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A non-contact laser method based on the imaging and analysis of scattered light used for assessment of surface imperfections

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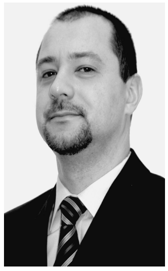

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Abstract

In the work laser scatterometry supported by image processing and analysis techniques was used for assessment of surface imperfections (SIM) of machined surfaces presented and discussed. During the experiment the ground and polished samples made from aluminium, brass, cast iron and steel, with visible SIM, were used. Surface topographies (Talysurf CLI 2000 - Fig. 1) and images of scattered light (experimental setup - Fig. 2) were acquired for selected areas of those surfaces. Analysis of the data obtained was carried out using Image-Pro® Plus and TalyMap Silver software (Fig. 3). The results of the experiment enabled us to conclude that the methods used were both useful and could offer an interesting assessment of machine parts characterized by various types of SIM.

Keywords: optical methods, laser scatterometry, image processing and analysis, surface imperfections, machined surfaces.

Bezstykowa metoda laserowa wykorzystująca obrazowanie i analizę rozpraszania światła przeznaczona do oceny skaz powierzchni

Streszczenie

Jednym z ważniejszych problemów we współczesnym wytwarzaniu i eksploatacji maszyn oraz urządzeń jest ich odpowiednia diagnostyka. Proces diagnostyczny może dotyczyć m.in. detekcji i analizy skaz powierzchni powstających w sposób niezamierzony lub przypadkowy podczas obróbki, przechowywania lub użytkowania powierzchni części maszyn. Ocena skaz powierzchni może być przeprowadzana z wykorzystaniem szeregu metod pomiarowych. Ważną rolę odgrywają tutaj metody optyczne w największym stopniu wykorzystywane w warunkach produkcyjnych. W pracy pokazano, iż optyczne metody skaterometrii laserowej wspomagane przez techniki przetwarzania i analizy obrazu mogą stanowić ciekawą alternatywę w przypadku oceny części maszyn, charakteryzujących się występowaniem różnego rodzaju skaz powierzchni. W pracy opisano metodę ARS wykorzystującą obrazowanie i analizą światła rozproszonego przeznaczoną do detekcji skaz powierzchni elementów maszyn obrabianych różnymi technikami obróbkowymi. Zaproponowana metoda charakteryzowała się m.in. dużą czułością, bezstykowym sposobem pomiaru oraz krótkim czasem przeprowadzenia oceny. Parametry uzyskane z analizy obrazu (oprogramowanie Image Pro®-Plus) porównywano z wybranymi dwu- i trójwymiarowymi mapami powierzchni skaz (oprogramowanie TalyMap Silver) rejestrowanymi profilometrem optycznym Talyscan CLI2000 firmy Taylor Hobson. Przeprowadzone badania potwierdziły dużą użyteczność zastosowanej metody rozpraszania światła, mogącej stanowić jedną z propozycji rozwiązania problemu diagnostyki części maszyn i urządzeń w warunkach laboratoryjnych lub przemysłowych.

Słowa kluczowe: metody optyczne, skaterometria laserowa, przetwarzanie i analiza obrazu, skazy powierzchni, powierzchnie obrobione.

1. Introduction

The surface texture [1] of modern manufactured machine parts contains the supposed surface imperfections described by the SIM acronym, as well as the apparent roughness, waviness and directionality of surface irregularities. They are defined in accordance with [2] as elements or irregularities (alternatively a group of elements or irregularities) of a real surface, created unintentionally or coincidentally during the machining, storage or general usage of the surface. Although these imperfections occur on a minor area of the workpiece surface, they exhort significant influence on its application and exploitative features. Standard [2] differentiates between 31 types of the SIM, created as a result of:

- interaction of other bodies (recessions, grooves, scratches),
- material flaws and tensions (cracks, cleavages, blowholes, warts, shrinkage holes),
- corrosion (pitting),
- erosion (craters).

