Journal of Machine Engineering, 2022, Vol. 22
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *20. November 2022* / Accepted: *07 December 2022* / Published online: *09 December 2022*

audible sound analysis,
grinding, electroplated tools,
process monitoring

Mariusz DEJA[1*]

METHOD OF MONITORING OF THE GRINDING PROCESS WITH LAPPING KINEMATICS USING AUDIBLE SOUND ANALYSIS

Utilising microphones as audible sound sensors for monitoring a single-side grinding process with lapping kinematics is presented in the paper. The audible sound generated during grinding depended on the cutting properties of electroplated tools with D107 diamond grains and different thicknesses of the nickel bond. The tool wear affected the obtained technological effects such as material removal rate and the surface roughness of Al_2O_3 ceramic samples. The relationship between the quantities that characterise the sound signal and the surface roughness of machined surfaces was examined with the use of spectral analysis of the sound signal in the frequency domain with a focus on the Ra parameter. The decreasing amplitude indicated a better surface finish, down to Ra = 0.23 µm. The developed method and the obtained results will facilitate the practical use of the electroplated tools in the lap-grinding technology without interrupting the process before obtaining the required surface roughness.

1. INTRODUCTION

Grinding and lapping are the basic manufacturing techniques used for precise removal of material [1, 2, 3]. Grinding is widely used for reducing the roughness of workpieces but the high temperatures generated at the grinding zone, where the wheel interacts with the workpiece, can cause burns and microstructural transformations in the subsurface layers [1]. Subsurface damage caused by grinding or other previous operations can be removed by lapping. Lapping is a loose abrasive machining process in which abrasive particles are suspended in oil or water based slurry. This process is less damaging than grinding and is used for reducing the roughness of workpieces and for producing the required thickness and flatness [4, 5]. Grinding with lapping kinematics is also known as lap-grinding [6, 7]. Lap grinding is carried out with abrasive particles bonded to a substrate and is faster than conventional lapping yet still providing similar flatness, parallelism, surface finish and size

---

[1] Department of Manufacturing and Production Engineering, Gdansk University of Technology, Faculty of Mechanical Engineering and Ship Technology, Poland
[*] E-mail: mariusz.deja@pg.edu.pl
https://doi.org/10.36897/jme/157255

tolerances. Due to that, the lapping process is now often replaced by a single- or a double-side lap grinding process [8, 9]. Double-side grinding with lapping (planetary) kinematics can be carried out at the speed higher than 20 m/s. Single-side lap-grinding is considered as a cool process with the low cutting speed ranging from 0.5 m/s to 3 m/s.

The monitoring of a tool condition in the machining process is the key issue for efficient and effective manufacturing. Vibrations, acoustic emission and sound signals generated during machining are closely related with tool state and/or process conditions. The experienced machine tool operator is able to recognize e.g. a dull tool due to sound which is generated during the machining process. It is important for industrial applications that sensors which are used for process monitoring are cheap, do not disturb the machining process and can ensure simple communication as well as quick analysis. The sound signal analysis is a possible and relatively simple method to monitor the tool wear and to predict quantities characterizing machined surface. Monitoring systems based on audible sound sensors were successfully applied for milling [11, 12] and turning [13, 14] processes. The vibration of the tool holder, together with the cutting insert, was considered as the main source of sound associated with tool wear [13]. Ease of mounting on the machine tool with good ratio cost/benefit were pointed out as the main advantages of these sensors which are basically microphones [15].

Monitoring of a single-side lap grinding process with the use of electroplated diamond tools and an audible sound sensor was proposed in [16]. The author presented the sound generated during grinding as waveforms at the beginning and at the end of a tool life. The basic difficulty in the application of electroplated tools that had diamond grits held by a galvanic nickel bond is the prediction of its wear [17]. Losing the cutting ability of abrasive grains influences the machined surface quality as well as the dimensional and shape accuracy of a workpiece [18]. That was investigated by Hwang et al. for high speed grinding of silicon nitride [19]. The results from [20] show that the wear rate of electroplated tools depends more on crystal exposure than on active grain density. Images of machined surface were used in [21] for the estimation of machined surface quality after abrasive micro-smoothing. The papers [22, 23] present a diagnostic method to be applied in the grinding process using the acoustic emission signal (AE) and image analysis.

The present investigation was undertaken to evaluate the effect of nickel plating thickness on lap grinding performance with electroplated diamond tools. Grinding tools with varying levels of the bond as a percentage of the grain size were used to examine the influence of crystal exposure above a bond on the surface roughness of ceramic workpieces and on the material removal rate. The audible sound generated during grinding depended on the type of tool (the thickness of the nickel plating) and on the cutting properties of the grinding tool (tool state). The sounds generated during the grinding process under investigation suggested that there is a close correlation between the quantities that characterise the sound signal and the surface roughness of Al_2O_3 ceramic samples. That correlation was examined with the use of spectral analysis of the sound signal in the frequency domain with a focus on the Ra surface roughness parameter. The decreasing amplitude of the sound signal indicated better surface finish of difficult-to-cut samples.

