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MONITORING OF A MICRO-SMOOTHING PROCESS WITH THE USE OF MACHINED SURFACE IMAGES

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Abstract

Industrial applications require functional surfaces with a strictly defined micro-texture. Therefore engineered surfaces need to undergo a wide range of finishing processes. One of them is the belt grinding process, which changes the surface topography on a range of roughness and micro-roughness scales. The article describes the use of machined surface images in the monitoring process of micro-smoothing. Machined surface images were applied in the estimation of machined surface quality. The images were decomposed using two-dimensional Discrete Wavelet Transform. The approximation component was analyzed and described by the features representing the geometric parameters of image objects. Determined values of image features were used to create the model of the process and estimation of appropriate time of micro-smoothing.

Keywords: Belt grinding process, Surface roughness & micro-roughness, Surface image, Wavelet decomposition.

1. Introduction

In today's industry, functional surfaces are produced by multi-process manufacturing methods. Thus the generated surface texture is the superposition of the successive manufacturing process signatures [1-3]. The micro-smoothing process provides a final finish of a surface topography in cases where the shape and structural properties of the surface are produced by the pre-operation [4-5].

Surface topography can mainly be described by three kinds of roughness parameters: amplitude, frequency and hybrid parameters. These surface parameters are based on a single surface characterization and they are weakly related to the variations in working process parameters [6-8].

Surface finish topography can be achieved by various methods. One way is to use the belt finishing method [9-10]. The abrasive process used in this research consists in applying a belt to the face of the rotating workpiece with a defined pressure and axial oscillation. During the abrasive tape motion, the abrasive grains undergo oscillation at a specific frequency in the direction perpendicular to that of the abrasive tape motion.

The problem concerns evaluation of the machining time in which the tape is capable of creating the desired micro-topography on the worked face (finishing time). The methods embrace optical evaluation of the tool and workpiece quality in the following categories: whether the tool was correct and used in a proper way with suitable parameters, whether the workpiece topography is achievable with the technology used, and whether the surface image is a suitable source of information for process evaluation.

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2. Theory

The method of micro-smoothing is shown in Fig. 1. The method is based on the continuous slow introduction of the abrasive tape in the working zone. The cutting tool consists of geometrically calibrated abrasive grains of aluminum oxide adhering to a polymer strip. The finishing film is applied to the rotating workpiece with a defined pressure and axial oscillation. This technique usually removes a depth of cut of about 4 µm [11-14].

The micro-smoothing method involves belt grinding operation with four different sets of parameters. Four different parameters of belt grinding operation were applied for micro-smoothing. The types used were micro-smoothing, micro-smoothing with axial oscillations, micro-smoothing with buffing compound, and micro-smoothing with axial oscillations and buffing compound (Fig. 1). Each type of finishing was run independently. The quality of the machined surface was evaluated as a function of time.

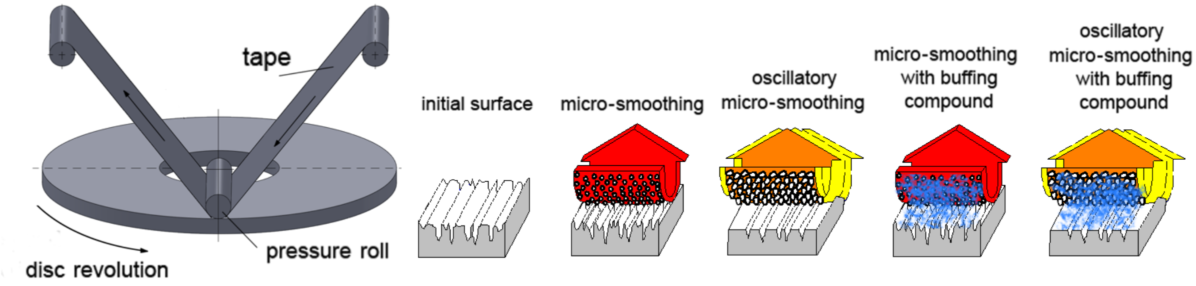


Fig. 1. Application of the belt grinding process for micro-smoothing.

The problem is how to carry out micro-smoothing and obtain the desired quality of the surface under the assumption that the initial surface has the specific geometric structure of a surface with well-defined tracks.

At the selected time the machined surface (initial surface) is in a steady state. The introduction of the belt grinding process (input signal) caused an immediate change in the output signal (machined surface) from its current value to some other constant value. The process causes a qualitative change in the micro-smoothing space – a change in the roughness parameters and change in surface texture. The process output signal (machined surface) is observed until a new steady state is reached (Fig. 2).

