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RECONSTRUCTION AND CHARACTERIZATION OF GRINDING WHEEL AND GRIT TOPOGRAPHY FROM SCANNING ELECTRON MICROSCOPY STEREO MICROGRAPHS WITH DIGITAL PHOTOGRAMMETRY

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ABSTRACT

Groundwood processes (GW, PGW) are among the major processes for mechanical pulping. Its major advantage over Thermomechanical pulping process (TMP) is lower requirement of electrical energy. Pulp stone (grinding wheel) plays a central role in groundwood process. The pulp stone consists of vitrified ceramic surface made of aluminium oxide grits. Condition of these grits on the pulp stone surface defines largely the pulp quality and energy consumption of groundwood process. Therefore, it is important to be able to quantify this kind of surfaces. This paper gives an introduction to the principle of automatic 3D reconstruction of surfaces from stereoscopic images and evaluates its applicability in reconstruction of surfaces of grinding wheels as well as of single grits. The paper also gives an example of the interrelation between topographic changes in grinding surface and groundwood wood pulp properties. Based on the results, reconstruction of the topography by the application of stereo photogrammetry is considered a suitable method for detailed 3D visualisation and quantification of a pulp stone surface or single grits in them. Topographic changes obtained in a grinding wheel and grit, for instance by dressing or by grinding, can be visualised and quantified in detail by using stereo photogrammetry and high resolution SEM images. Stereo photogrammetry is applicable in the basic research of grinding surfaces and grinding grits. The fact that the preparation of specimens and the production of SEM micrographs require specific instruments and skills appears as a limitation of the applications. The authors intend to apply digital photogrammetry in future basic research of the groundwood processes. The main objective of these studies is to resolve interactions between the grinding grits and wood, including the impact on mechanical pulp quality and energy consumption.

Keywords: Grinding, mechanical pulping, pulp stone, stereophotogrammetry, topography

INTRODUCTION

Groundwood (GW) and pressure groundwood (PGW) are among the major processes for mechanical pulp manufacture. Their annual capacity is about 10 million tons, and they are mainly used for SC, LWC and FBB (folding boxboard) manufacturing. The groundwood processes are still lucrative and viable choices for these papers and boards because their energy efficiency *versus* pulp quality combination is competitive with the other main process for mechanical pulping – Thermomechanical pulp, TMP.

Groundwood processes are quite simple mechanical systems, where wood logs are pressed against rotating pulp stones by mechanical means. The pulp stone consists of vitrified ceramic surface made of aluminium oxide grits. These grits have a dual role in wood grinding. On one hand the grits are subjecting repeated cyclic loading to the wood fiber structure. Repeated loading loosens the wood fiber structure. As a viscoelastic material wood absorbs the mechanical energy which transforms into heat by dissipation. On other hand, the grits are peeling the wood fibers of the softened wood surface. It has been realised that the grit surface characteristics play an important role in this process. In the field of mechanical pulping, characterization of grit surface has traditionally been subjective or has been assessed indirectly by its performance in grinding. In doing so, adjectives like "sharp" and "dull" has been used. The process performance has been characterised as "sharpness value" of the pulp stone, even if this value is a result of pulp stone and wood interaction, not solely a character of pulp stone. A more precise and quantitative methods for grinding surface characterization have become a necessity in order to gain better understanding of the grit to wood interaction, and to develop of better grinding surfaces. Even if groundwood process refers directly to grinding, it differs much from more traditional processes involving grinding, like metal grinding. Maybe the most significant difference in these processes is that in metal grinding

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one targets for certain characteristics of the work piece, but in groundwood the interest is to release wood pieces with specific characteristics suitable for papermaking. In groundwood process the condition of work piece is of little interest. However, it is common for both these grinding surfaces that the result depends of the condition of grinding surface and, thus, there is an interest to explore and apply similar methods in characterization of both surfaces.

In metal grinding it has been known for a long that the grinding wheel topography has a direct impact on the work piece surface quality. Thus, characterization of the grinding wheel topography has been one of the most important topics on the way to understand and control the grinding process. Increasing demands for better quality and higher productivity in the surface finishing process have been a major motivator.

