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REVIEW OF THE ADVANCED MICROSCOPY TECHNIQUES USED FOR DIAGNOSTICS OF GRINDING WHEELS WITH CERAMIC BOND

A wide range of abrasive tools is used in modern removal machining techniques. Their condition has significant influence on the quality of the shaped surfaces of the produced elements and the functions they perform. Abrasive tools diagnostics is in this case an essential element of the production process, connected with assessment of the abrasive tool surface condition. Such an assessment can be carried out with microscopic methods. The work presents selected microscopic techniques on the cutting edge of technology such as: digital microscopy, confocal laser scanning microscopy and scanning electron microscopy. Characteristics of each of the methods and the applied devices were briefly presented. The experimental part presents exemplary results of measurements and analyses carried out using the described methods. The works were carried out on, among others, grinding wheels with ceramic bond used in internal cylindrical grinding processes. The assessed tools were characterized by a number of features such as impregnated active surface, modified bond microstructure or smearing the active surface with chips of the machined material. The obtained results confirmed the possibility of application of the above-mentioned microscopic techniques in abrasive tools diagnostics.

1. INTRODUCTION

A number of modern technological processes connected with obtaining high-quality surface finish is carried out using plenty of material removal machining techniques [1]. Modern machining varieties such as, among others: HSG (*High Speed Grinding*) [2], SHSG (*Super-High Speed Grinding)* [3], HEDG (*High-Efficiency Deep Grinding*) [4], SFG (*Speed Feed Grinding*) [5], SSG (*Speed Stroke Grinding*) [6], CPCG (*Continuous Path Controlled Grinding*) [7], HSP (*High Speed Peelgrinding*) [8], traverse grinding [9], guarantee favorable machining results and contribute to obtaining appropriate exploitation parameters of the shaped surfaces. The enumerated machining techniques, both in modern and classical variations, use a wide range of abrasive tools. These are usually various types of abrasive segments, bricks and grinding wheels.

One of the crucial elements of high-efficiency automated production processes is proper diagnostics of the used abrasive tools. This process can be defined as assessment

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of the tool condition in order to determine the dependence between the cause and the existing problem (effect). In relation to grinding wheels, it is used mainly to detect symptoms of their wear. Such phenomena as blunting of the abrasive grain edges, cracking of the ceramic bond bridges or smearing free intergranular spaces with grinding products (mostly with the machined material chips) may result in grinding wheel shape errors or excessive temperature increase in the area of contact between the grinding wheel and the machined material. As a result, this leads to a decrease in the quality of the workpiece surface layer and even to grinding defects such as grinding burns or microcracks.

The diagnostics of abrasive tools is a complex process. The dependence between the cause and the occurring problem (result) can be determined on basis of, among others:

- observation of the machining tool's real surface (visual observation in macroscale, device observation in microscale),
- detection (manual or automatic) of the defect or flaw occurrence area,
- acquisition of the digital image/micrograph of the assessed surface,
- image/micrograph processing and analysis using special computer software,
- proper interpretation of the image/micrograph and measurement data obtained as a result of observation and analysis.

The above actions include a number of tasks typically completed using modern microscopic techniques. These techniques are used in a variety of tasks, from relatively easy observations carried out in workshop conditions, through visual observations combined with fast digital micrographs processing and analysis of the machined surfaces in manufacturing conditions, to sometimes very advanced analyses of digital micrographs of surfaces assessed in laboratory conditions. The high complexity of the laboratory assessment makes it possible to carry out advanced research works concerning the diagnostics of abrasive tools. The great aid in such undertakings is the wide range of modern solutions in the field of both optical and electron microscopy. This allows for selection of the proper device for the given type of measurement task.

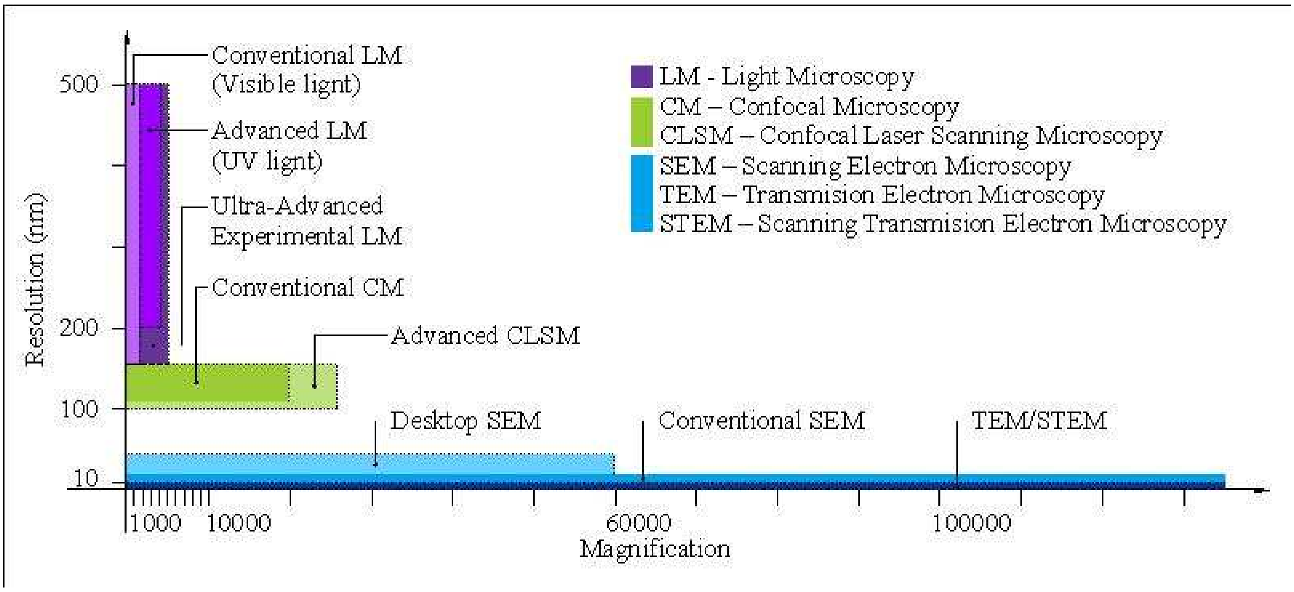

Fig. 1. Classification of selected microscopic techniques in relation to the obtained magnifications and resolutions

Figure 1 presents classification of selected microscopic techniques in relation to the obtained magnifications and resolutions. Some of these techniques are used in assessment of the abrasive tools' surfaces.

2. EXPERIMENTAL INVESTIGATIONS

2.1. THE MAIN GOALS OF THE TESTS

The main goal of the realized experimental tests was checking whether the selected microscopic techniques could be used in assessment of abrasive tools. Table 1 includes microscopic techniques used in the tests, as well as the general features of the assessed samples.