The gain ratio of the model of the micro-smoothing process is determined by the relation of the output signal increase to the input signal increase from one steady state to another. An identification of the parameters of the model must describe the character of the process on the basis of the nature of the time response function. Then, on the basis of an approximation of the obtained response of the object, the coefficients of the model are defined [15].

If we assume that the process is described by the first-order homogeneous differential equation

$$\frac{d\,y(t)}{d\,t} + a\;y(t) = 0\,, \tag{1}$$

then we obtain a solution in the form of Equation (2)

$$y(t) = y(t=0)e^{-at} + C_O\,. \tag{2}$$

If we assume that the process is described by the first-order homogeneous differential equation with the input function in the form of a step function

$$\frac{d\,y(t)}{d\,t}+a\;y(t)=b\,u(t), \tag{3}$$

then we obtain a solution in the form of Equation (4)

$$y(t)=y(t=0)e^{-at}+\frac{b}{a}\left(1-e^{-at}\right)+C_O, \tag{4}$$

where: $y(t)$ is the output value (surface feature), $u(t)$ the input function (parameters of finishing process), $1/a$ the time constant parameter and b/a the gain parameter.

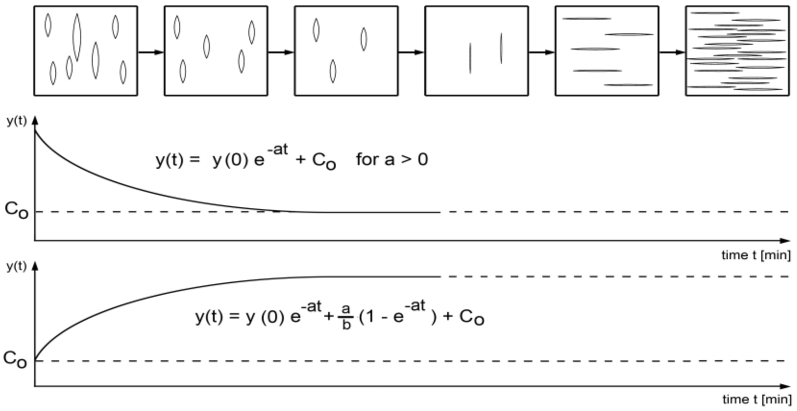


Fig. 2. Determination of machining time using machined surface features.

The parameter $1/a$ for $a>0$ can be interpreted as the period T. For $t=T$ we achieve a 63% steady-state surface (for $t=3T$ we achieve a 95% steady-state surface). The parameter b/a can be interpreted as gain.

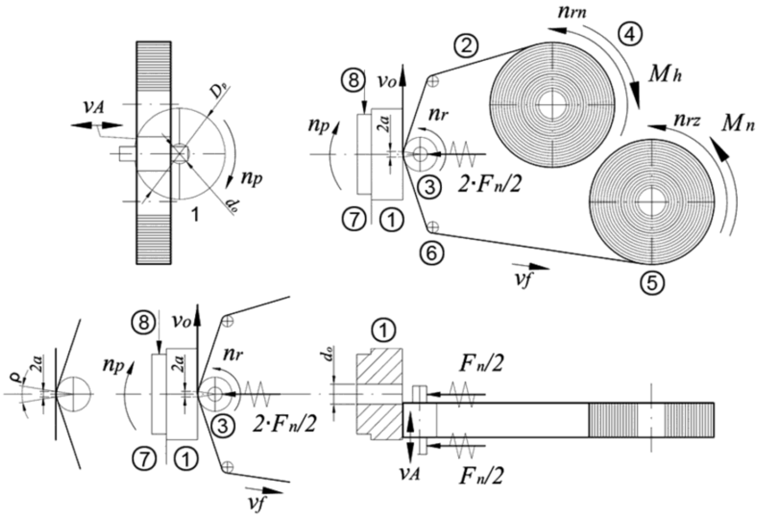
Each of the parameters supplies information about the grinding (pre-process). Visible effects of the pre-operation can be seen as ridges, which gradually disappear over the finishing time. First the traces are shallower, and then their number decreases. Gradually they are replaced by the traces of the belt grinding process.

Based on the image features of the machined surface gathered over time, it can be seen that some of the features decrease (such as the area of objects) while others increase (including some shape ratios). Based on the evolution of image parameters over time it was possible to estimate the finishing time when the dominant surface characteristics are grinding ridges.