Difficult access to the machining zone during lapping and grinding with lapping kinematics forces the use of new methods to monitor the course of the machining process,

MOST WIEDZY Downloaded from mostwiedzy.pl

especially without interrupting the process before obtaining the required surface roughness. Presented results showed that utilising microphones as audible sound sensors is a suitable approach for monitoring a single-side lap grinding process due to the low levels of noise generated by the drives of a machine tool. The low flow of the cutting fluid and the low kinematical parameters involved in the grinding process allowed for mounting the microphone far from the machine drives and close to the machining zone, minimizing the impact of drive noise. Results presented in the paper confirm that sound signal analysis is a feasible and relatively simple method to monitor a lap-grinding process with the use of an audible sound sensor. Moreover, the sound signal can also be used to identify the abrasion mechanism occurring in the machining zone, and the process transition from grinding treated as two-body abrasion to conventional lapping treated as three-body abrasion.

2. EXPERIMENTAL SET-UP AND TECHNOLOGICAL RESULTS

Experiments were conducted on a prototype machine tool designed and manufactured at the Department of Manufacturing and Production Engineering (Gdansk University of Technology, Gdansk, Poland) which was used for flat grinding with a single-disc kinematical configuration – Fig. 1. Three Al_2O_3 ceramic workpieces were placed in a separator and loaded with appropriate pressures. The workpieces were located on a flat surface of a rotating tool with diamond grits held by a galvanic nickel bond. The main aim of the experiments was to examine the influence of the thickness of the bond on the surface roughness of ceramic workpieces and on the material removal rate. Three types of grinding tools (Diamondback Abrasive, Walled Lake, USA) were used during experiments with varying levels of thickness of the bond as a percentage of the grain size: h_s = 35%, 50% and 65%. These values were calculated in relation to the nominal dimension a_z = 107 μm of D107 diamond grains according to international standards ISO 6106-2013 (ISO 6106:2013 Abrasive products - Checking the grain size of superabrasives).

The microphone was located close to the machining area at a distance of 10 mm. The experimental area was isolated from environment noise that could contaminate the detected signals collected with the constant noise level, without the influence of other devices and under the same ambient conditions.

Cutting fluid (based on kerosene and machine oil) was introduced drop by drop into the contact region between the workpieces and the electroplated diamond tool, at a flow rate of Q = 3 mL/min. The linear material removal rate was measured using a digital micrometer (Mitutoyo, Kawasaki-shi, Japan) with a resolution of 1 μm. Surface roughness parameters were measured with the use of the Hommel Tester T1000 contact profilometer (HOMMEL ETAMIC, Villingen-Schwenningen, Germany). Three surface roughness measurements were performed on each machined surface, with the cut-off λc = 0.8 mm, evaluation length L = 4 mm, using the stylus with the radius of r = 5 μm and the Gaussian filter. Grinding conditions of the performed experiments are presented in Table 1. The grinding pressure was increased after test T6 due to the decreasing material removal rate caused by the tool wear. The other parameters were not varied during the experiments.

MOST WIEDZY Downloaded from mostwiedzy.pl

The change in height of each sample due to the material removal as well as surface roughness parameters were measured after each of twelve consecutive tests T1–T12. The effect of the thickness of nickel plating on the material removal rate is shown in Fig. 2. The use of thicker plating resulted in the material removal rate being the highest for the thickest bond (h_s = 65%). For the thinnest bond (h_s = 35%), the lowest material removal rate (Fig. 2) and the best surface finish (Fig. 3) were recorded. The surface roughness was not found to be significantly reduced after grinding with two bond heights, i.e. h_s = 50% and h_s = 65%, but the initial shape errors were removed in all grinding tests carried out in kinematic configuration with a single wheel [24]. The relationship between the material removal and the processing time was accurately approximated by asymptotic mathematical functions in [25]. Although, the surface roughness data were also fitted by the linear and nonlinear regression models as a function of time [25] but it was expected from the sound generated during a grinding process that there is a close correlation between quantities characterizing sound signal and the surface roughness of machined surfaces. Results presented in the following Section confirm that sound signal analysis is an applicable method for monitoring the lap grinding process to predict the surface roughness influenced by the type and the condition of electroplated tools. The cutting ability of the electroplated tools was reduced by the tool wear accompanied by a decrease in the material removal and in the surface roughness of machined samples. Due to the decreasing grinding performance in subsequent tests from T1 to T6, after the T6 test, an increase in the surface pressure was applied. The higher pressure applied after 540 seconds of processing slightly decreased the surface roughness most likely due to the tool wear – Fig. 3, which should be directly reflected in the sound signal.