Table 1. The general characteristics of microscopy techniques and samples used in experimental investigations

No.	Group of methods	Measurement method	Measurement system	Samples characteristics
1.	Optical Microscopy	Digital Microscopy	Keyence VHX-600 (Japan)+ VHX-H2MK software (Japan) VHX-500 3D Viewer 1.02 (Japan)	Active surface of the 1-35×10×10-SG/F46G10VTO grinding wheel before and after impregnation with silicone
2.		Confocal Laser Scanning Microscopy	Olympus LEXT OLS3100 (Japan) + LEXT 5.0 software (Japan) + TalyMap Platinum 5.0 software (France)	Active surface of the 1-35×10×10-SG/F46G10VTO grinding wheel
3.			Olympus LEXT OLS4000 (Japan) + OLS4000 2.1 software (Japan) + TalyMap Platinum 5.0 software(France)	Active surface of the 1-35×10×10-SG/F46N7VDG grinding wheel after machining of Titanium Grade 2® alloy
4.	Electron Microscopy	Scanning Electron Microscopy (Conventional)	JEOL JSM-5500LV (Japan) + JEOL SEM software	Active surface of the 1-35×10×10-SG/F46L7VDG grinding wheel after machining of Titanium Grade 2® alloy
5.		Scanning Electron Microscopy (Tabletop)	Phenom-World Phenom G2 Pro (Netherland) + Phenom™ Pro Suite software (Netherland) +Olympus AnlySIS® software (Japan)	Breakthrough of the 1-35×10×10-SG/F46G10VDG grinding wheel with glass-crystalline ceramic bond

Efforts were made to test the used methods thoroughly and to check out the feasibility of the devices in various program configurations. This allowed for determination of the possibilities of each tested microscope in relation to the given type of assessed abrasive tool.

2.2. MICROSCOPY TECHNIQUE I: THE DIGITAL MICROSCOPY

Routine observations of the abrasive tools' surfaces in manufacturing or laboratory conditions can be carried out using digital microscopy techniques [10],[11], also called opto-digital microscopy. This technique is the modern variation of the classical light microscopy, in which the modern solutions of optical systems were used (aberration-free optics, telecentric lenses) and integrated with the detecting systems (matrix detectors of CCD (*Charge-Coupled Device*) or CMOS (*Complementary Metal-Oxide-Semiconductor*) type). Application of photoelectric detectors allowed for transmission of the digital signal directly onto the monitor screen, which resulted in complete elimination of the possibility to observe the image in the eyepiece (the classical eyepiece was omitted in such solutions). The image transmitted onto the monitor can not only be observed but also processed and analyzed. This can be done due to the dedicated computer software, which also allows for (in more advanced variants) controlling particular elements of the device, e.g. with the column move in the *z* axis or motorized stage in *x*-*y* axes.

The first devices were introduced in late 1980s. Hirox developed hand-held video microscope system in 1986 which was supplied to the Japanese police force. It formed the basis for construction of commercial consumer devices. The following companies, among others, currently produce digital microscopes: Caltex Scientific, Celestron, Hirox, Keyence, Leica, Olympus and Sony.

The digital microscope of VHX-600 series by Keyence (Japan) was used in the carried tests [12]. Its general view and construction details are presented in Fig. 2.

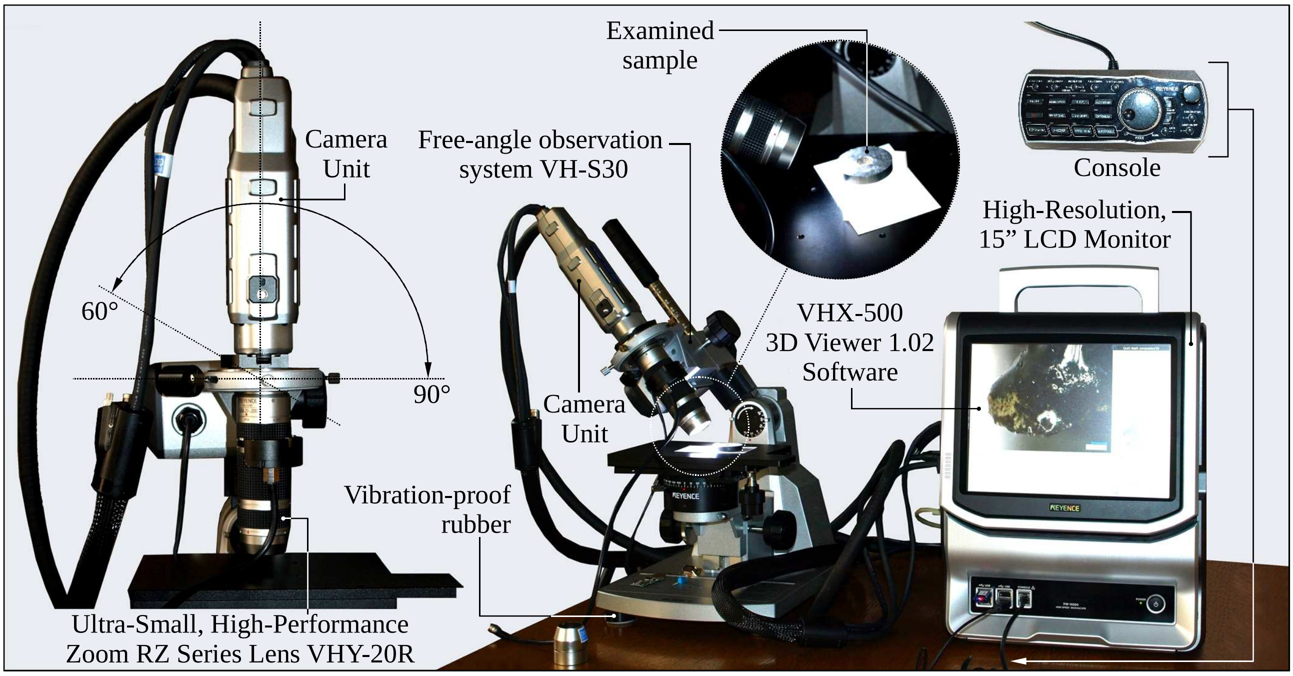

Fig. 2. General view and construction details of digital microscope VHX-600 produced by Keyence

The VHX-600 digital microscope was a device designed for carry out observations in reflected light. The system was composed of the following main elements:

- movable measurement stage and free-angle observation system with the possibility to control the elevation angle within the range 0°-60° and 0°-90°,
- camera unit using color triple matrix system of CCD type with resolution of 54 Mpixels,
- a set of additional prime and zoom lenses of RZ series with mag. 5000×,

- integrated visual module, equipped with a 15-inch monitor with UXGA resolution (1600×1200 pixels), hard drive 160GB and CD-R/RW recorder,
- VHX-H2MK and VHX-500 3D Viewer 1.02 software designed for acquisition, processing and visualization of the acquired images.

The device was characterized by high versatility and relative user-friendliness. The set of dedicated lenses and other accessories [13] allowed for configuration of the system for proper observation and measurement tasks. Such a system can be upgraded to VHX-600 Gen. II standard [14], which increases the observation and measurement precision. Owing to a number of its advantages, the VHX-60 microscope is used in numerous technique fields, some of which are presented in works [15],[16],[17].

This Section presents the exemplary tests results obtained using VHX-600 digital microscope produced by Keyence. The grinding wheel used in the tests was 1-35×10× 10-SG/F46G10VTO and its active surface was impregnated with silicone. The impregnation process consists in introduction of the impregnating substance, in this case silicone (synthetic organosilicone polymer), into the given grinding wheel. Impregnation is used in order to be able to actively influence the chemical conditions in the area of contact between the grinding wheel and the machined material. In case of silicone, the anticipated result is a decrease in the chip adhesion to the abrasive grains' surface. The obtained results are compared in Fig. 3. The top part of the figure presents exemplary GWAS (*Grinding Wheel Active Surface*) SEM *(Scanning Electron Microscope*) micrographs before and after the impregnation process. The SEM micrographs depicted in Fig. 3a-3b were acquired with mag. 200× and they present a GWAS AOI (*Area of Interest*) sized 650×478μm. The visual analysis of this AOI revealed the following characteristic of the GWAS elements: different abrasive grain sizes, areas with high concentration of silicone and free intergranular spaces. The SEM micrographs were acquired using JSM-550LV by Japanese JEOL. The other SEM micrographs obtained from this microscope are presented in Section 2.4. The micrographs presented in Fig. 3c-3e were acquired with the same 200× magnification with VHX-600 digital microscope by Keyence. On these AOIs the aforementioned characteristic elements of the GWAS can be also observed. As the GWAS image can be acquired in real color, these elements can be precisely recognized and analysed.