3. Experimental procedure of micro-smoothing technology

A metallic workpiece made of C45 steel was prepared in the form of a disk. The front face was first machined using the grinding process. Then the finishing process was applied. The finishing film was located in such a way as to smooth the machined surface. The machined surface texture after the smoothing process consists of concentric circles.

The method of micro-smoothing with foil tapes (IMFF 9 AO 12 mm) is shown in Fig. 3. A workpiece is mounted in the self-centering rotary chuck. The face of a workpiece is pressed by the tape with force F_n, which gives a processing zone with a width of $2a$. The tape is used only once in the finishing zone, and after its passage is regarded as worn out. This is a feature of the method. The tape is rewound at a low speed from a roll of new tape to one with used tape. The tape in the intergranular spaces carries chips from the cutting zone and is wound onto the roll of used film, ensuring a clean surface finish. A more complex variation of the kinematic method of micro-smoothing is one with oscillations. The oscillating motion along a surface is possible to achieve at an applied speed of oscillation v_A, depending on the amplitude and frequency.



Workpiece diameter	D_p	*mm*	*32*
Speed of workpiece rotation	n_p	rev./min	500
Maximal cutting speed	v_o	mm/min	50.26
Tape feed	v_f	mm/min	80
Cycle machining time	t_1	s	30
Shore's hardness of pressure roll	-	Sh	60
Speed of pressure roll rotation	n_r	rev./min	2.12
Speed of tape oscillations	v_A	mm/min	+/- 1885
Diameter of pressure roll	d_r	mm	12
Speed of worn-out tape rotation	n_{rz}	rev./min	0.8
Oscillations frequency	f	1/min	600
Normal force	F_n	N	31
Width of cutting zone	2a	mm	1.8
Total machining time	t	s	150
Width of tape	b	mm	12
Speed of new tape rotation	n_m	rev./min	0.5
Magnitude of oscillations	A	mm	0.5
Diameter of new tape roll	d_m	mm	50

Fig. 3. Experimental procedure of the micro-smoothing process.

4. Measurement procedure and results

4.1. Technology evaluation

The technology was evaluated with the use of the ECLIPSE MA200 – a large inverted microscope. The microscope uses Nikon CFI 60 optics to ensure image quality. The microscope and its accessories allow the use of conventional research techniques used in metallography, such as bright and dark field, polarization, and interference contrast. The MA 200 Nikon microscope is a device with an inverted structure; if needed, it is possible to examine samples of large or irregular shape with a wide range of magnifications from 10× to over 2000×.

On a new tape (NT in Fig. 4) the abrasive grains are visible in the form of bright polygons. On the tape used in the smoothing process (T in Fig. 4) the single abrasive grains are difficult to distinguish. The results of micro-smoothing presented on the same scale as the tape images reveal a directional smooth surface (S in Fig. 4).

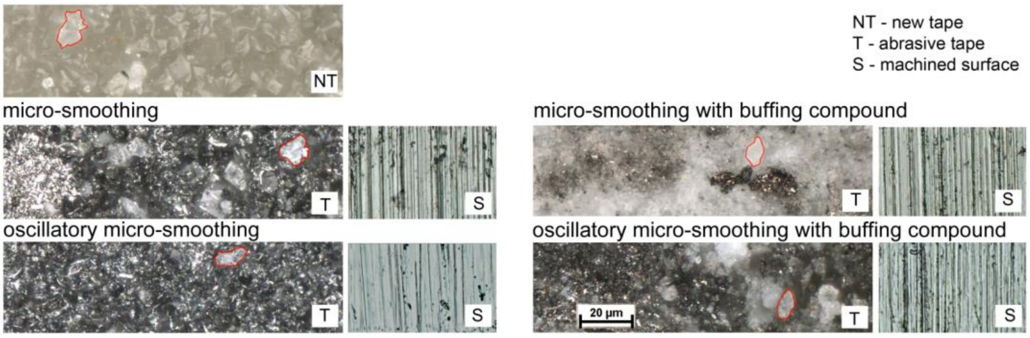


Fig. 4. Image of abrasive tape and machined surface (cutting time 2.5 min) taken by Nikon Eclipse MA200.