Table 1. Grinding conditions

Grinding wheel	
Outer tool diameter r_o	380 mm
Inner tool diameter r_i	90 mm
Grain material	diamond D107
Grain size d_g	107 µm
Surface concentration of abrasive grains in the bond C_{107}	70 mm^{-2} ± 10%,
Bond type	Nickel
Thickness of the bond as a percentage of the grain size h_s	35% 50% 65%
Grinding parameters	
Cutting speed v_c	0.76 m/s
Grinding pressure p	0.010 N/mm² for tests T1–T6 0.014 N/mm² for tests T7–T12
Coolant flow rate Q	3 mL/min
Duration of a single test	90 s
Workpiece	
Material	Al_2O_3
Vickers hardness HV10	1100 MPa
Diameter d_w	34 mm
Initial height	20 mm
Sensor	
Frequency range	100 Hz – 16 kHz
Sampling frequency	44100 Hz

MOST WIEDZY Downloaded from mostwiedzy.pl

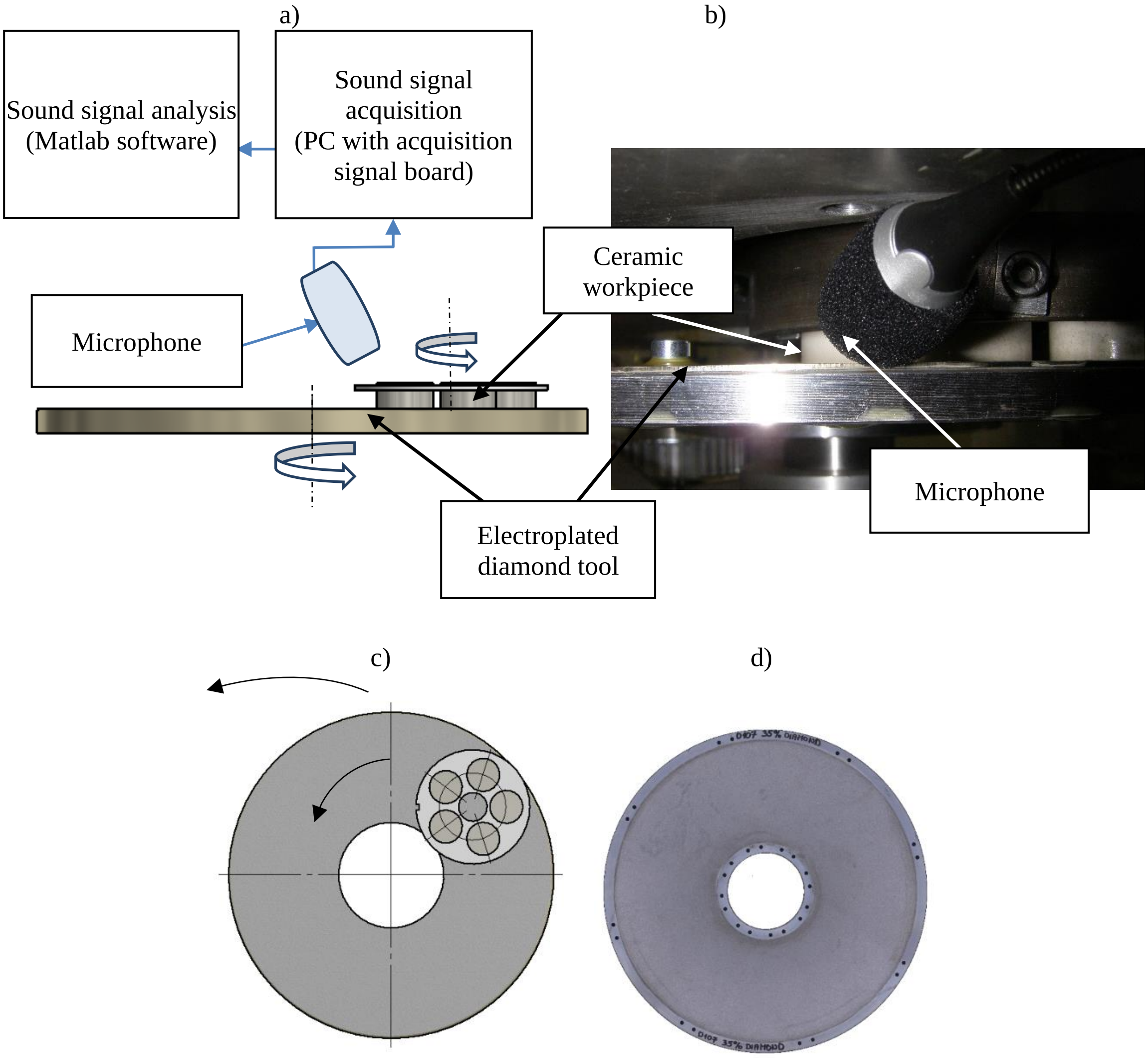

Fig. 1. Single-side lap grinding with an electroplated diamond tool: a) scheme of the sound signal acquisition system, b) experimental layout, c) flat grinding kinematics, d) exemplary tool with diamond grits D107 and the bond thickness h_s = 35%

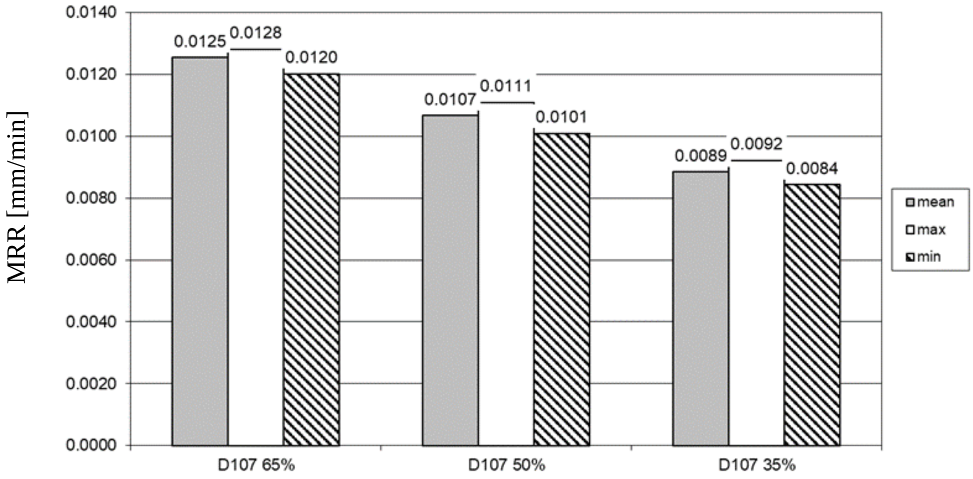

Fig. 2. Influence of nickel plating thickness on the material removal rate (MRR) in flat grinding of ceramic workpieces (Al_2O_3)

MOST WIEDZY Downloaded from mostwiedzy.pl

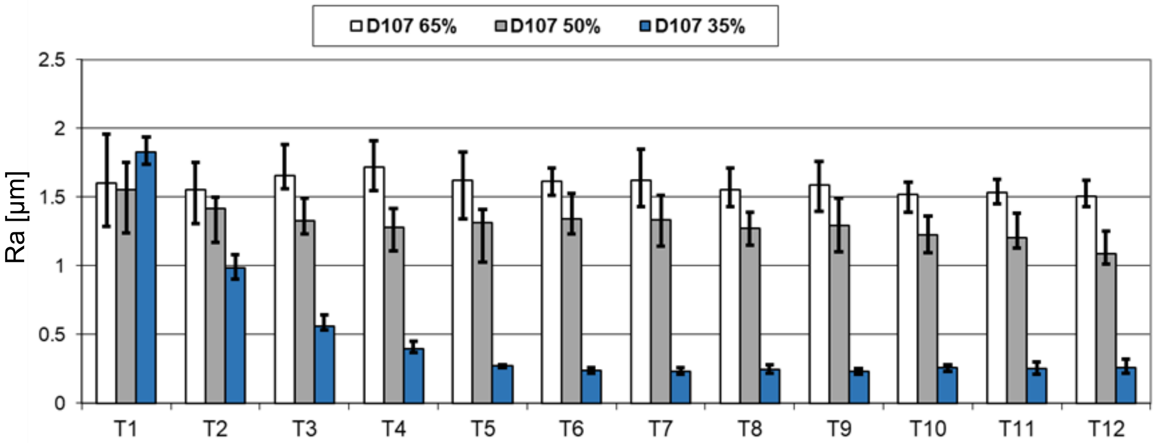

Fig. 3. Average surface roughness parameter Ra after grinding with the use of electroplated diamond tools with varying levels of thickness of the nickel bond [24, 25].