Analysis of the acquired micrographs revealed that the silicone penetrated deep into the grinding wheel pores in the impregnation process and covered the abrasive grains apexes with a thin layer. Accumulation of silicone in the free intergranular spaces suggests that it will influence the chemical conditions in the area of contact between the active abrasive grains and the machined material.

Figure 3f presents a 3D reconstruction of the GWAS from Fig. 3e. The reconstruction was carried out using by image processing and analysis ImageJ 1.45 software. W. Rasband (National Institutes of Health, Bethesda, USA) is the author of this software The interactive 3D surface plot 2.1 plugin developed by K. U. Barthel (Internationale Medieninformatik, Berlin, Germany) was used to generate the 3D reconstruction. The 3D visualization is often a useful element, especially in case of visual analysis of the given object. Even though an agreed value scale was assumed for the *z* axis, the spatial GWAS presentation is interesting and allows for a far broader interpretation of the grinding wheel internal structure than in case of typical 2D images.

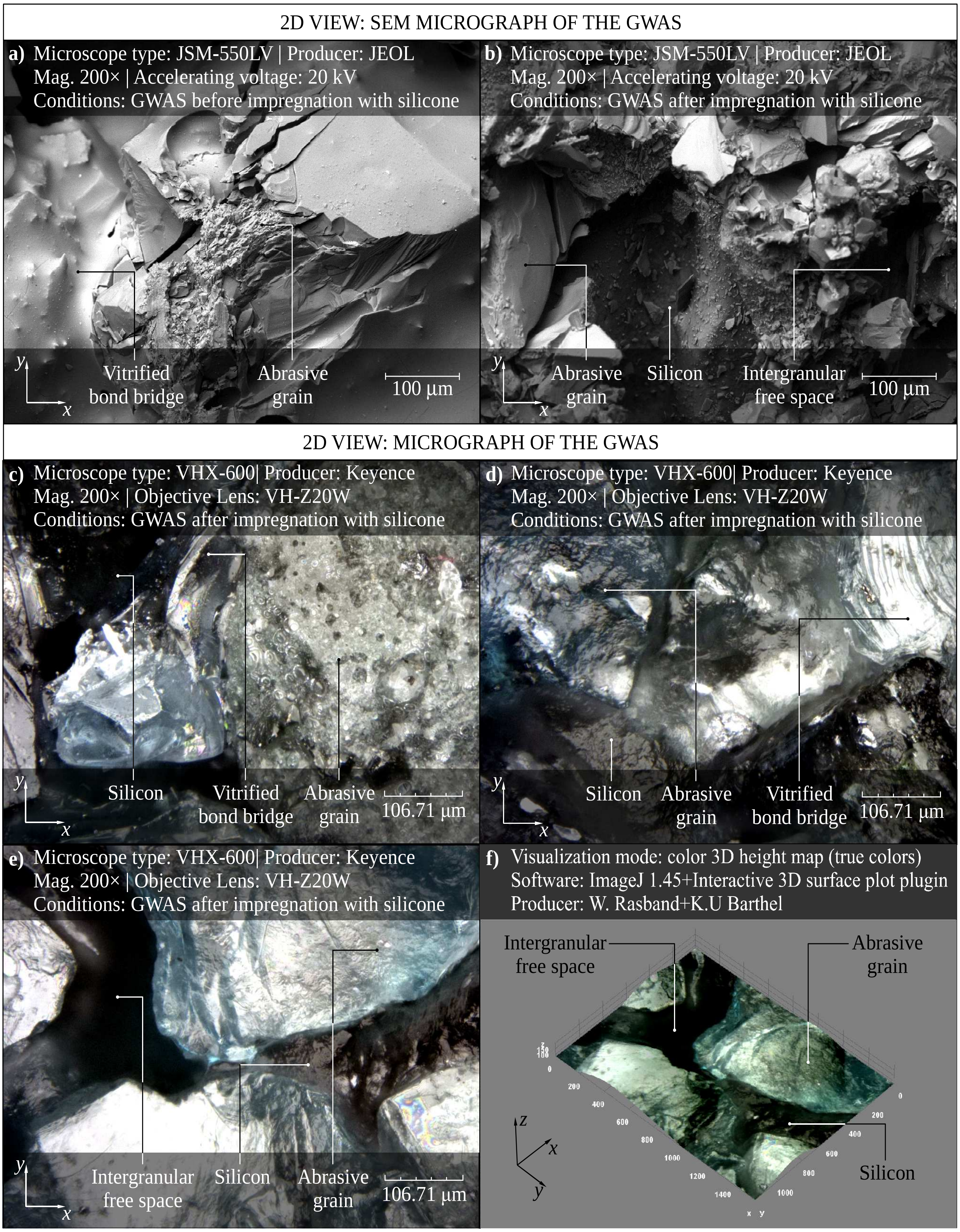

Fig. 3. Collection of selected results of experimental tests carried out on the GWAS type 1-35×10×10-SG/F46 G10VTO by using of: a), b) SEM microscope JSM-550 LV produced by JEOL, c)-e) digital microscope VHX-600 produced by Keyence, f) Image J 1.45 software using interactive 3D surface plot plugin

2.3. MICROSCOPY TECHNIQUE II: THE CONFOCAL LASER SCANNING MICROSCOPY

One of the most thorough optical microscopic techniques are the modern variations of confocal microscopy, named CLSM (*Confocal Laser Scanning Microscopy*) [18] or 3D laser microscopy [19].These techniques allow for, among others:

- acquisition of contour images and generating a 3D surface image/map of the examined object on this basis,
- fast acquisition of high quality images in the magnification range up to ~24.000×,
- assessment of the surface without the need to carry out the preparation process,
- assessment of a wide range of surfaces, including smooth and supersmooth surfaces, as well as those that are not resistant to pollution.

The theoretical basis of classical confocal microscopy was developed in mid 1950s by M. Minsky (Harvard University, Cambridge, USA) [20]. The first works on development of the confocal microscope construction were carried out in 1970s and 1980s. [21]. The first commercial device was introduced onto the market in mid 1990s. It used He-Ne lasers as source of light and made it possible to perform simple linear 2D scanning. The structure was improved and modified over the years and special efforts were made to:

- substitute the gas lasers with more stable semiconductors lasers (currently mostly lasers with wavelength within the range λ = 405-408nm are used),
- develop optical elements that minimize deformations of the obtained image, caused by the aberration phenomena that occurs in the short waves range, as well as to maximize the transmission of light with wavelength ranging λ = 405-408nm),
- develop scanning systems, that allow for carrying out precise 3D measurements of the assessed objects surfaces (scanners using MEMS (*Micro Electro-Mechanical Systems*)),
- design new measurement data processing algorithms,
- develop special computer software for procedures related to measurement data processing, analysis and visualization.