Detection of the SIM is a complex matter. In the simplest case it amounts to a visual observation of the workpiece surface and the classification of SIMs depending on the size and number of the existing imperfections. Human sight is an excellent and useful tool in this case. It is characterized by a high sensitivity to changes in surface reflectiveness, which allows for rather easy detection and visual assessment of the SIM.

However, human vision is limited in a number of ways and therefore better and more efficient methods for detection and assessment of the SIM are necessary. This problem is of exceptional importance in inspections of workpiece surfaces in industrial conditions, where visual observation is often replaced with modern measurement methods.

Nowadays numerous methods of this type are used e.g.: optical methods (light microscopy, optical profilometry, interferometry, structured light methods, light scattering methods) [3], imaging methods (SEM, CLSM, AFM) [4] as well as vision methods [5]. These methods are often supported by image processing and analysis techniques [6], and those techniques which use artificial intelligence (e.g. neuron networks [7]). The group of light scattering methods [8] can be derived from these optical methods. Such methods have been successfully developed for many years at Koszalin University of Technology. A number of research works carried out in professor Cz. Łukianowicz's group included, among others, assessment of the workpiece surface roughness (in static conditions [9] and in motion [10]), as well as inspection of the abrasive tools surface [11]. The group also developed the image processing and analysis techniques, which provide useful support to the above-discussed methods [12].

During analysis of further applications of the light scattering methods, the Authors have drawn attention to the possibility of assessment of the SIM after various machining processes, including grinding and polishing. An attempt to use one of the scatterometric methods is then the subject of this paper.

2. The experiment

The main goal of the completed experiment was to confirm the possibility of using laser scatterometry and image analysis in the detection and analysis of the SIM of machined parts.

2.1. Characteristics of the samples

5 cylindrical samples in the form of rings with external diameter ϕ_z = 20 mm, internal diameter ϕ_w = 14 mm and height z = 10 mm were used in the experiment. The surfaces of all samples underwent roughing through turning on a SK-1 lathe (offset side turning tool NNBe with burned-on sintered carbide insert P20 by Pafana (Poland), rotational speed n_w = 685 rev/min, hand feed). Next, the samples were ground with abrasive sheets that had a grain granulation from 200 to 1200 (rotational speed n_w = 1370 rev/min, grinding time t_s = 120 s) and from 2000 to 2500 (rotational speed n_w = 2740 rev/min, grinding time t_s = 100 s). Additionally, samples No. 1, 3, 4 underwent polishing (abrasive compound based on Al_2O_3 by Sonax (Germany), polishing time t_p = 90 s).

After a 14-month long exploitation in workshop conditions numerous imperfections, such as cracks, corrosions, delaminations and stains, appeared on the sample surfaces. The general characteristics of the samples used in the experiment is presented in Tab. 1, while Tab. 2 characterizes the imperfections occurring in the assessed samples surfaces.

Tab. 1. The general characteristics of the samples used during the experiment
Tab. 1. Ogólna charakterystyka próbek wykorzystanych w badaniach

Sample No.	Material	Surface machinig	Surface roughness parameters			
			Ra [µm]	*Rp* [µm]	*Rt* [µm]	*Rz* [µm]
1	Aluminium AW6082	T+G+P	0.06	0.15	0.76	0.4
2	Brass CW612N	T+G	1.28	3.48	15.6	7.93
3	Gray cast iron GJL150	T+G+P	0.05	0.12	0.94	0.41
4	Steel C45	T+P	0.45	1.5	2.95	2.95
5	Steel St5	T+G	1.48	4.23	9.75	7.04

T – turning (roughing), G – grinding (finishing), P – polishing (finishing)