In Fig. 5 the profile along the traces is presented for each micro-smoothing process. The cross-section through the traces of pre-operation demonstrates the process of removing material. For the process without oscillation the abrasive grains work intermittently. They strike the material perpendicular to the traces, separate it or burnish it. The use of buffing compound causes a decrease in the thickness of the layer which can be cut off by the abrasive grains. Use of oscillations causes the abrasive grains to strike the material at different angles, which has a favorable impact on the micro-smoothing effect. This can be seen in Fig. 5 in the form of valley erosion of pre-operation traces.

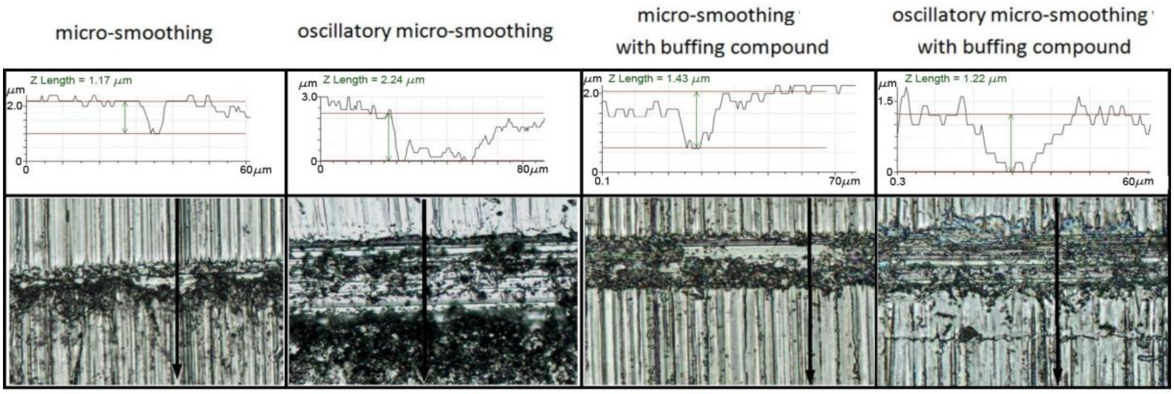


Fig. 5. Machined surface analysis with the use of Nikon Eclipse MA200 and NIS Elements.

4.2. Surface roughness evaluation

The quality of the machined surface was evaluated with the use of an interferometric technique. Images from the white light interferometer Talysurf CCI 6000 combine the advantages of image quality obtained by the optical microscope with the potential to enrich the description by the increased possibilities as regards profile measurements. The principle of the image acquisition system is to use complex image processing algorithms to combine image interference fringes, which are obtained by interference of two beams of light falling on the surface of the reference and test surfaces. As a result of combining light interference images a three-dimensional image of the surface is obtained [16]. Data presented as a simulation of the photographic pseudo-color image, contour maps and other 3D data representations represent the height of points.

After the belt grinding operation, analysis was performed to characterize the influence of this process on the surface topography. A global analysis of surface topography over the time of micro-smoothing (Fig. 6) reveals that the belt grinding operation has changed the initial surface topography.

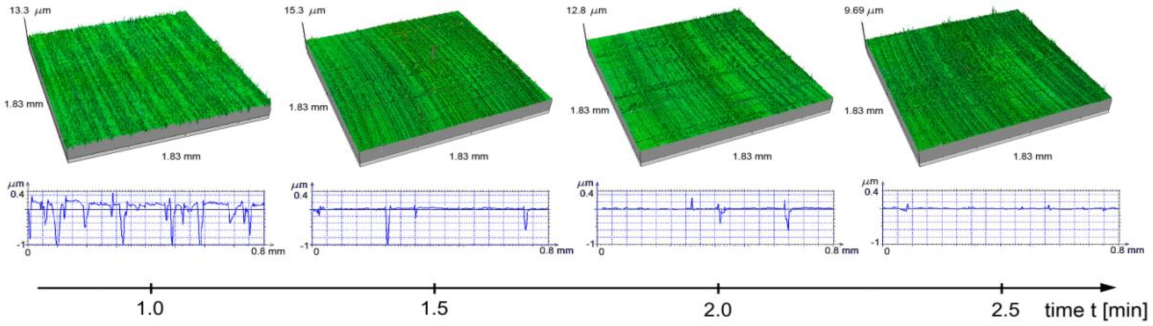


Fig. 6. Machined surface after the micro-smoothing operation.

Four different surface roughness area parameters were evaluated: Sa, Sq, Sz and St (Fig. 7). Surface roughness area parameters were measured in order to analyze the quality of the finishing process and surface quality. Five different regions on the surface were measured for roughness evaluation, located along the workpiece radius. In the range of cutting speeds applied, the values for the machined surface along the diameter were measured. The differences in the values were statistically insignificant, and thus they could be treated jointly.