Links between the grinding wheel topography, the surface quality and the productivity in finishing are clearly present, but not easy to quantify. Many researchers have explored this relation by modelling and by simulations[1-8], or through experimental work[9] in order to find relations between the grinding wheel topography and the condition of the work piece surface. Common for all the studies has been the need for a reliable and easy method to measure the grinding wheel topography, so that experimental data can be acquired and simulation results can be verified.

The characterization of the grinding wheel topography has taken advantage of the new methods that have been introduced for general characterization of various surfaces. On one hand, these methods range from rough averaging measurements in order to estimate the grinding wheel roughness to detailed microscopic methods, which provide 3D information on a micrometer scale. On the other hand, some methods are intended to be used by engineers for on-line measurements or even for closed loop process control of the grinding process or dressing operation, while scientific groups are interested only in the basic research.

A comprehensive collection of traditional techniques for determination of the grinding wheel topography can be found in a CIRP publication[10]. On the one hand, various stylus methods are in general widely applied in roughness measurements. Thus, it is not surprising that these methods have their application also in determination and quantification of the grinding wheel topography [9-16]. By this measurement process, a stylus is mechanically manoeuvred over an abrasive material. Therefore, such a measurement requires a very accurate mechanical xy stage or x traverse and wheel rotation system. Wear has been regarded as one significant restriction when stylus methods are applied on abrasive materials. Employment of the oscillation, where the stylus tip is raised, stage moved and the tip lowered again has significantly reduced such artefacts[17].

On the other hand, the laser triangulation method can be seen as an optical stylus. As a non-contact method, it is also easily applicable and faster for in-process measurements than a mechanical stylus. This instrument is basically a high resolution distance meter, which employs the so called triangulation method and a coherent laser as a light source. Applications for characterization of general type surfaces have been in existence for some time. Such a method has been tested by Björkqvist[18] and Brinksmeier[19] particularly on grinding wheels. In the experiments, it has been discovered that the grinding wheel topography can be measured and visualised, although the maximum resolution is limited by the spot size. In optically active materials like white aluminium oxide grits, scattering of light blurs the laser spot, which makes the measurement less accurate. A total reflectance in the grit material is also possible, which may totally block the information from the sight of the laser detector. Despite some disadvantages associated with this method, it has been used for reconstruction of the grinding wheel topography in some studies[20, 21].

One unique method applied in contact type measurements is based on detection of the contact points between a rotary grinder wheel and a dresser[22]. Touch points are detected by the acoustic emission (AE) signal bursts that are generated each time a dresser hits a grit. This method may be used to determine the active grits and their position in the surface, but also to control the dressing operation itself.

Pancewicz [23] applied a holographic contouring method for topographic measurement of grinding wheels. Even though this method could be applied only on transparent replicas of the grinding surface and involved quite sophisticated measuring arrangements and data processing procedures, it compares favourably to the mechanical stylus method[24].

Some of the methods described above have a limited resolution because of the measuring device (stylus method). They may be subject to human errors (manual measurements of stereoscopic pictures) and may give only averaged information of the grinding wheel roughness (hydrodynamic method). Some only consider the highest contact points between wheel and work piece (detection of touch points of a dresser with AE signals).

In grinding of materials with viscoelastic nature, e.g. wood, the impact of the grinding wheel topography is not limited to the cutting edges of grinding grits, but also by the grit morphology below the grit tops. The main reason for this is, of course, that the grinding grits have a greater intrusion in viscoelastic materials than in rigid materials like metals. Therefore the rate of strain caused by the grits is highly dependent of the grit morphology below the highest grit tips as well.

This paper introduces a new method for characterization of the topography of grinding wheel surfaces as well as single grinding grits. The method involves digital photogrammetry, which employs information of the stereoscopic images and a pattern matching method to achieve equivalent details. In fact, this method is identical with the stereoscopic method applied on grinding surfaces by Matsuno *et al.*[25]. However, digital imaging, computerised pattern matching technology, fast digital computer and software has made it hundreds of times faster, more accurate and less sensitive to human influence.

EXPERIMENTAL

Stereo photogrammetry method

The basic principle of this 3D-reconstruction process is to discover homologous details from two images taken of the same object but from two different view angles. As the equivalent points are found in the pictures, their height information can be calculated from the lateral shift of each point from one picture to the other, and from the geometrical assessment in the imaging **(Figure 1** and **Formula 1**). The human eye intuitively finds the equivalent points of the images, but in digital processing the information of two images needs to be correlated pixel by pixel using the information around the target pixel. A matching pair of pixels is found where the correlation is the highest. The most important condition in matching the stereoscopic pictures is that there is enough texture in the pictures.

