and deceleration of the stage, areas of 11 mm x 23 mm were measured in an automatic regime, while discarding 1 mm in the beginning and end of the acquisition. A measurement speed of 500 mm/min was used. A high resolution measurement of 0.1

mm x 0.1 mm step increment of the ø 0.9 mm measurement spot covering the whole surface was performed in 5 min. A lower measurement resolution of 0.1 mm x 0.9 mm, while still ensuring total coverage of the whole surface was performed in 0.6 min. Such areal measurements allow for observation of the surface texture distribution over the whole polished surface.

3. RESULTS

A representative trend in measured surface roughness parameters Sa (reference) and Aq (scattered light) during 160 polishing passes is shown in figure 5 (left). The graph represents 7 measured surfaces on one work piece with error bars representing measurement standard deviation. The trend was seen well repeatable among all the 5 process repetitions (5 work pieces), resulting in robust correlation between Sa and Aq shown in the graph in figure 5 (right). The variability of the measurements results reflects poor uniformity of the pre-polished surfaces, progressively improving during polishing. The deviation in the linearity of the trend between Aq and Sa is due to fact that the surface is the result of two processes (stone polishing with bonded abrasives and paste polishing with loosen abrasives), with their importance varying during the process (i.e. the stone polishing contribution is progressively fading). The difference in the drop rate in Aq and Sa can be explained by the fast generation of flat area on the top of the surface scallops (see figure 6 - no progression after 80 passes, thus not shown). This strongly affects Aq, since more light is reflected from the flat areas on the surface onto the center of the sensor detector, thereby lowering the variance of the scattered light distribution acquired – Aq. The response of the Sa parameter is slower due to the small variation in height of the surface profile over the whole evaluation area. The average parameters Sa (or Ra for 2D) are known to take large changes in the surface to make these parameters react, however, they are widely used and accepted (Nielsen 2012). Based on the results, the trend in Aq appears to be robust, well describing progression in the surface topography of fine polished surfaces. Also a robust correlation with the variation of the roughness parameter Sa was observed, with explainable differences in their drop rate. Particularly important observation is that the trend in Aq allows the identification of an asymptote representing the process completion, reliable for the correct in-line determination of the process endpoint.
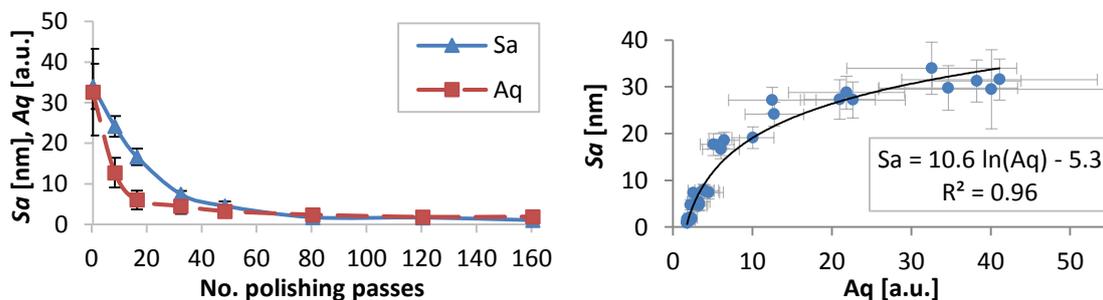

Figure 5; Trend in Sa and Aq surface roughness parameters during 160 polishing passes (left) and correlation of Sa and Aq from all measurements on 5 work pieces (right), with error bars representing ± one measurement standard deviation.
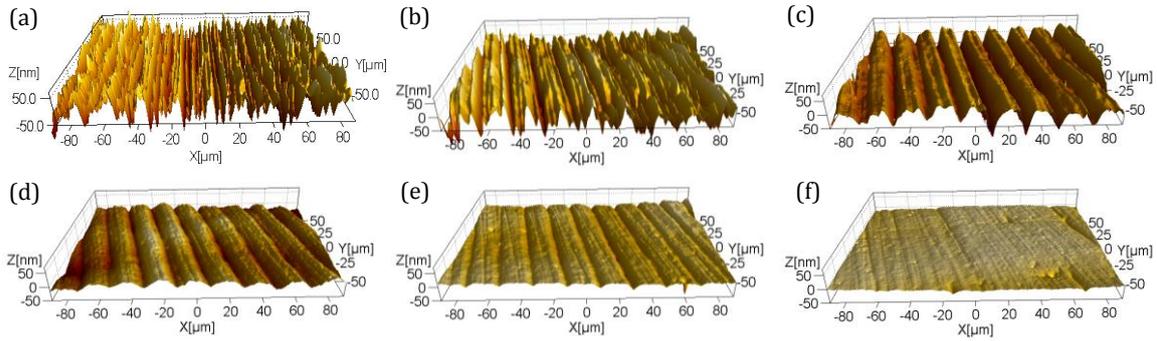
Figure 6; Surface topography after: pre-polishing – 31 nm Sa (a), 8 passes -23 nm Sa (b), 16 passes – 20 nm Sa (c), 32 passes – 8 nm Sa (d), 48 passes – 6 nm Sa (e), and 80 passes – 3 nm Sa (f).