Nowadays 3D laser microscopes with fully automated measurement devices are produced and they allow for carrying out advanced tests of machine parts, semiconductor components, optical elements (machine, automotive, aviation, electronic industries), as well as new materials (metal and its alloys, composites, plastics, glass) and abrasive tools. The wide range of measurement possibilities of these devices contributed to broadening of the scope of their applications in numerous fields of modern science and technology [22],[23],[24]. Two types of 3D laser microscopes of the LEXT series produced by Japanese Olympus – OLS3100 [25] and OLS4000 [26] were used in the carried out tests, whose results are presented in this Section. A detailed description of these devices with, among others, the most important parameters and examples of use is presented, in works [22],[27],[28]. The general views of both microscopes are presented in Fig. 3-4.

3D laser microscope LEXT OLS3100 was used for detailed analysis of a small GWAS AOI (0.064×0.047×0.016mm) type 1-35×10×10- SG/F46G10VTO. The aim of these observations was to check the possibility of registering topography, that would present the structure of microcrystalline sintered corundum SG™ abrasive grains which the examined grinding wheel was made from.

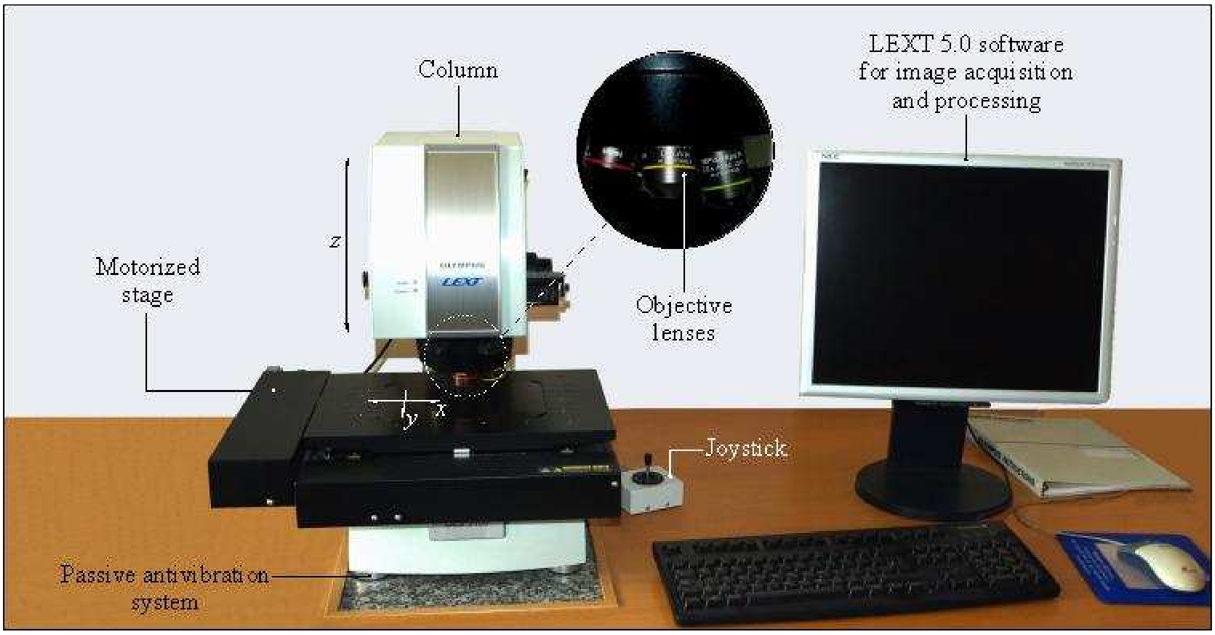

Fig. 4. General view of 3D laser microscope LEXT OLS3100 produced by Olympus

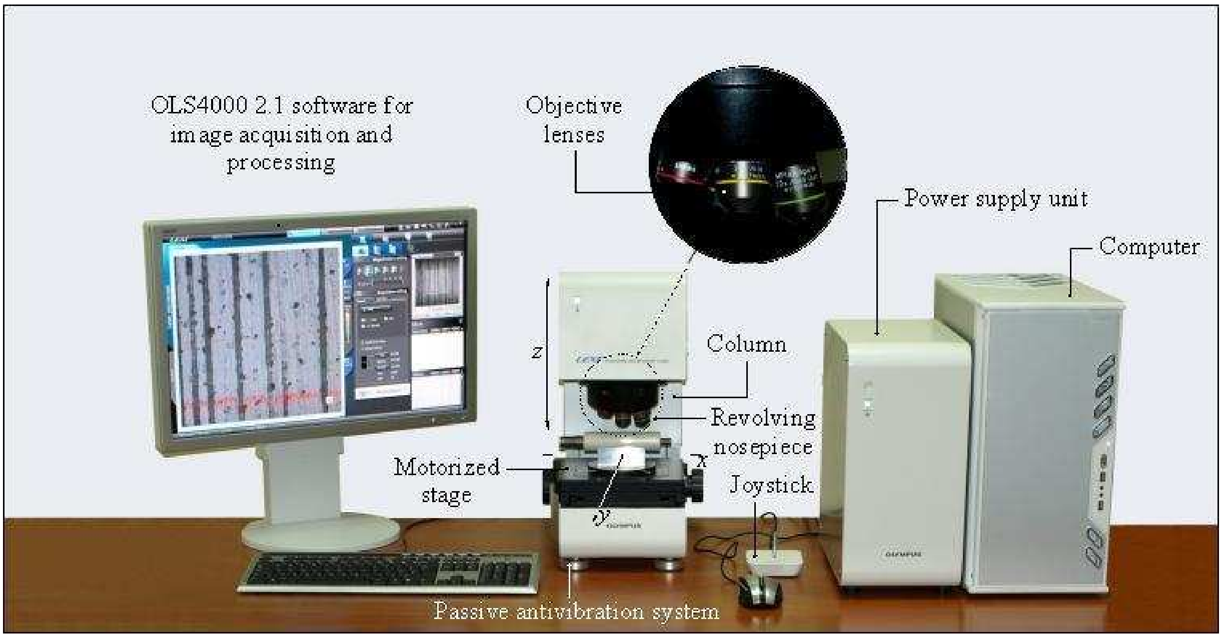

Fig. 5. General view of 3D laser microscope LEXT OLS4000 produced by Olympus

The analysis results presented in Fig. 6, reveal very detailed mapping of the abrasive grain surface topography by the measurement system. However, certain problems occurred in the measuring AOIs characterized by considerable height differences and relatively large gradients. Measurement errors, in the form of optical disturbances of high intensity, were detected in the top left hand corner of the registered topography, where free intergranular space was located.