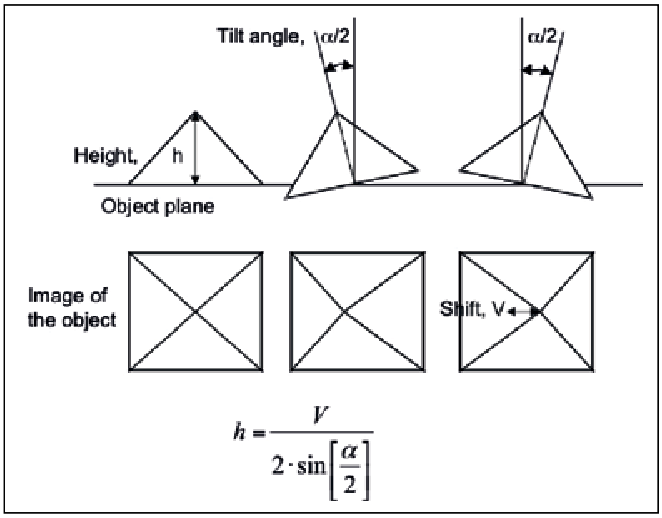

Figure 1. Geometrical assessment in stereo photogrammetry

$$h = \frac{V}{2 \cdot \sin\left[\frac{\alpha}{2}\right]} \qquad [1]$$

$where,$

$h = height\ of\ the\ pixel\ in\ the\ image$

$\alpha = tilt\ angle\ between\ stereo\ pair\ images$

$V = lateral\ shift\ of\ pixel\ between\ images$

The Formula 1 is only valid for symmetrical tilting and for parallel projection geometry.

The image information becomes distorted when the angle of view relative to the object is changed. This may be indicated by a lower correlation of the values calculated in pattern matching procedure. A low correlation value does not necessarily indicate poor matching, but merely a steep change in the topography. Of course, if some details are not apparent in both images, a relevant correlation cannot be found. A change of the view angle will distort the optical perspective and subsequently change the aspects of the object. This is usually not considered in commercial programs, but as compensation some freedom is provided to find the best matching correlation points in the equivalent stereo images. For good accuracy, it is essential that the distance to the camera (or SEM detector) is as long as possible in relation to the height of the object. The assumption of parallel projection geometry is necessary, so that the simplified calculation formula (Formula 1) would not cause a significant error.

Commercial analysing programs are capable to calculate the height values for each pixel of the picture. Since the displacement of each pixel is calculated from information provided by a larger group around the pixel, it is even possible to interpolate the height measurements at a sub-pixel level[26]. This capability is particularly important for objects with steep height changes, where, accordingly, even one pixel may cause a substantial error.

Application of stereo photogrammetry on photographs taken far from the object, *e.g.* a building, does not involve major problems. This is because these images can usually be taken with a digital camera, so that the requirement for parallel projection geometry becomes satisfied. Also, the depth of field in these pictures is usually high enough to provide adequate sharpness. Though it would be possible to apply the method on images taken of smaller objects by a light microscope, they do not have the required depth of field. Also the wavelength of visible light limits the theoretical resolution of light microscopy. Therefore, SEM micrographs are superior in this respect, when high magnifications are required.

Reconstruction of grinder wheel surface in 3D

The method of stereo photogrammetry was tested with a piece of vitrified ceramic surface taken from a pulp stone recently discarded from an industrial pressurised grinding machine. A test piece of 20 mm in diameter and 30 mm in length was drilled out from the surface of the grinding stone, specified as Norton 38A601N7V21. The imaging of the ceramic sample was carried out at Åbo Akademi University using the Cambridge Instrument StereoScan 360 scanning electron microscope (SEM) and the PGT (Princeton Gamma Tech) IMIX (Image and X-ray analyzer) imaging software. The SEM was equipped with the sample stage, which could be tilted manually. The tilt angle was measured by the digital resolver, which could provide ± 0.1 degrees accuracy. From this number and Formula 1 it can be estimated that the tilt angle may generate up to ± 2.8% error in height calculations.