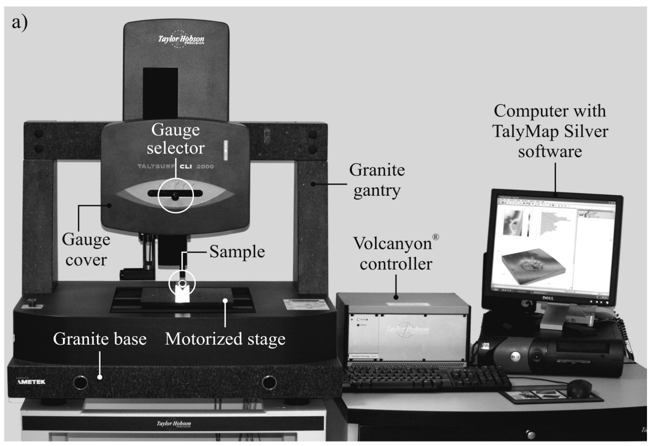
Tab. 2. The characteristics of SIM occurring on the examined samples surfaces
Tab. 2. Charakterystyka skaz występujących na powierzchniach badanych próbek

Sample No.	Number of AOIs with visible defects	Type of SIM*	Interpretation
1	3	Groove	SIM in the form of an elongated recession with a flat or rounded bottom.
2	2	Scratch	SIM in the form of irregular recession and arbitrary direction.
3	3	Spot	The area of the surface, which is visually distinguished from the neighboring surface.
4	2	Pit	SIM in the form of depressions and small holes mostly deep and dispersed on the large surface area.
5	4	Cleavage	SIM resulting from the exfoliation of the surface layer of the object.

* in some cases on the sample occurred several types of SIM simultaneously

2.2. Optical measurements of the samples

After the machining process, all the sample surfaces underwent optical measurements to determine the selected surface roughness parameters (in areas of the samples without visible imperfections) and geometric parameters, which characterized the detected imperfections. In the first case profiles of the surface roughness were registered in 10 selected areas of the samples. In the second case the topographies of selected areas of surfaces with visible imperfections were registered. The measurements were carried out using the 3D optical profiling system Talysurf CLI 2000 produced by Taylor Hobson Ltd.(UK). This system was described in more detail in [13]. The general view of this system is shown in Fig. 1.



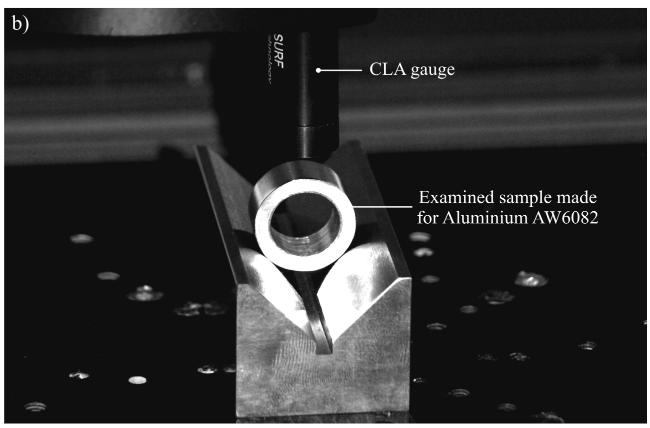


Fig. 1. 3D optical profiling system Talysurf CLI 2000 produced by Taylor Hobson Ltd.: a) general view of the system, b) close-up of examined sample made for Aluminium AW6082 mounted in v-block

Rys. 1. System pomiarowy Talysurf CLI 2000 firmy Taylor Hobson Ltd.: a) widok ogólny systemu, b) zbliżenie na ocenianą próbkę wykonaną z Aluminium AW6082 zamocowaną w pryzmie

During the measuring process the system was equipped with a CLA gauge (scanning frequency: 2000 Hz, measuring range: 3 mm).

Talyscan CLI 2000 ver.2.6.1 software provided by the manufacturer was used for operating this system. Analysis and visualization of the measurement was carried out using TalyMap Silver ver. 4.1.2 software, with Mountains Technology™ produced by DigitalSurf (France).

Tab. 3 shows example parameters of the surface topography obtained for selected AOIs from sample No. 4 made from steel C45 (Ra = 0.15 μm).