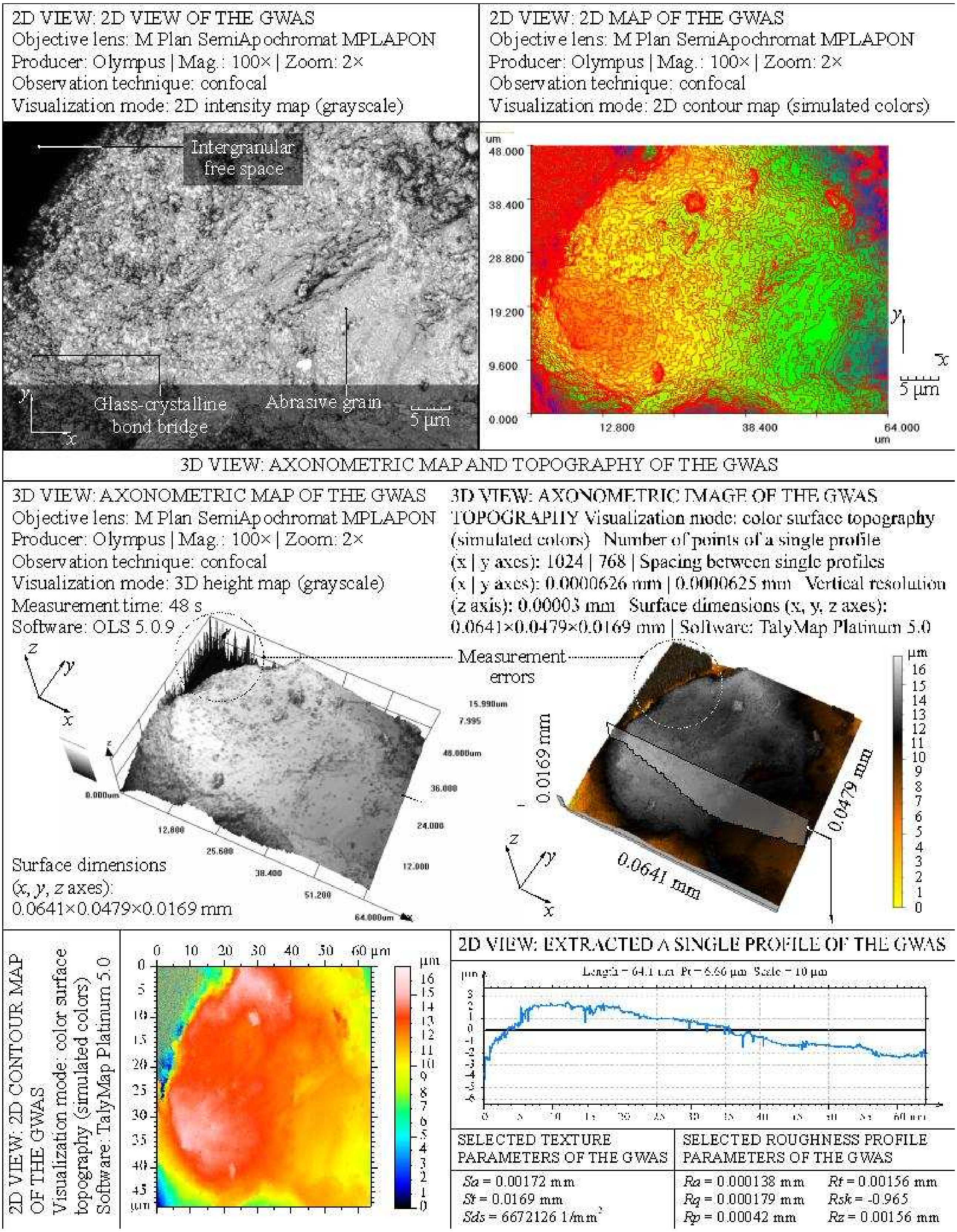

Fig. 6. Collection of selected results of experimental investigations carried out on the GWAS type 1-35×10×10-SG/F46G10VTO by using of 3D laser microscope LEXT OLS3100 produced by Olympus

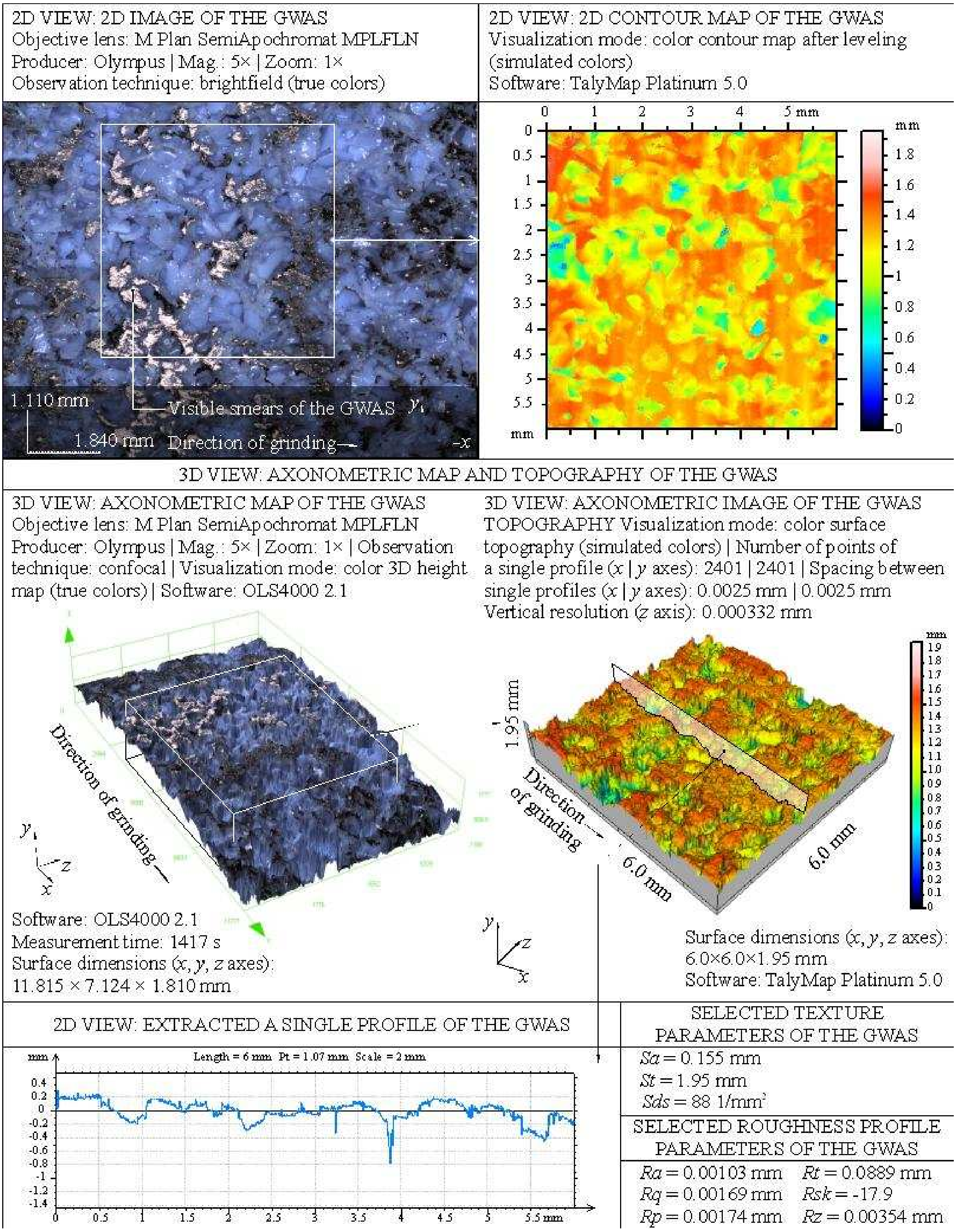

Fig. 7. Collection of selected results of experimental investigations carried out on the GWAS type 1-35×10×10-SG/F46N7VDG by using of 3D laser microscope LEXT OLS4000 produced by Olympus

This optical effect, typical of many optical devices, can be eliminated during the surface topography analysis by using filtrating procedures available in the dedicated computer software.