The sample preparation and analysis procedure were as follows: Initially the sample was gently cleaned from loose cutting dust with a dense nylon brush, and then sputtered in a vacuum chamber with carbon to improve its conductivity, which is a standard SEM procedure for imaging of non-conductive materials. The sample was accordingly placed in a SEM microscope for stereoscopic photographs.

In the second phase, fibre and wood resin residues of the ceramic sample were destroyed by incinerating in an oven for 20 h at 950°C. The charred organic matter was removed by an ultrasonic washer, and the sample was then dried in an oven for 20 h at 200°C. The purified sample was subsequently sputtered with gold, which is another sample preparation standard for non-conductive SEM samples, and stereoscopic pictures were taken again.

The stereoscopic pictures were taken as follows: The sample holder was tilted from the zero planes 3.5 degrees towards and then 3.5 degrees away from the detector. Images with 1024 x 800 pixels were taken at a magnification of 25´, which resulted in a pixel size of 0.6 μm. For imaging the sample topography, the information provided by the secondary electron (SE) detector was used.

It is apparent from the SEM micrograph of an unpurified ceramic sample (**Figure 2**) that the surface was blocked by wood fibre fragments and wood extractives. After cleaning, the ceramic sample appeared to be much more open (**Figure 3**).

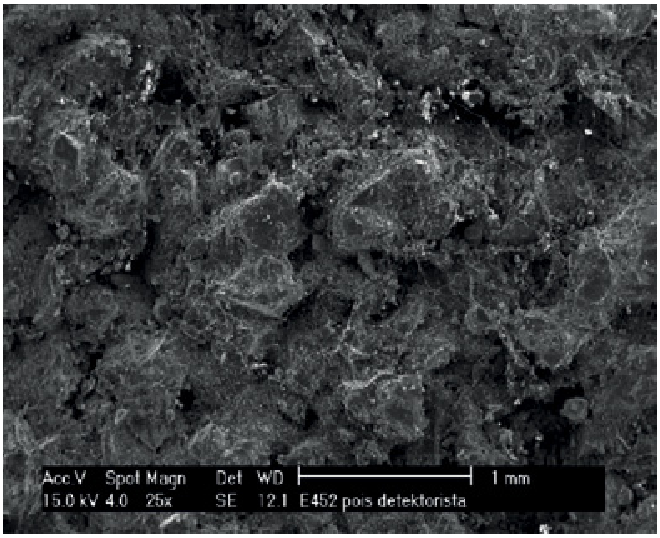

Figure 2. SEM image made of an unpurified pulp grinding surface after carbon coating

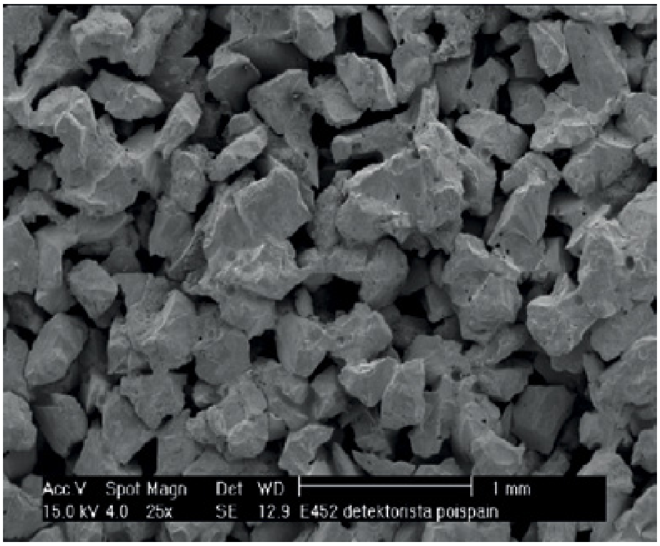

Figure 3. SEM image made of a purified pulp grinding surface after gold coating

The digital stereoscopic images were processed by application of the Stereo module of the AnalySIS software[26]. For topography visualisation the software produced a greyscale image, where each height value is presented in an 8 bit grey scale in the range from 0 to 255 (**Figure 4**). In this case, the height difference between the reference plane and the highest peak of the grit was about 250 µm, which provided a theoretical resolution of 1 µm in height for visualisation on the screen. However, the quantitative computer calculations took advantage of the full image resolution in the matching procedure. The AnalySIS software was applied in the sub-pixel matching mode in order to minimise errors in peak-point locations, where the height changes of the object were large.