Tab. 3. The parameters of the surface topography obtained for selected AOIs from sample No. 4 made from steel C45 (Ra = 0.15 μm) acquired using the 3D optical profiling system Talysurf CLI 2000

Tab. 3. Zestawienie parametrów pomiarów topografii powierzchni wykonanych za pomocą systemu pomiarowego Talysurf CLI 2000 dla wydzielonych obszarów powierzchni próbki nr 4 wykonanej ze stali C45 (Ra = 0,15 μm)

Number of AOI	1	2	3
Type of defect in the selected AOI	Polished surface without SIM*	Scratch	Pit
Measured surface area (axes x, y, z) [mm]	1×1×0.87	5×1×2.38	1.2×1.5×0.50
The number of profile points (axis x)	101	101	61
Distance between profile points (axis x) [μm]	10	50	20
The number of profiles (axis y)	1001	1001	1501
Distance between the profiles (axis y) [μm]	1	1	1
Vertical resolution (axis z) [μm]	0.000233	0.000233	0.000233
Measuring speed [μm/s]	200	200	200
Measuring time [s]	790	733	635

*reference measurement

The assessment of the data obtained was carried out using TalyMap Silver version 4.1.2.4307 software, produced by DigitalSurf. Assessment included a number of procedures concerned with processing and analysis of measurement data, such as the setting: 2D pseudo-color surface map, 2D contour diagrams, 2D surface roughness profiles with the determined parameters, 3D surface topographies with the determined parameters, Abbott-Firestone curves, etc. All of the above mentioned procedures were focused on the assessment of selected areas of measured surfaces containing visible SIM's.

2.3. Acquisition of images of scattered light

During the acquisition of images of scattered light one of the laser scatterometry methods, which is described by the acronym ARS/DS (*Angle Resolved Scattering/Differential Scattering)* was used.

The realizing of this method was possible by using a special experimental setup. A schematic diagram of this setup is shown in Fig. 2. The setup was constructed from two basic elements: a measuring stage with a sample-holding handle, as well as a grip to mount the light source and a TV camera. The measuring stage was mounted on two horizontal movement mechanisms of KB 11737 type by Cobrabid (Poland). These mechanisms guaranteed precise manual adjustment of the stage position in x and y axes. The range of displacement in both axes was 25 mm with an accuracy to 0.01 mm.

A laser diode with designation CPS182 by Thorlabs, Inc. (Sweden), continuously emitting a light beam from the visible light range with wavelength λ = 635 nm was placed in the light source grip. The beam, directed at a 60 degree angle of incidence, illuminated the sample, creating a dot of 1 mm diameter upon its surface. The wave of light falling upon the sample surface reflected from it and partially scattered, generating an optical scattered light pattern in the observation plan. A matt screen, sized 315 × 245 mm, with a scale for preliminary determination of the geometry of the generated image, served as an observation plan.

The images were acquired in two series. During the first series, the plane of incidence was perpendicular, while in the second one it was parallel to the samples axes and chatter marks. The number of images depended on the amount of SIM's detected. For each detected SIM an area of interest (AOI), divided into measuring points, was created. The number of points was dependent on the size of the area and, thus, on the SIM size. The size of each measuring point corresponded to the laser spot diameter, which was 1 mm. Fig. 2b shows a schematic detailing the principle for measuring the example SIM in the form of a groove, using 21 measurement points.