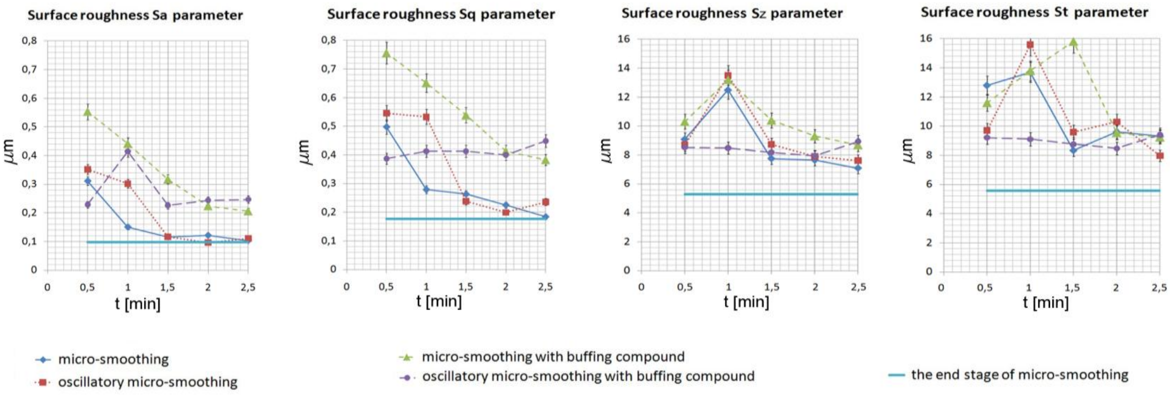


Fig. 7. Surface roughness area parameters vs. finishing time.

In order to determine how different parameters are able to describe the quality of the process, on each of the graphs the values were compared with the surface roughness values for a sufficiently long time of cutting. When multiple values were averaged, it turned out that all the types of micro-smoothing lead to the same results in terms of roughness parameters, differing only in the finishing time after which the value of a parameter is obtained. As can be seen on each individual plot (Fig. 7), the parameters of roughness do not give unambiguous information about the state of the surface finish.

5. Machined surface image analysis

The machined surface image for the analysis was acquired with the use of a vision system consisting of a computer with frame-grabber card, digital camera, lenses and a lighting system. The vision system was built to offer the possibility of being applied in a monitoring system in the future. Thus the whole system was connected to an industrial PC computer, and LabView was used as the environment for control of external subsystems, data acquisition and transmission.

A digital Basler A311fc camera with IEEE 1394 interface was used for image acquisition. The optical system was composed of lenses and extender sets. It made it possible to obtain digital images with a field of view of 1 mm^2 and depth of field 100 µm. The monitored machined surface was illuminated with the use of a white halogen light to ensure the uniform illumination of the whole field of view.

The goal of the micro-smoothing was to eliminate traces of pre-operation, and the image of the machined surface becomes a source of information about the process. The machined surface image carries information about the disappearance of traces of abrasive machining. However, its use in a monitoring system makes it necessary to convert visual information into a set of data relating to the shape and size of traces of pre-operation. Each image was therefore described with the use of geometrical features of image objects identified by a process of segmentation as abrasive traces.

The machined surface image acquired with the vision system shows the directional texture. The images of the initial surface are determined by the uneven distinct lines left by the abrasive process. The application of micro-smoothing introduces damage to the initial traces. They become less clear, fuzzy, shorter and thinner. However, the micro-smoothing process begins to cause the transition traces of the abrasive belt to be arranged perpendicularly to the traces of pre-operation. In this case, the fewer traces of pre-operation, the more favorable was the surface.

The raw data acquired with the vision system are redundant in nature. They include a number of correlated data. Hence the whole processing of the acquired images was reduced of recognition on the basis of several characteristics able to appropriately describe the traces in the image.