3. ANALYSIS OF SOUND SIGNALS

The proper setup and location of a sound sensor is a crucial factor in the successful application of the monitoring technique. Due to this, the sensor axis was placed at the height of the workpiece (900 mm from the ground) at a distance of 10 mm from the working zone of a machine tool. The acoustic signals were simultaneously monitored and recorded during machining. The recorded sound signals were preliminary viewed with the Audacity 2.2.1 software for audio recording and editing. As the frequency domain spectrum analysis is better than the time domain for finding an adequate correlation between AE signals and various machining characteristics, further detailed analysis was conducted in the frequency domain using the Matlab® software, release R2017b.

Sample soundtracks recorded during four grinding tests T1, T3, T6 and T12 with a tool with D107 diamond grains and the thickest nickel bond (h_s = 65%), are presented in Fig. 4. The differences in the amplitudes of the generated signals are clearly visible for the tests T1, T3 and T6 – Fig. 4a, b, c. The amplitude of the signal that corresponds to the volume of sound is greater for the later tests T3 and T6 compared to the first test T1 carried out with an unworn tool. The differences in the amplitudes of the signals from tests T6 and T12 (Fig. 4c, d) are much smaller as a result of the progressive wear of the tool. More advanced and detailed spectral analysis was carried out with the use of the Matlab® software to compare the results from all tests and in order to find the correlation between sound signal and Ra parameter.

The signal samples with a duration of 45 s were taken 45 s after the beginning of each audio track (Fig. 4). This enabled automatic signal processing and analysis of the sound generated during all grinding tests. The data in the frequency were obtained after computing fast Fourier transform (FFT) of the signals with framing (n = 1024) without overlapping and with the use of a Hamming window function. The differences in peaks of the signal's magnitude, are clearly visible at some characteristic frequencies, for all tests and for different crystal exposure. The highest amplitude was observed for the thickest bond (h_s = 65%) – Fig. 5, while the smallest signal dispersion was observed for the intermediate bond (h_s = 50%) – Fig. 6. When the thinnest bond was used (h_s = 35%), the signal's magnitude decreased

MOST WIEDZY Downloaded from mostwiedzy.pl

rapidly at the beginning of grinding to stabilise after test T3 due to the progressive tool wear – Fig. 7. Because the differences in the sound spectrum are very small for most of the tests, even after the pressure increase after test T6 (see Fig. 5, 6, and 7), the maximum magnitudes from spectrums of sound recorded during all grinding tests are presented in Fig. 8. The microscopic observations of the active surface of the tool and the abrasive slurry identified the process transition from grinding treated as two-body abrasion for the thickest bond (T_b = 65%) to conventional lapping treated as three-body abrasion for the thinnest bond (T_b = 35%) [25]. The obtained results confirm that the sound signal can also be used to identify the abrasion mechanism occurring in the machining zone, i.e. the presence of either only bonded or loose and rolling micrograins.