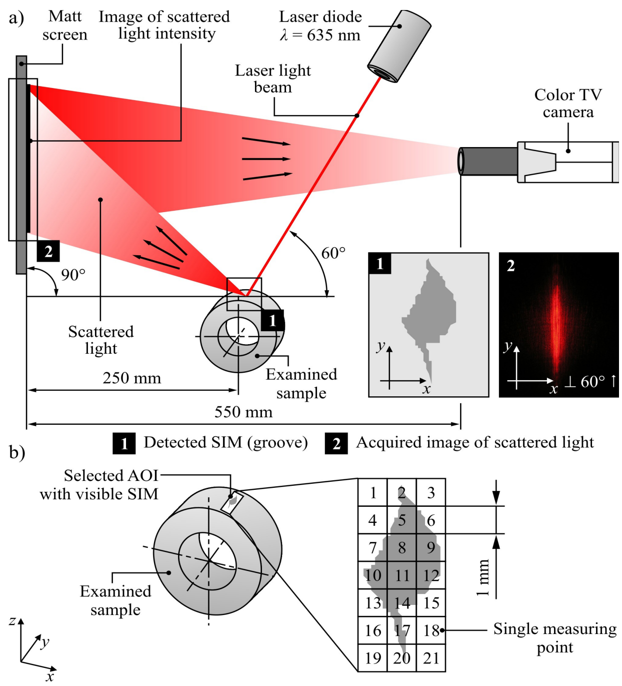


Fig. 2. Experimental setup used for the acquisition of scattered light: a) schematic diagram of the experimental setup, b) principle of the image acquisition using measuring points

Rys. 2. Stanowisko pomiarowe do akwizycji obrazów światła rozproszonego wykorzystywane podczas prowadzanych badań: a) schemat stanowiska, b) zasada akwizycji obrazu z wykorzystaniem punktów pomiarowych

Acquisition of the images of scattered light with a resolution of 1600x1200 pixels, saved in *.BMP format, was made possible using a color TV camera OPTI-630C with SONY Exview HAD CCD type matrix detector. The camera was equipped with a dedicated lens (2.8 - 12 mm, F1.4). The signal from camera was transmitted to the Pinnacle PCTV Hybrid Express Card by Pinnacle Systems (USA). The card was installed in the PCMCIA link of Packard-Bell Easynote MB85-P-012 laptop (Netherlands). The TV card could function properly due to TVC Pro 4.8 software supplied by the TV card producer.

2.4. Processing and analysis of the images of scattered light

All acquired images of the scattered light after transmission to the computer were analysed by Image-Pro® Plus 5.1 software produced by Media Cybernetics, Inc. (USA). The main goal of the analysis was to determine the values of the geometric and photometric parameters of the assessed images. A number of parameters the authors had used in previous experiments was now used. The procedure used during the analysis consisted of carrying out segmentation of the images of scattered light and then conducting a count of the number of objects present in the images. The counting process was carried out automatically by the

Count/Size tool. On the basis of this image object count, the software determined the average values of the given parameters, which are shown in Tab. 4.