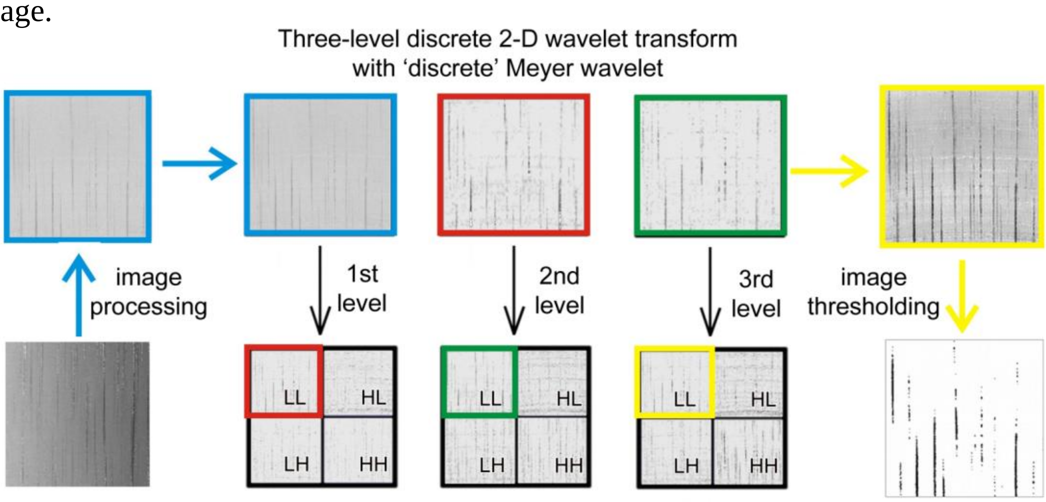


Fig. 8. Wavelet decomposition of machined surface image.

Accordingly, the surface images were initially processed – filtered – to remove noise and compensate for the lighting (Fig. 8). The filtration process was based on the methodology described in [17-19]. Image data were then decomposed using the Discrete Wavelet Transform with the use of the Meyer wavelet. Then the selected components were chosen for which segmentation was carried out – the approximation component of the third level of decomposition was used in further processing. The data were segmented (Fig. 9) and the identified objects were described by geometrical features. Nine averaged features of image objects formed the basis for surface and process evaluation.

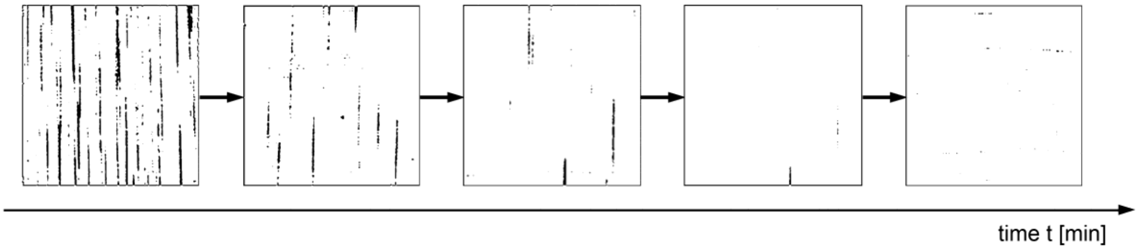


Fig. 9. Images of surface finish after the process of segmentation taken during micro-smoothing.

Each of the image features describes different properties of the machining traces. The Euler number is a measure of the topology of an image. It is defined as the total number of objects in the image minus the number of holes in those objects. the total area estimates the area of the objects in the binary image. The value corresponds roughly to the total number of pixels identified as holes (traces of pre-operation). The length of the major (minor) axis specifies the length (in pixels) of the major (minor) axis of the ellipse that has the same normalized second central moments as the region. The convex hull area gives information about the total area of points in the smallest convex region containing all of the points of a region. Eccentricity specifies the eccentricity of the ellipse that has the same second-moments as the region. Equivalent diameter describes the diameter of a circle with the same area as the region. Solidity evaluates the proportion of the pixels in the convex hull that are also in the region. Extent specifies the ratio of pixels in the region to pixels in the total bounding box.