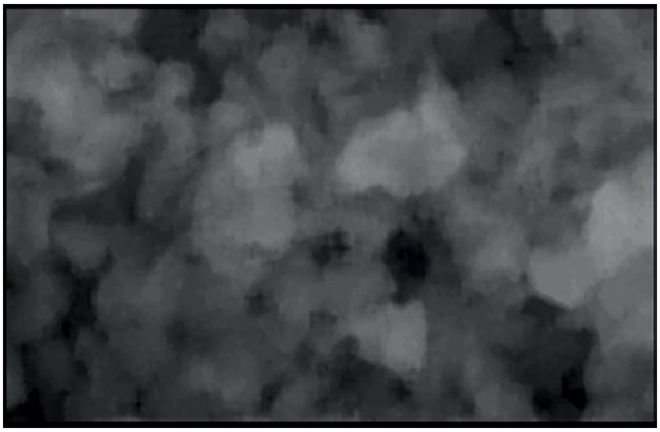

Figure 4. Topographical height map as a grey scale image made of a purified pulp grinding surface

By application of the Stereo module of the AnalySIS software, it is possible to visualise the surface in a 3D mode as a false colour or surface contour mapping. Also, a more realistic view to the object is available as one of the stereo pair pictures can be combined with the height map in a 3D image. However, the image becomes distorted as the 2D picture pattern is stretched over the reconstructed 3D topographic surface.

Stereo reconstructions of the unpurified and purified ceramic surfaces are shown in **Figure 5** and **Figure 6**, respectively.

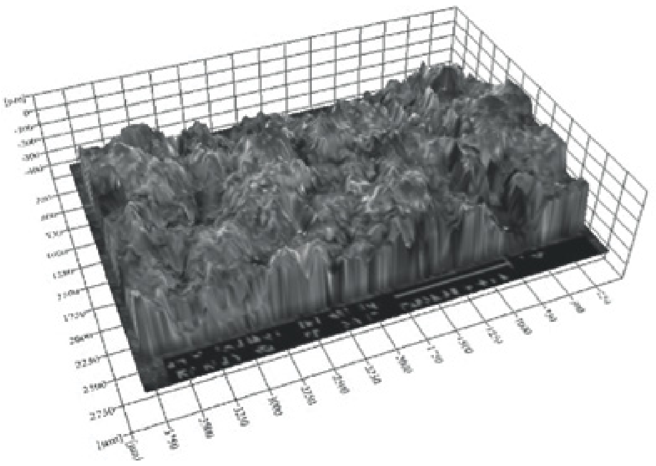

Figure 5. Stereo reconstruction of an unpurified pulp grinding surface

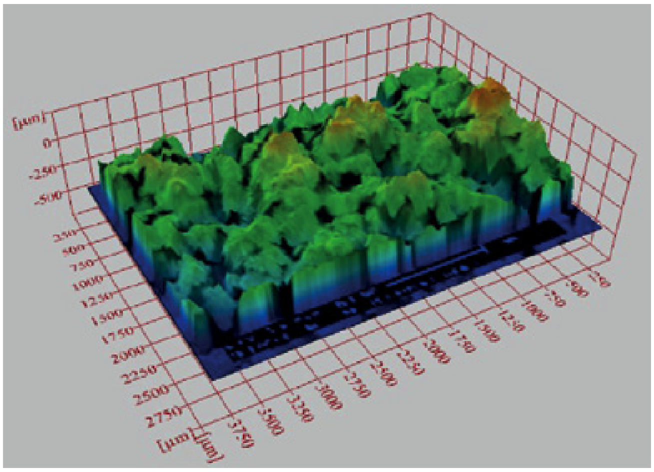

Figure 6. Stereo reconstruction of a purified pulp grinding surface

Visualisation and quantitative measurements of a single grit

Another challenge of this evaluation was the reproduction and quantification of the topography of single grits of a pulp grinding surface.

The grinding tool was made with Treibacher SCTSK #60 mesh aluminium oxide grits by brazing them on a surface of a stainless steel wheel. The wheel of 300 mm in diameter was built of 18 segments, each of which was attached to the wheel body by four M5 bolts underneath of the segments. It allowed dismantling the wheel segments after grinding for examination by SEM.