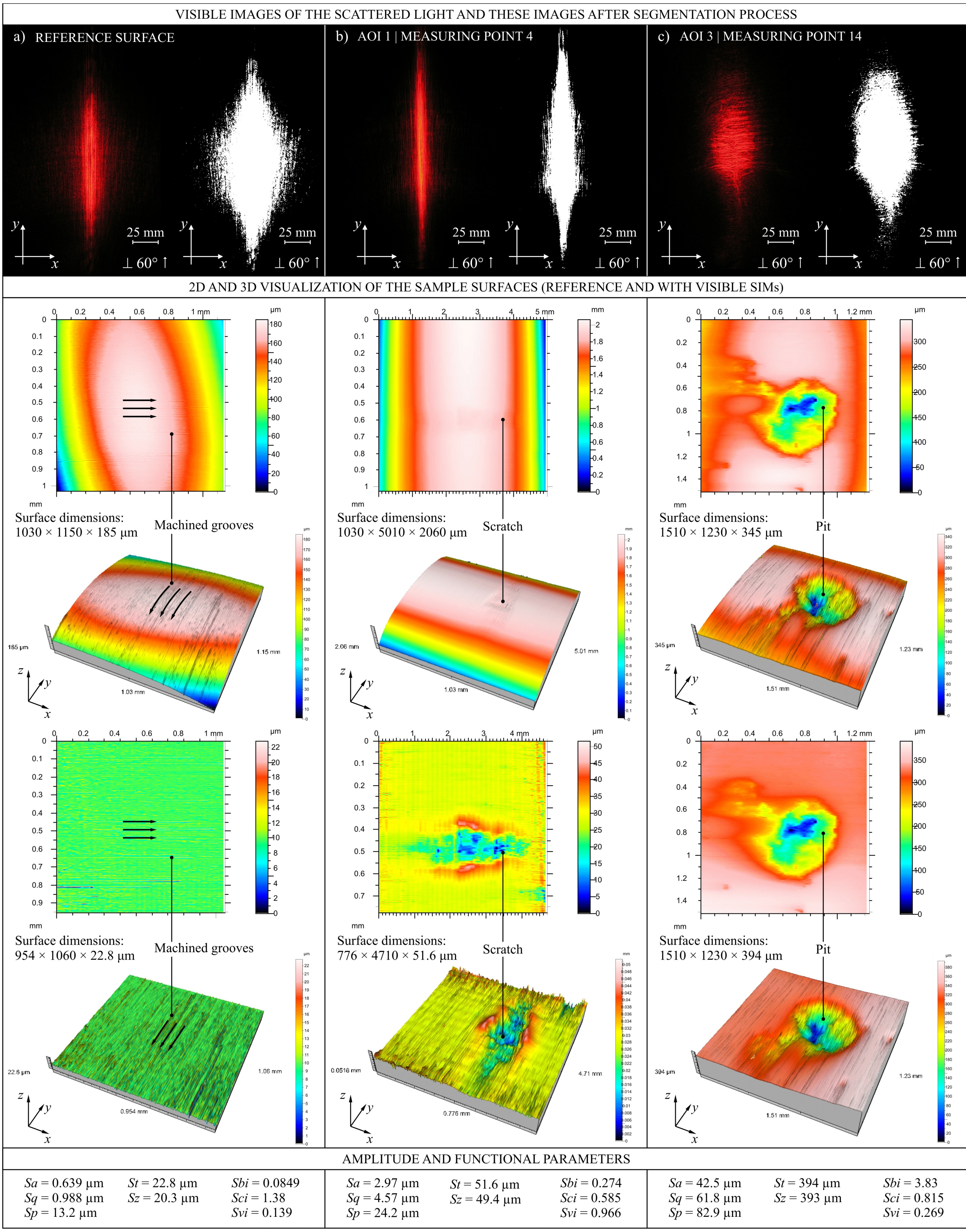


Fig. 3. The collected results from the experiment conducted on polished sample No. 4 made from steel C45 (*Ra* = 0.15 µm): a) results obtained for area without visible SIM's, b) results for area with visible SIM in the form of a scratch (size: 3416×150 µm), c) results for area with visible SIM in the form of a pit (size: 523×612 µm). The sequence of images: image of scattered light both real and post-segmentation process (top), 2D pseudo-color surface map and 3D surface topography (data without filtering) (middle), 2D pseudo-color surface map and 3D surface topography (data after waviness filtering, Gaussian filter, cut-off 0.08 mm) with surface texture parameters (bottom)

Rys. 3. Przykładowe wyniki eksperymentu otrzymane dla próbki polerownej nr 4 wykonanej ze stali C45 (*Ra* = 0.15 µm): a) wyniki otrzymane dla obszaru bez widocznych skaz powierzchni, b) wyniki otrzymane dla obszaru z widoczną skazą powierzchni w postaci rysy (wymiary: 3416×150 µm), c) wyniki otrzymane dla obszaru z widoczną skazą powierzchni w postaci wżeru (wymiary: 523×612 µm). Sekwencja obrazów: obraz światła rozproszonego (rzeczywisty i po procesie segmentacji) (góra), dwuwymiarowa mapa powierzchni (kolory indeksowane) oraz topografia powierzchni (dane nie filtrowane) (środek), dwuwymiarowa mapa powierzchni (kolory indeksowane) oraz topografia powierzchni (dane po odfiltrowaniu falistości, filtr Gaussowski, długość odcięcia 0,08 mm) wraz z wybranymi parametrami SGP (dół)

Tab. 4. The calculated values of selected geometric and photometric parameters using Image-Pro® Plus 5.1 software
Tab. 4. Wyznaczone wartości wydzielonych parametrów geometrycznych i foto-metrycznych za pomocą oprogramowania Image-Pro® Plus 5.1

Group of parameters	Parameter*	Designation	Value			Unit
			1	2	3	
-	Number of measured objects in image (Total/In range)	-	385/ 136	691/ 212	1256/ 394	-
Geometric	Area	*An*	42.94	43.39	46.67	pixel
	Size (length)	*l*	11.45	9.42	9.99	pixel
	Size (width)	*t*	3.47	5.36	5.41	pixel
Photometric	Heterogeneity	*SF*	0.03	0.05	0.09	a. u.
	Integrated Optical Density (IOD)	I_Σ	10951	11064	11900	a. u.
	Margination	*M*	0.44	0.44	0.44	a. u.