Figure 7 presents results of measurements and analyses of the GWAS type 1-35×10×10-SG/F46N7VDG carried out using 3D laser microscope LEXT OLS4000. A grinding wheel AOI sized 11.815×7.124×1.818mm underwent assessment. The GWAS was shaped in the process of grinding of internal cylindrical surfaces made from Titanium Grade 2® alloy. This material is classified as hard-to-cut because of the machining conditions. Smearing the GWAS with long and ductile chips of the alloy is an exceptionally significant problem in case of the grinding processes. The results of this phenomenon are well visible in the registered 2D map and on the measured topography of the examined sample's surface (Fig. 7). Precise comparative assessment of the influence of changes in the grinding wheel construction or the machining parameters on the level of the GWAS smearing in the hard-to-cut material grinding processes is possible with the application of the presented exemplary.

2.4. MICROSCOPY TECHNIQUE III: THE SCANNING ELECTRON MICROSCOPY

One of the classical microscopic techniques that has been in use for over 80 years is SEM (*Scanning Electron Microscopy*) [29]. The first devices were developed in 1930s [30],[31] and they were improved over the subsequent decades [32],[33] to obtain modern advances solutions. Scanning microscopy is one of the most important modern technical inventions that is widely applicable in various fields of science and technology. The basis and numerous applications of this technique were described in detail in a great number of books, handbooks and scientific papers [34],[35],[36].

One of the latest technical trends in SEM are desktop microscopes. They are a group of small-sized (in comparison to the classical SEM) devices characterized by compact construction in which a wide range of miniaturized elements, such as low-power electron guns and columns, were integrated. The desktop SEMs are also characterized by:

- high quality of the acquired SEM micrographs with magnification up to ~60.000× and resolution up to ~30nm,
- relatively short measurement time (a few minutes),
- the possibility to mount additional modules, that enhance the device's measurement possibilities (e.g. EDS (*Energy-Dispersive X-ray Spectroscopy)*),
- the price relatively lower, than that of the conventional SEM microscope.

The features of desktop SEMs, favored by many scientists and engineers, contributed to an increase in the interest in such solutions. This is clearly visible in numerous publications that describe interesting practical applications of desktop SEMs, that have been written in the recent years [37],[38],[39].

The hereby Section presents exemplary results of measurement carried out with two types of SEMs – conventional JSM-550LV by JEOL (Japan) and desktop Phenom™ G2 Pro by Phenom-World (Netherland). The general views of both microscopes are presented in Fig. 8-9.

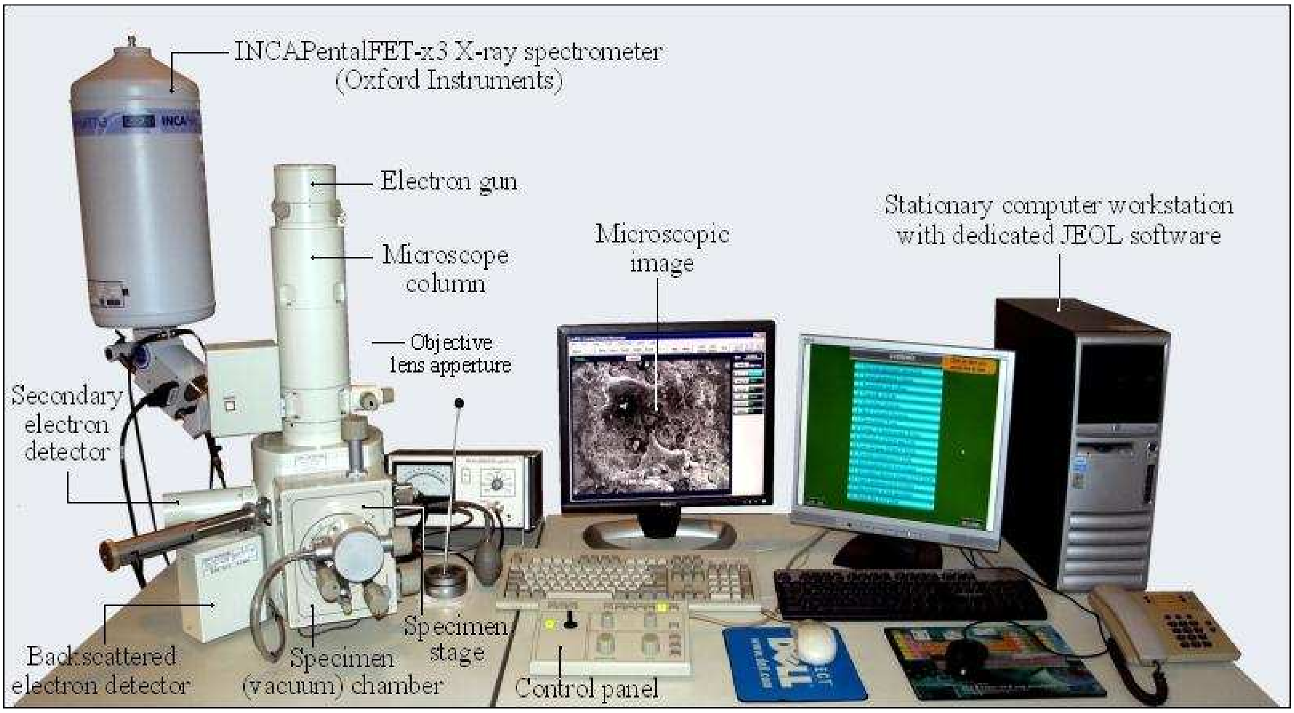

Fig. 8. General view of scanning electron microscope JSM-550LV produced by JEOL

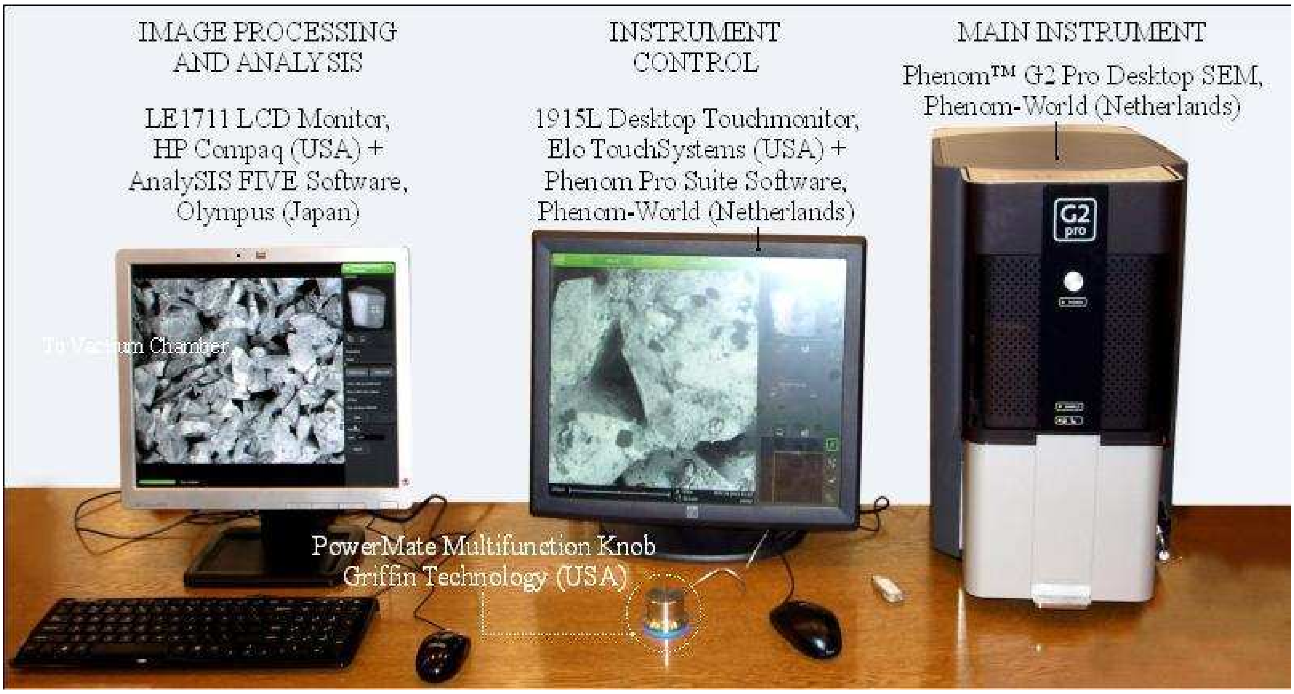

Fig. 9. General view of desktop scanning electron microscope Phenom G2 produced by Phenom-World