3.1. 100% quality control by scattered light measurement

A 3D representation of scattered light surface roughness parameter *Aq* covering one whole polished surface after 32 polishing passes is shown in figure 7. The higher resolution measurement on the left hand side consists of 23 100 measurements acquired in 5 min. The lower resolution measurement on the same surface is shown in the right hand side figure, consisting of 2 940 measurements acquired in 0.6 min. In both figures, higher surface roughness at the borders of the surface can be clearly seen. The border areas were excluded from the reference (optical) and spot by spot measurement with the scattered light sensor on the machine. However, a surface non-conformity in the middle of the area can be observed, which would cause spread of the single measurements and could be considered as outliers (measurement accident) and excluded from the measurements. Cause of the non-conformity was verified by a microscope as inherent surface feature, probably caused by a hard particle of a bigger size than the polishing abrasive trapped in the soft carrier (pad), being swept over the surface in the tool feed direction (20 mm) and with the feature width corresponding to the tool oscillation stroke length (1 mm). The lower resolution measurements have been observed sufficient for detection of surface roughness non-conformities in nanometer *Sa* range, while providing cost-efficient productivity of the measurement.
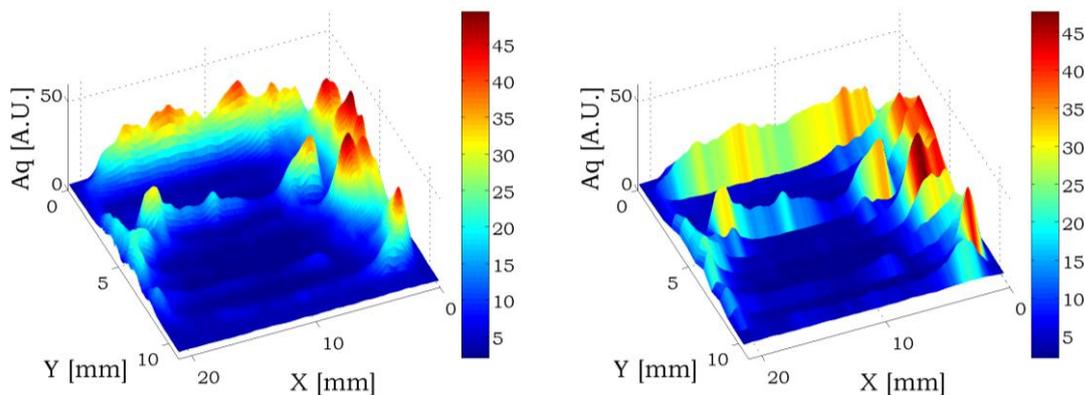

Figure 7; high resolution (left) and low resolution (right) 3D representation of measured Aq covering one whole polished surface after 32 polishing passes (8 nm Sa).

4. CONCLUSIONS

The applicability of a commercial scattered light sensor for in-line characterization of fine polished surfaces has been validated for its implementation in Robot Assisted Polishing. A robust correlation in the trend of traditional *Sa* surface roughness and scattered light surface roughness *Aq* parameters, well describing the progression in the surfaces topography during a polishing step, was documented. The method has been shown to provide robust process endpoint detection, thereby enabling process control and automation of the multi-step RAP sequence.

Moreover, a cost-efficient applicability of the method for 100% in-line quality control has been demonstrated, being sensitive to observation of surface non-conformities at a nanometer *Sa* roughness level. This provides the possibility of in-line 100% quality assurance of polished parts, before any handling possibly introducing surface defects such as scratches, etc.

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