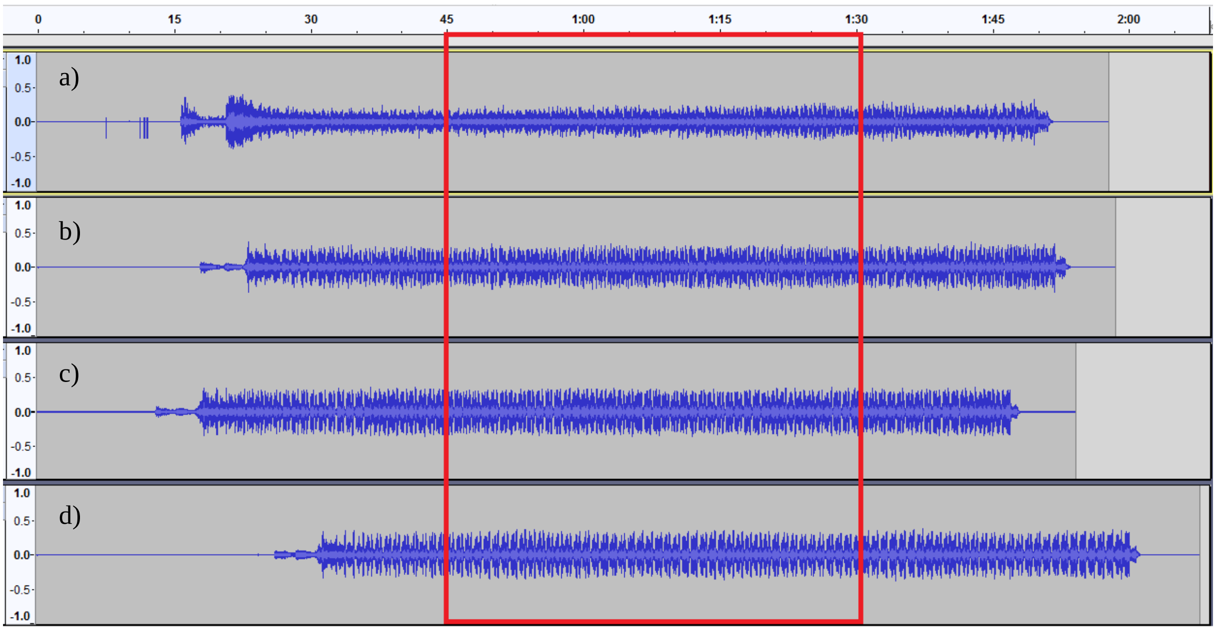

Fig. 4. Exemplary audio tracks recorded during four lap grinding tests with the use of the tool D107 65%, presented in a waveform view: a) test T1, b) test T2, c) test T6, d) test T12; red rectangle shows the data taken for further spectral analysis

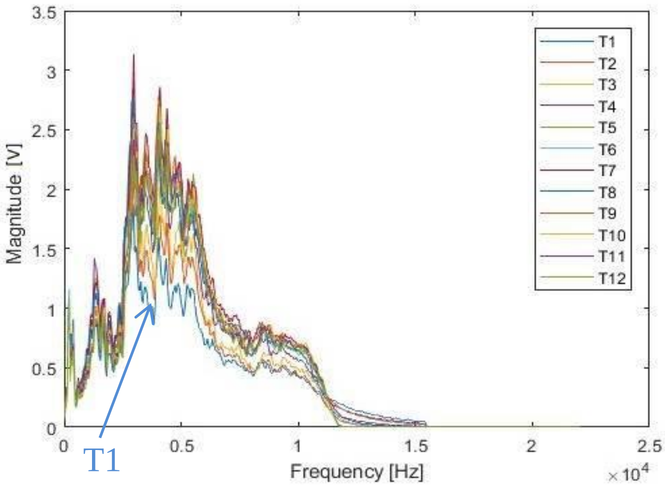

Fig. 5. Sound spectrums from all lap grinding tests with the use of the tool D107 65%

MOST WIEDZY Downloaded from mostwiedzy.pl

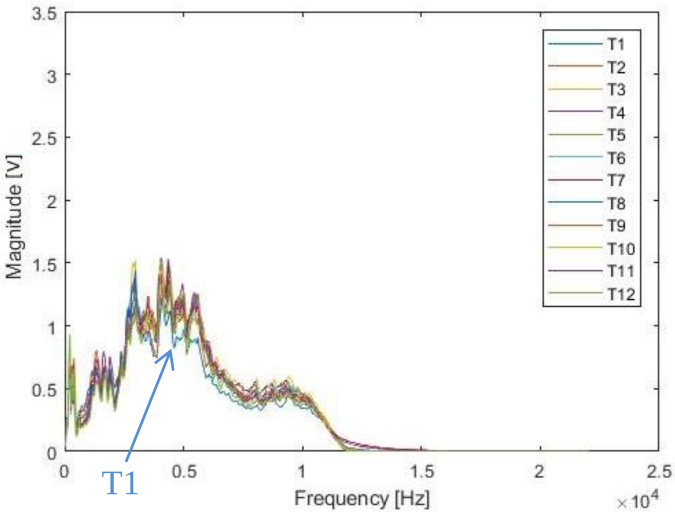

Fig. 6. Sound spectrums from all lap grinding tests with the use of the tool D107 50%.

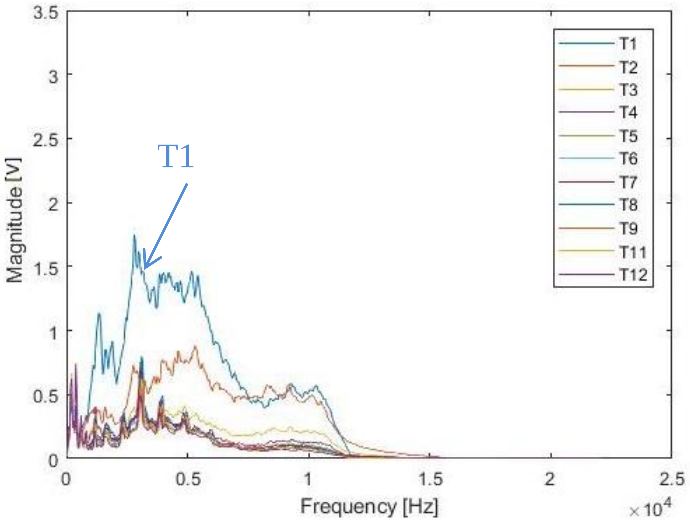

Fig. 7. Sound spectrums from all lap grinding tests with the use of the tool D107 35%.