The first of the enumerated microscopes was presented in greater detail in work [40], and for this reason its description was deemed redundant here. The latter one is a construction that takes advantage of the possibilities of optical (digital) and electron microscopes. The complete magnification scope of Phenom™ G2 Pro ranged from 20× to 45000×, with resolution ~25nm [41]. The SEM micrographs were acquired with constant accelerating voltage *Ua* = 5kV. The acquisition time was relatively short and was <5s (optical mode) and <30s (electron mode).

Phenom G2™ Pro microscope operated under Linux operational system and used the dedicated computer software Phenom™ Pro Suite (system control, image acquisition and simple processing) and AnlySIS® by Olympus (advanced image processing and analysis).

Figure 10 depicts a collection of selected SEM micrographs acquired using JSM-550LV by JEOL, which presents subsequent stages of observation of the extracted GWAS AOI of 1-35×10×10-SG/F46L7VDG type. Figure 10a presents the input SEM micrograph sized 2545×1916μm, mag. 50×. This SEM micrograph formed the starting point for further observations. An AOI was extracted from it, sized 644×484,8μm, mag. 200× (Fig. 10b), from which two more AOIs sized 253×190,4μm, mag. 500× (Fig. 10c and Fig. 10d respectively) were extracted. The final stage of the observations was extraction of AOIs sized 121×91μm, mag. 1000×, from the above-mentioned SEM micrographs (Fig. 10e and Fig. 10f respectively). The GWAS analyzed using SEM micrographs from Fig. 10a-10f was characterized by clearly visible work conditions in the process of grinding made from Titanium Grade 2® alloy.

Acquisition of SEM micrographs was aimed at identifying the dominant grinding wheel elements' wear mechanisms (abrasive grains and bond) and the phenomena that cause them. SEM micrographs formed the basis for drawing conclusions about the intensity and form of the abrasive grains wear, the intensity of bond bridges chipping, processes of chip formation and the intensity of the GWAS smearing.

Microchipping of the abrasive grain apexes was observed on the analyzed surface, which showed that the resistance wear, caused by mutual influence of abrasive grains and bond bridges on the machined material surface, was dominant during the grinding process. The considerable volume of the GWAS smearing with chips of the machined material was also observed. These included microsmearings of active grain apexes and larger intergranular space smearings. They result from the properties of Titanium Grade 2® alloy which contains approximately 99,375% titanium with a small amount of alloy additions (Fe – 0,25%, O – max. 0,25%, C – 0,08%, Ni – 0,03% and H – max. 0,015%) and is characterized by high resistance and ductility.

SEM micrographs depicted in Fig. 11, obtained using the desktop SEM Phenom™ G2 Pro by Phenom-World, show a fracture in grinding wheel of 1-35× 10×10-SG/F46G10VDG type, which is characterized by ceramic bond with microcrystalline structure. In case of this grinding wheel the observation aim was to determine the fraction, size and layout of the crystalline phase (wilemit) in the crystalline residue matrix. This can be observed in the AOI extracted from Fig. 11a, sized 53,6×41μm, mag. 5000× and the GWAS AOIs from Fig. 11e and Fig. 11f, obtained in significant magnification (25500× and 10000× respectively). The effect of inhibition of the fracture propagation in the bond bridge (Fig. 11a and 11b), as well as the zone size on the border of contact between the bond and the microcrystalline sintered corundum SG™ abrasive grain (border phase on Fig. 11e and 11f) be observed in the acquired SEM micrographs.

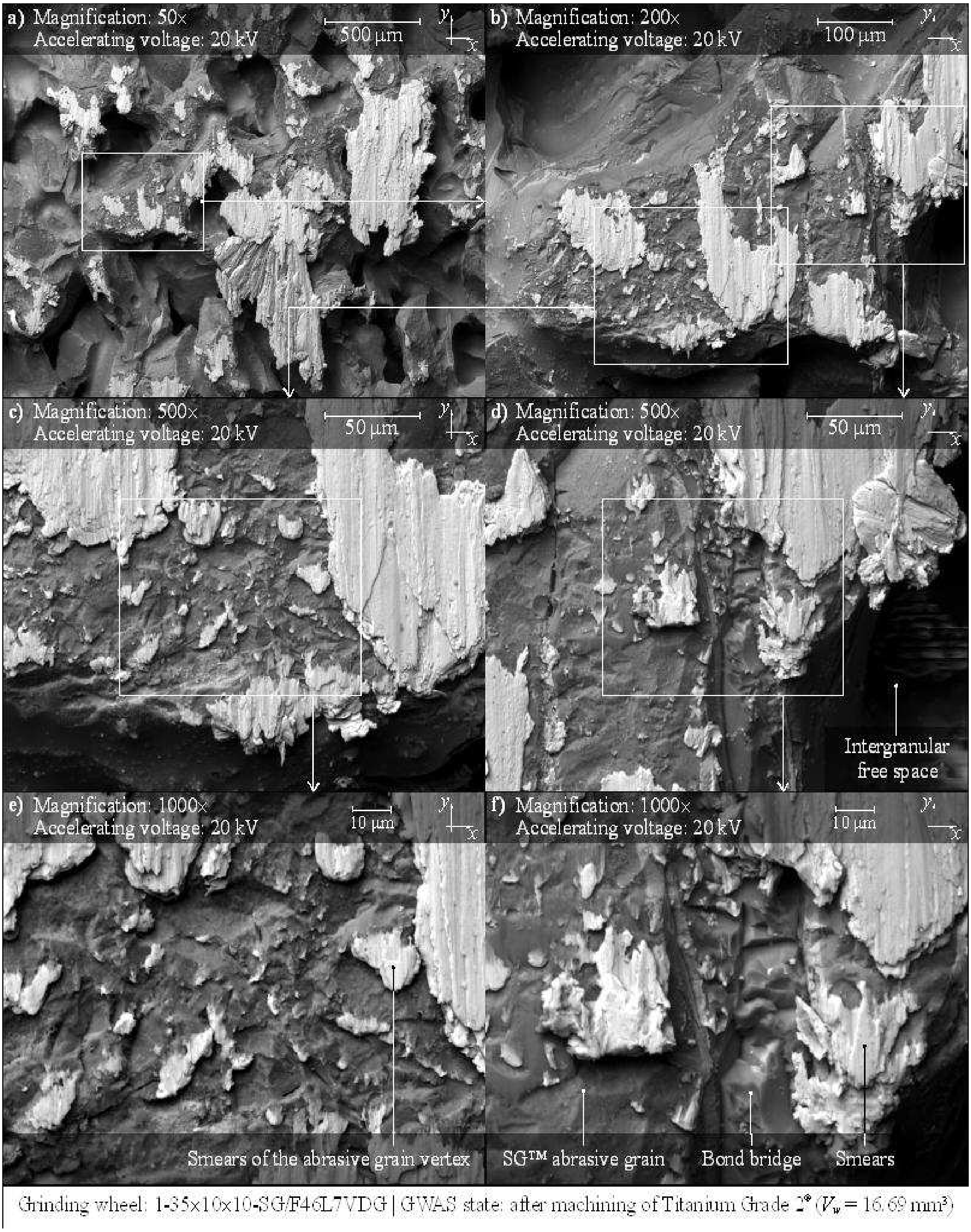

Fig. 10. Collection of selected results of experimental investigations carried out on the GWAS type 1-35×10×10-SG/F46L7VDG after machining process of Titanium Grade 2® alloy obtained by using of JSM-550LV produced by JEOL: a) mag. 50×, b) mag. 200×, c), d) mag. 500×, e), f) mag. 1000×