Before the insertion of a segment in the SEM, it was cleaned from debris with water and acetone and its surface plated with carbon to suit the SEM examination. The first SEM analysis recorded the location coordinates of each grit and examined it for later evaluation. The stereo imaging and quantification procedures of the surfaces by stereo matching were conducted as explained earlier in this paper. Tilting of the sample (+ and -3.5 degrees) was done perpendicularly to the direction of the wheel rotation. The tilt angle was a compromise between the visibility of details in both images and a good peak resolution.

Figure 7 shows the right hand SEM micrographs of the sample grit before conditioning, and **Figure 8** the same grit after conditioning. The conditioning was done with a 180 mesh flap wheel that was rotated in contact with the grinding surface under wet conditions.

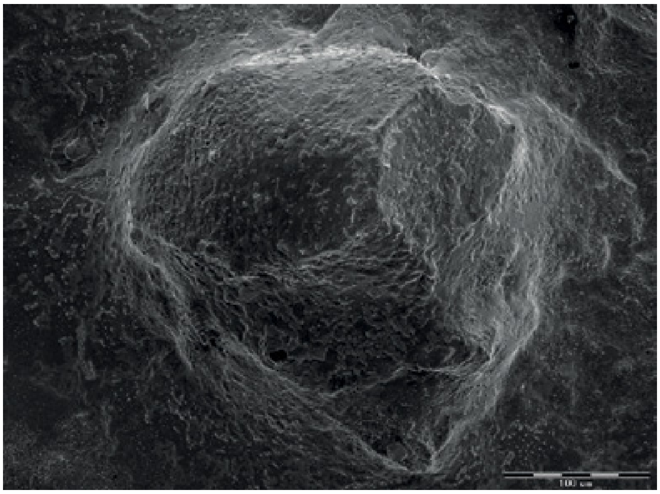

Figure 7. SEM image of a 60-mesh aluminium oxide grit in the grinding wheel surface before conditioning

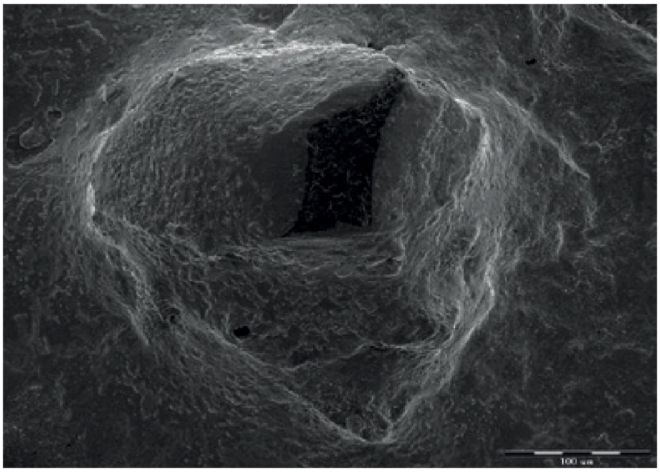

Figure 8. SEM image of a 60-mesh aluminium oxide grit in the conditioned grinding wheel surface

Three-dimensional reproductions of the grits are shown in **Figure 9** and **Figure 10**, respectively. The clearest change caused