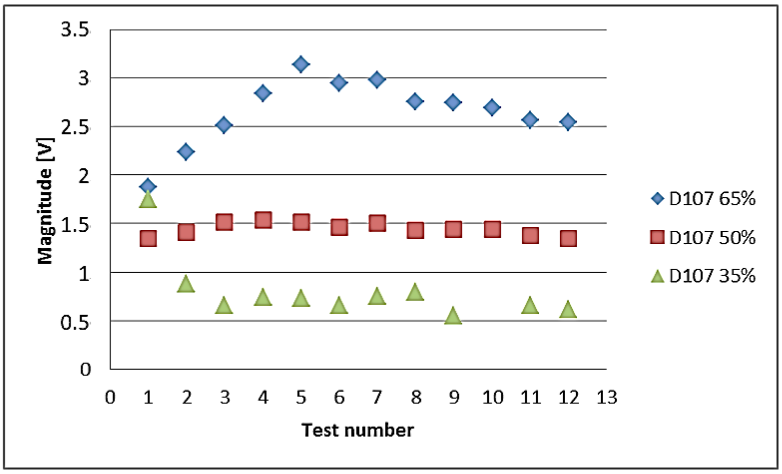

Fig. 8. Maximum magnitudes from spectrums of sound recorded during all lap grinding tests using prototype electroplated tools with varying levels of thickness of the bond

MOST WIEDZY Downloaded from mostwiedzy.pl

The closest relationship between the roughness and the sound, with the smallest Root Mean Squared Error RMSE, was obtained at a frequency of 1.292 kHz determined with the accuracy ±10 Hz. The surface roughness increases as the magnitude of a sound signal increases – Fig. 9. The substantial reduction in the surface roughness after grinding with the thinnest bond (h_s = 35%) resulted in the decreasing magnitude of a sound signal. Therefore, the relationship between the value of the Ra parameter and the magnitude of the sound signal at the selected frequency was approximated taking into account the shapes of the experimental curves [26], using equation 1:

$$\mathrm{Ra} = b_1 \cdot \exp(b_2/A_f)\ , \tag{1}$$

where, Ra is the surface roughness parameter in [µm], A_f is the magnitude in [V] of the sound signal at the selected frequency and b_1 as well as b_2 are model coefficients.
Matlab® software was used for curve fitting, and the estimated coefficients for equation 1 are: $b_1 = 2.20$, $b_2 = -0.33$. Both coefficients of a model are significant at a significance level equal to $\alpha = 0.05$.

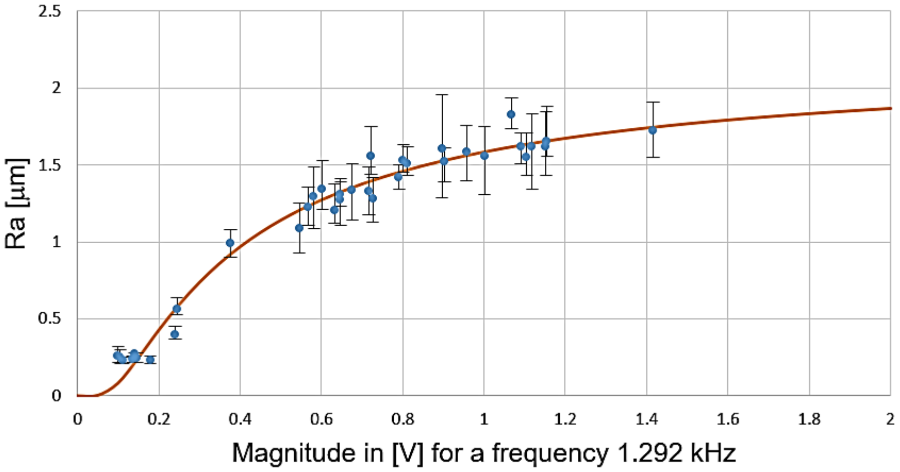

Fig. 9. Ra parameter of the surface roughness as a function of a magnitude of a sound signal generated during lap grinding of Al_2O_3 ceramic samples with electroplated diamond tools

4. CONCLUSION

Three types of prototype tools were used during lap grinding experiments with varying levels of thickness of the bond as a percentage of the grain size: h_s = 35%, 50% and 65%. The depth of the embedding of D107 diamond grains in the nickel bond had a significant impact on the progressive wear of the tool, and thus on the technological effects. Difficult access to the machining zone during lapping and grinding with lapping kinematics forces the use of new methods to monitor the course of the machining process, especially in terms of predicting the obtained surface roughness. Presented results showed that utilising microphones as audible sound sensors is a suitable approach for monitoring a single-side lap grinding process. The audible sound generated during grinding depended on thickness of the