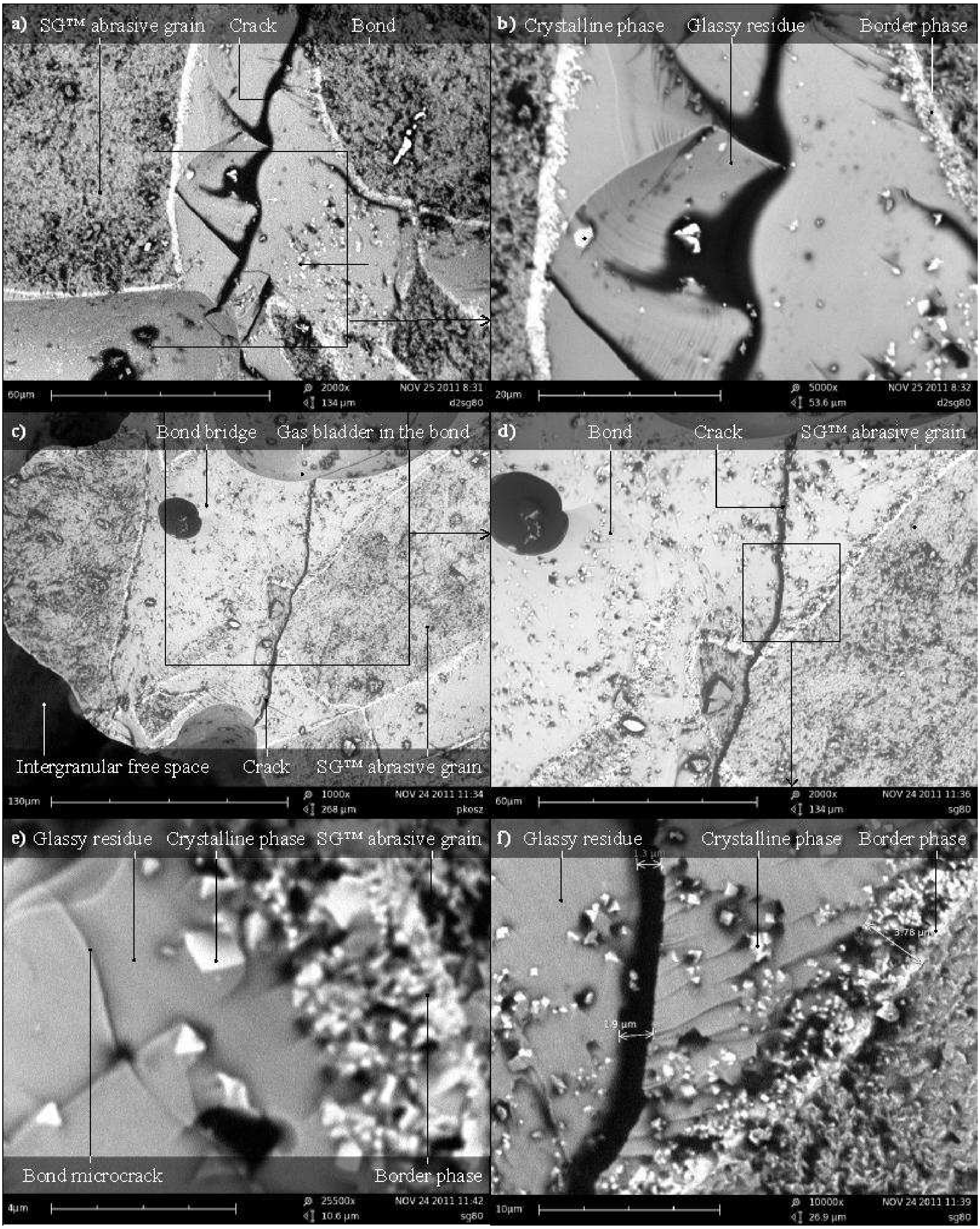

Fig. 11. Collection of selected results of experimental investigations carried out on the breakthrough of the GWAS type 1-35×10×10-SG/F46G10VDG obtained by using of Phenom™ G2 Pro produced by Phenom-World: a) mag. 2000×, b) mag. 5000×, c) mag. 1000×, d) mag. 2000×, e) mag. 25500×, f) mag. 10000×

3. CONCLUSIONS

The hereby work contains a review of advanced microscopic techniques as far as their possible application in diagnostics of abrasive tools is concerned. A number of tools in the form of grinding wheels with ceramic bond was subject to assessment. The grinding wheel surfaces were analyzed using three microscopic techniques – digital microscopy, confocal laser scanning microscopy and scanning electron microscopy.

Taking into consideration the overview character of the publication, the Authors decided not to present the detailed research carried out with one of the methods. Instead, they focused on presenting the possibilities of each of the methods, especially in relation to the used equipment and the process of registration, processing and analysis of the measurement results.

The obtained results of the carried out experimental tests formed the basis for drawing the following conclusions of general nature:

- selecting the proper microscopic technique is not an obvious decision and results from making (at least) a few assumptions concerning the used equipment, measurement methodology and the measured surfaces' characteristics,
- digital microscopy is a new useful measurement technique designed for routine assessment of abrasive tools surfaces, with magnification up to ~5000×. One of the advantages of the used digital microscope VHX-600 by Keyence was the possibility to obtain high quality color micrographs acquired for elevation angles ranging 0°-60° and 0°-90°. Moreover, it was also possible to install a wide range of zoom and prime lenses and various accessories on the device, which made it possible to configure the system in adjustment to the assumed observational – measurement tasks,
- CLSM is a far more advanced microscopic technique using 3D laser microscopes. This technique can be used in measurement tasks that require high precision of mapping the examined surface of the abrasive tools. The high quality and resolution of the obtained images, the possibility to generate 3D images/maps and wide range of magnifications – >17000×, make it possible to carry out advanced grinding wheel surface analyses. The 3D laser microscopes by Olympus – LEXT OLS3100 and LEXT OLS4000, presented in the work, are devices with significant observation and measurement possibilities,
- the possibility to assessment the abrasive grains structure in very big magnifications over 60000×, is provided by scanning electron microscopy. The technique, in development for over 80 years, is now represented by, among others, a new class of desktop-type devices. A number of advantages of this technique, enumerated in Section 2.4, makes it possible to apply this method in the GWAS assessment. The tested Phenom G2™ microscope produced by Phenom-World proved its high usefulness in numerous measurements carried out as part of the research. Versatility of the device and relative user-friendliness predispose it to application in broadly defined assessment of abrasive tools.

The presented overview of selected advanced microscopic techniques and examples of the obtained measurement results may turn out to be helpful in proper selection of observation – measurement techniques for certain applications.

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