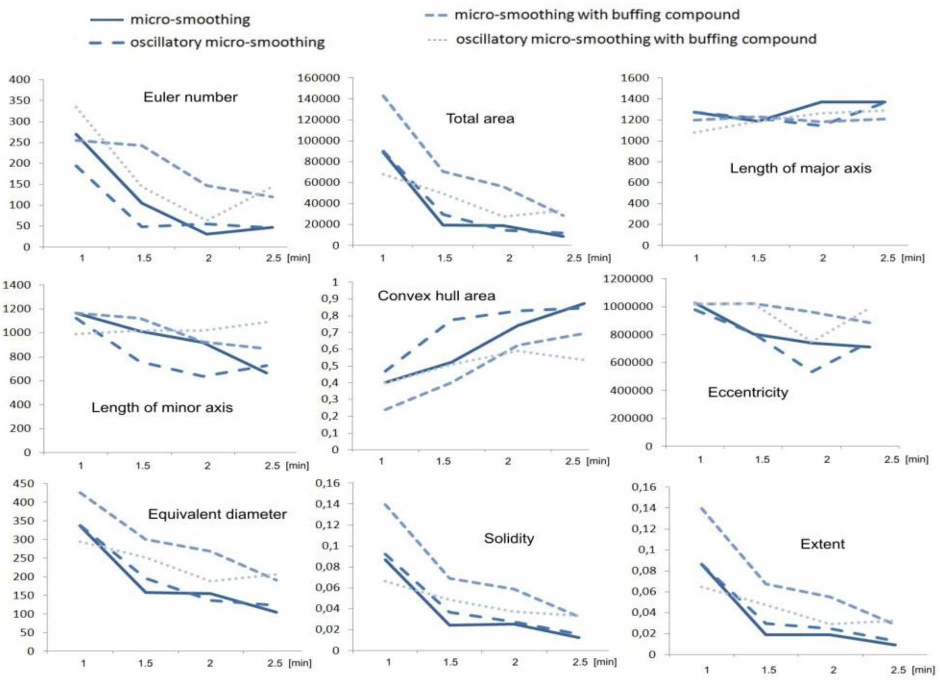


Fig. 10. Parameters of machined surface image features based on [20].

Each surface image was described by nine features, which were then plotted as a function of time (Fig. 10). Each of the image features was described by the inertial model (Equation 2 or Equation 4). The determination of time period required to stabilize the value of the image feature was carried out independently. The average value out of nine was recorded as the finishing time. Then the estimated value of the finishing time was determined as the average value out of twenty (five repetitions, four outputs). The average values and standard deviations of finishing time are summarized in Fig. 11.

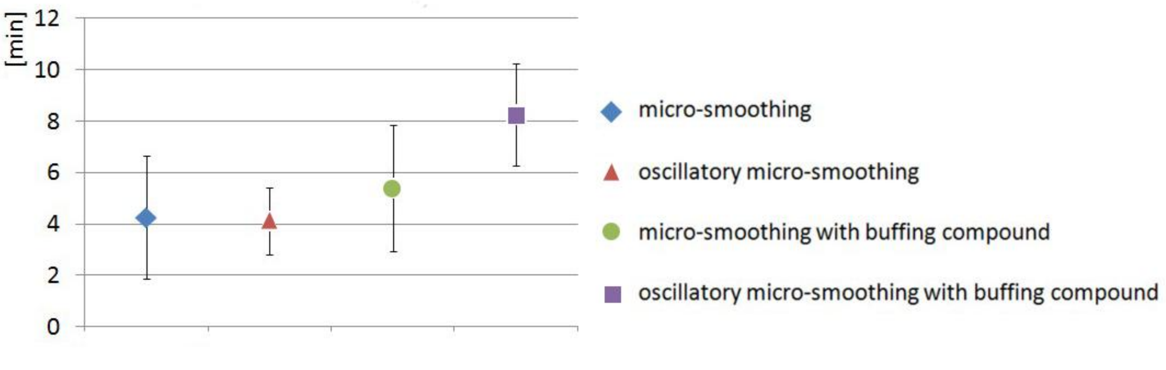


Fig. 11. Finishing time for obtaining the desired parameters of the machined surface.

For each type of micro-smoothing the finishing time was determined independently using the same procedure.

Surface roughness parameters (Fig. 7) for sufficiently long time of cutting with the use of the presented micro-smoothing technologies had statistically the same average value and standard deviation. Given the assumption that the final result (machined surface) of the micro-smoothing is the same, Fig. 11 shows the average estimated time to obtain the desired surface topography. As can be seen, the best results were obtained when micro-smoothing with oscillation was applied. The worst result was achieved when micro-smoothing was supported with both oscillation and the buffing compound. Buffing compound applied in micro-smoothing with belt grinding operation adversely affected the sharpness of the tool, thereby increasing the time needed to remove a certain thickness of cut.

6. Conclusions

Belt grinding operation is a finishing technique used after a range of pre-operations. In this paper micro-smoothing was applied to C45 steel after the process of grinding. The desired machined surface was expected to be very smooth. For different cases of micro-smoothing the machined surface was obtained after several minutes.

The quality of the surface was described with the machined surface image, which was pre-processed and analyzed with the use of the two-dimensional Discrete Wavelet Transform. The approximation component of the wavelet decomposition was examined to identify traces of pre-operation, which were then described with the use of image features.