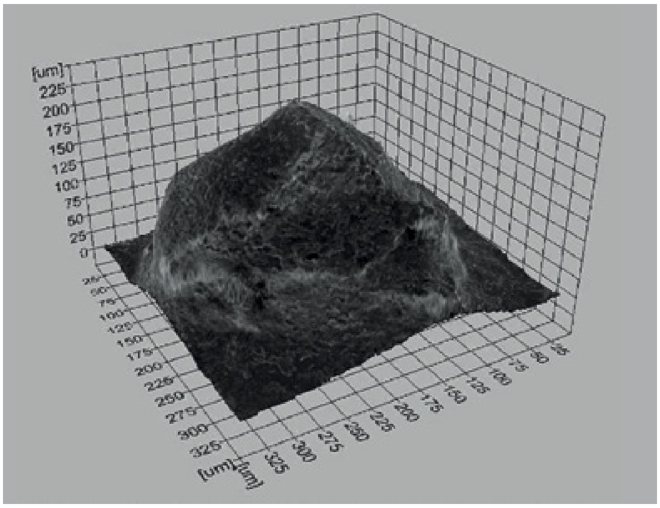

Figure 9. Stereo reconstruction of a 60-mesh grinding grit before conditioning

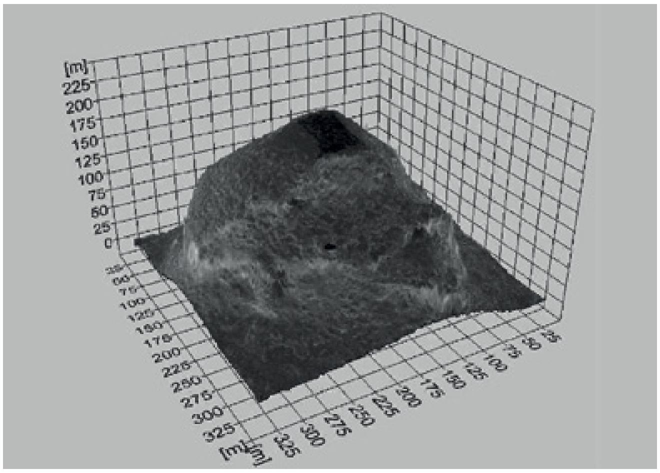

Figure 10. Stereo reconstruction of a 60-mesh grinding grit after conditioning

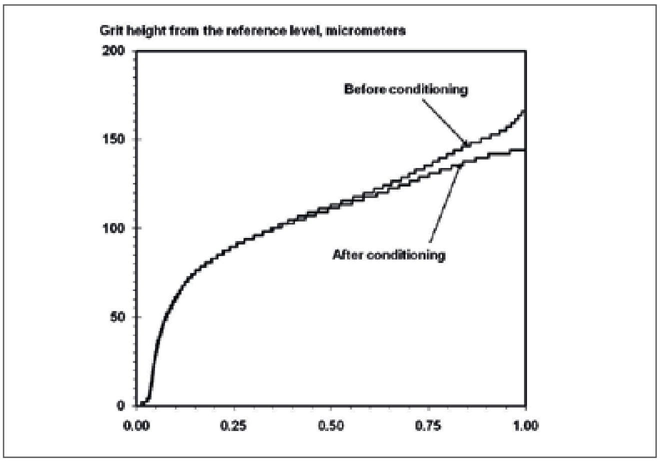

Figure 11. Cumulative height distribution of the grinding grit surface before and after conditioning

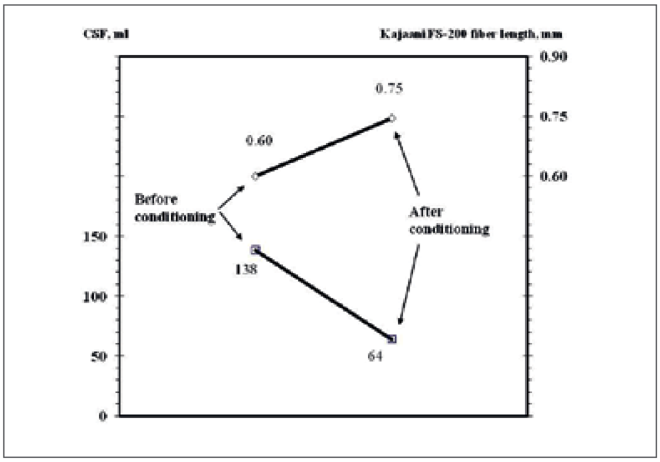

Figure 13. Impact of grinding surface conditioning on groundwood pulp CSF and fiber length

by the conditioning is the flattening of the top of the grit, which is visible both in 2D as well as in the 3D images.

Figure 11 illustrates the cumulative height distributions that have been produced from the reconstructed surfaces that were produced by the stereo photogrammetry method. The measurements appear in the graph in increasing order along the relative abscissa axis.

In the cumulative height distribution curve it is noticeable that major grit changes caused by the conditioning took effect in the highest peak of the grit, which before conditioning was about 190 µm above the reference plane. The conditioning lowered the peak height by 20 µm. Some changes were apparent also in the lower regions of the grit, but as these were not accessible for the conditioning tool, the changes evidently appear as a result of errors in the surface reconstruction process. The height region ranging from 25 to 100 µm had the steepest height changes (**Figure 12**), which are subject to errors in stereo matching as explained above. For the range from 100 µm to the grit top, however, the measurements are more accurate. The visual impression provided by the SEM micrographs appears to be in agreement with the measurements.