* the values of all parameters were given as a mean value, 1 – surface with SIM (scratch), 2 – surface with SIM (pit), 3 – reference surface (without SIM)

3. Results and discussion

Fig. 3 presents a comparison of the results obtained during the realisation of an experiment on one of the assessed samples. In this case it was the polished sample No. 4 made from steel C45 (*Ra* = 0.15 µm). It was characterized by the occurrence of localised SIM's in the form of scratches and pitting.

In the top part of the figure is a comparison of the real light of the scattered images, acquired using the experimental setup described in Section 2.3, as well as images after the segmentation process obtained with the use of Image-Pro® Plus 5.1 software. The visual observation of the scattered light images allowed the Authors to see differences in the geometry and level of light scattering, resulting from the occurrence of the given SIM. In the case of a scratch imperfection (illuminated perpendicularly to the chatter marks and axis), the scattered light image would take the form of a straight line with minor side scatterings. In the case of the pitted imperfection (illuminated in a similar way) the scattered light image took on an oval shape, with increased scattering value in the bottom section. The central part of this image was particularly interesting due to the occurrence of numerous linear light scatterings. Such a pattern, as that which was presented in this image, constituted a reflection of the complex structure of the imperfection's surface.

The above visual observations were completed with an analysis of images obtained after the segmentation process. Such images were necessary for the determination of selected parameters by the software. They constitute the comparative material for visual assessment of real images.

The middle and bottom parts of Fig. 3 present 2D and 3D visualizations of the measuring data corresponding with the images of scattered light which were obtained using the Talyscan CLI 2000 optical profilometer, and later on adequately processed using the TalyMap Silver software. The visualizations were divided into two groups containing the same elements, i.e. the 2D pseudo-color surface map, as well as a 3D surface topography. The first of the groups contained the aforementioned visualizations obtained without the filtration procedure, while the second group consisted of those obtained with the use of such a procedure. This procedure consisted of removing the waviness to demonstrate the SIM structure in a clear manner. In this case, Gaussian filter with cut-off 0.08 mm was used.

The second group of visualizations, visible in the bottom part of Fig. 3, were obtained after the waviness had been filtered off, and allowed for considerably better analysis of the SIM. They were properly modeled and their geometric dimensions could be determined (scratch: 3416 × 150 µm, pit: 523 × 612 µm). Additionally, the values of selected amplitude and functional parameters were determined. These values were stated for information purposes, in addition to the presented visualizations.

The above experimental results should be treated merely as a guideline, or example. Further, more complex analyses carried out using the TalyMap Silver software could be added to them, depending on the assumed goal of the realized measurements.

4. Conclusions

The results obtained during the experiment carried out allow the authors to conclude that the optical methods used, combined with the image analysis techniques outlined, might constitute an interesting proposition for improved assessment of machine parts that are characterized by a variety of SIMs. The exceptional utility evinced, especially in the case of laser scatterometry, results from the potential use of such a method in acquiring measurements of SIMs, when an object is in motion. This facilitates quicker inspection of a given part without the necessity to stop machine operations. This is vitally important in industrial conditions where the use of other methods is limited to a large extent. The light scattering method could be practically implemented in a small-size measurement system (an optical head) for automatic inspection of SIMs in industrial conditions.

Positive experimental results encourage the authors to continue their work in the presented field. They will concentrate on, among other things, developing and testing different methods of processing and recognizing registered image data, perfecting the research methodology and developing the construction of the measurement head.

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