The features of image objects were recorded as a function of time and then a model of the evolution in time of each feature was built. The parameters of the model were identified. For each type of micro-smoothing the process of identification was performed independently. The definition of finishing time was taken to be the time after in which the value of the image parameter stabilized.

The shortest finishing time was found to be slightly greater than 4 minutes for micro-smoothing with oscillations. For this type of finishing the dispersion of results was the smallest.

Acknowledgements

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References

[1] Grzesik, W., Rech, J., Wanat, T. (2007). Surface finish on hardened bearing steel parts produced by superhard and abrasive tools. *International Journal of Machine Tool & Manufacture,* (47), 255-262.

[2] Lewkowicz, R., Kacalak, W., Ściegienka, R., Bałasz, B. (2009). The new methods and heads for precision microfinishing with application of microfinishing films. *Proceedings of the 5th International Congress on Precision Machining ICPM 2009*.

[3] Mezghani, S., El Mansori, M., Zahouani, H. (2009). New criterion of grain size choice for optimal surface texture and tolerance in belt finishing production. *Wear*, (5-6), 578-580.

[4] Lewkowicz, R., Kacalak, W., Ściegienka, R. (2010). Finishing microsmoothing super smooth ceramic surface. *Materials of XXXIII School of Science Abrasive Machining.* (in Polish)

[5] Mezghani, S., El. Mansori, M. (2008). Abrasiveness properties assessment of coated abrasives for precision belt grinding. *Surface & Coatings Technology,* (5-7), 786-789.

[6] Adamczak, S., Makieła, W. (2002). The simulation method for the determination of the measuring error of a curvilinear profile exemplified by a circle using a co-ordinate measuring machine. *Metrology & Measurement Systems,* (3), 291-302.

[7] Zawada-Tomkiewicz, A., Storch, B. (2009). Surface evaluation with the use of combined material probability curve calculated for machined surface image. *Materials of XXXII School of Science Abrasive Machining.*

[8] Zawada-Tomkiewicz, A. (2010). Estimation of surface roughness parameter based on machined surface image. *Metrology & Measurement Systems*, (3), 493-504.

[9] Jourani, A., Dursapt, M., Hamdi, H., Rech, J., Zahouani, H. (2005). Effect of the belt grinding on the surface texture: Modeling of the contact and abrasive wear. *Wear,* (259), 1137-1143.

[10] Mezghani, S., El Mansori, M., Sura, E. (2009). Wear mechanism maps for the belt finishing of steel and cast iron. *Wear,* (1-4), 86-91.

[11] Ściegienka, R. (2008). *Fundamentals of conditions and parameters of selection processes, micro-smooth surface using a plastic abrasive belts,* PhD thesis, Koszalin University of Technology. (in Polish)

[12] Lewkowicz, R., Ściegienka, R. (2009). Modern methods of treatment of super-smooth surface of the precision cars components. *Materials of XI National Science Symposium „SYMROZ'2009".* (in Polish)

[13] Lewkowicz, R., Ściegienka, R., Piątkowski, P., Bałasz, B. (2009). Modern methods of microfinishing super-smooth surfaces of car engines and suspensions parts. *Logistics*, (6).

[14] Reference materials from the producers of grinding tools: 3M, GEM. LÖSER, SUPFINA.

[15] Tomkiewicz, D. (2002). A measurement system for estimation of the water content in grain based on dynamic drying process model. *Metrology & Measurement Systems*, (4), 401-410.

[16] Zawada-Tomkiewicz, A., Storch, B. (2010). Measurement of tool flank wear with the use of white light interferometer. *PAK*, (8), 950-953.

[17] Zawada-Tomkiewicz, A. (2010). Application of discrete wavelet transform to reduce noise in the image of machined surface. *Engineering and Production Management,* (13), 173-178. (in Polish)

[18] Zawada-Tomkiewicz, A., Tomkiewicz, D. (2007). Monitoring the quality of machined surface using the LabView environment. *PAK*, (8), 79-82. (in Polish)

[19] Adamczak, S., Makieła, W. (2011). Analyzing the variations in roundness profile parameters during the wavelet decomposition process using the MATLAB environment. *Metrology & Measurement Systems,* (1), 25-34.

[20] Zawada-Tomkiewicz, A. (2007). Image analysis of machined surface for the purpose of estimating the parameters of the surface. *Acta Mechanica et Automatica*, (2), 21-26. (in Polish)