The changes to single grits may appear small, but effect for process performance is clear. **Figure 13** illustrates the pulp CSF and fiber length produced with the same grinding surface, first in the state representing before conditioning and secondly after conditioning.

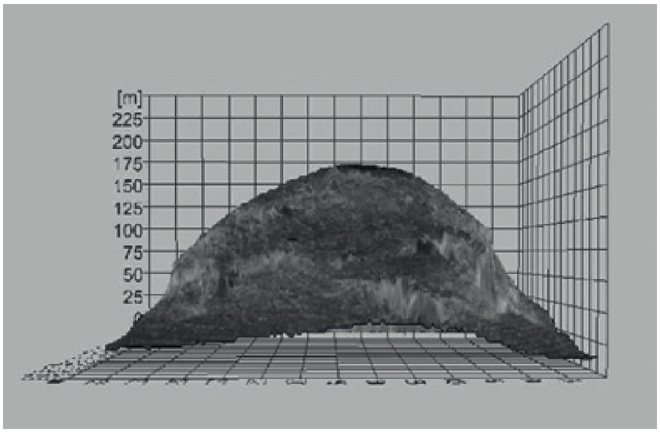

Figure 12. 3D reconstruction of a grinding grit after conditioning. Grit viewed from the side

DISCUSSION

In the past, stereo reconstruction of grinding surfaces had little practical value because it involved a lot of manual work and subject to human errors. The technical advance in modern high resolution digital imaging technology, fast computer programs and pattern matching procedures have made digital photogrammetry a suitable and interesting method for detailed studies of the topography of a grinding wheel surface or even a single grit.

Another technique, the laser triangulation method, is more frequently used for topographical characterization of various surfaces, including grinding wheels. It generates the topographic information from individual measurement points, but it depends on the accuracy of the mechanical machinery that moves the laser beam and detector over the target object. Stereoscopic reconstruction again is dependent on the detection of a number of homologous points. The only mechanical variable affecting the measurement is the tilt angle applied in the stereoscopic imaging, and an error in this variable does affect the 3D reconstruction result dramatically. So, the adjusted tilt angle in the SEM on the one hand, and, on the other hand, the angle between the laser beam and detector define the accuracy of the height determination values in the methods described. A wide angle would enable better resolution, but for an object with steep height changes the details may disappear for either of the two stereo images, or out of the sight of the laser detector. Thus a compromise may be required to simultaneously obtain the best resolution and visibility.

Even though the accuracy of stereophotogrammetry method is dependent on the basic calibrations of SEM instrument and its imaging geometry, and realistic error estimation can be done on the basis of these factors, the calibration procedure should be considered in the future measurements. The stylus method is the only ISO recognised method for quantitative characterization of surface roughness (ISO standard 5436:1985). A comparison between the stereophotogrammetry method and the stylus method may be done by a suitable test piece that is subjected to both methods.

CONCLUSIONS

Reconstruction of the topography by the application of stereo photogrammetry is considered a suitable method for detailed 3D visualisation and quantification of a pulp stone surface or single grits in them. By combination of two 2D SEM micrographs stereo reconstruction of the surface becomes possible and provides a realistic impression of the true topography of a grinding surface or grit. Topographic changes obtained in a grinding wheel and a grit, for instance by dressing or by grinding, can be visualised and quantified in detail by using stereo photogrammetry and high resolution SEM images. Even though digital photogrammetry would be feasible for images obtained by light microscopy, limitations on the theoretical resolution and the depth of field would not provide the conditions for a successful evaluation of individual grits in a grinding surface. Stereo photogrammetry is applicable in the basic research of grinding surfaces and grinding grits. The fact that the preparation of specimens and the production of SEM micrographs require specific instruments and skills appears as a limitation of the applications. SEM instruments can normally accommodate only small specimens and, subsequently, only a relatively small piece of a grinding wheel can be analysed. This requires the extraction of a small sample of the wheel surface and would thus imply its destruction, unless it is made of very small detectable segments or replicas are produced of the surface. The authors intend to apply digital photogrammetry in future basic research of the groundwood processes. The main objective of these studies is to resolve interactions between the grinding grits and wood, including the impact on mechanical pulp quality and energy consumption. ■

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