MOST WIEDZY Downloaded from mostwiedzy.pl

nickel bond and on the cutting properties of the tools applied in the machining of difficult-to-cut materials. The analysis of the sound generated by the lap grinding process confirmed that there is a close relationship between the quantities that characterise the sound signal and the surface roughness of Al_2O_3 ceramic samples. This relationship was examined with the use of spectral analysis of the sound signal in the frequency domain with a focus on the Ra parameter. The estimated amplitude of a sound signal significantly increased as the surface roughness increased. The decreasing amplitude indicated better surface finish, down to Ra = 0.23 μm. The developed method and the obtained results will facilitate the practical use of the electroplated tools in the lap-grinding technology without interrupting the process before obtaining the required surface roughness. The sound signal can also be used to identify the abrasion mechanism occurring in the machining zone, and the process transition from grinding treated as two-body abrasion, with bonded grains, for the thickest bond (T_b = 65%) to conventional lapping treated as three-body abrasion, for bonded as well as loose and rolling grains, for the thinnest bond (T_b = 35%).

The obtained data confirmed that the proposed analysis of audible signals can be used as a quick indicator of technological effects in a lap-grinding process, as well as in other manufacturing processes like milling or turning. It shows promise for being a reliable tool in industrial applications among other mathematical models to predict material removal and surface roughness. Further research should aim to use an additional data acquisition system based on acoustic emission (AE) as well as vibration sensors for the concept of sensor fusion technology. Sound signals should also be analysed in relation to other 2D and 3D parameters which can more precisely describe the surface topography after different machining method.

ACKNOWLEDGMENTS

Computations carried out with the use of software from Academic Computer Centre in Gdansk – TASK http://www.task.gda.pl. Experiments were partially financed by Polish budget funds for science as a research project N N503 157638. Special thanks to Mrs. Dorota Truchanowicz from the Doctoral Studies at the Faculty of Electronics, Telecommunications and Informatics, Gdansk University of Technology for conducting the spectral analysis.

REFERENCES

[1] MALKIN S., GUO, C., 2007, *Thermal Analysis of Grinding,* CIRP Annals – Manufacturing Technology, 56/2, 760–782.

[2] BARYLSKI A., DEJA M., 2010, *Finishing of Ceramics in a Single-Disk Lapping Machine Configuration,* Solid State Phenomena, 165, 237–243.

[3] ZAK K., GRZESIK W., 2017, *Metrological Aspects of Surface Topographies Produced by Different Machining Operations Regarding their Potential Functionality,* Metrology and Measurement Systems, 24/2, 325–335.

[4] DEJA M., 2010, *Simulation Model for the Shape Error Estimation During Machining with Flat Lapping Kinematics*, ASME, International Manufacturing Science and Engineering Conference, 1, 291–299. *http://dx.doi.org/10.1115/MSEC2010-34262.*

[5] UHLMANN E., HOGHE T., 2012, *Wear Reduction at Double Face Grinding with Planetary Kinematics,* Production Engineering, 6/3, 237–242.

[6] KHOSHAIM B.A., XU Z., MARINESCU D.I., 2015, *Chapter 9 – ELID Grinding with Lapping Kinematics*, Handbook of Ceramics Grinding and Polishing (Second Edition), William Andrew Publishing, Boston, 394–448, ISBN 9781455778584, https://doi.org/10.1016/B978-1-4557-7858-4.00011-X.

MOST WIEDZY Downloaded from mostwiedzy.pl

[7] DEJA M., LICHTSCHLAG L., UHLMANN E., 2021, *Thermal and Technological Aspects of Double Face Grinding of C45 Carbon Steel*, Journal of Manufacturing Processes, 64, 1036–1046.

[8] SANCHEZ L.E.A., JUN N.Z.X., FIOCCHI A.A., 2010, *Surface Finishing of Flat Pieces when Submitted to Lapping Kinematics on Abrasive Disc Dressed Under Several Overlap Factors*, Prec. Engineering, 35/2, 355–363.

[9] DEJA M., 2012, *Correlation Between Shape Errors in Flat Grinding*, Journal of Vibroengineering, 14/2, 520–527.

[10] DEJA M., LIST M., LICHTSCHLAG L., UHLMANN E., 2019, *Thermal and Technological Aspects of Double Face Grinding of* Al_2O_3 *Ceramic Materials*, Ceramics International, 45/15, 19489–19495.

[11] AI C.S. et al., 2012, *The Milling Tool Wear Monitoring Using the Acoustic Spectrum*, International Journal of Advanced Manufacturing Technology, 61/5–8, 457–463.

[12] RUBIO E.M., TETI R., 2009, *Cutting Parameters Analysis for the Development of a Milling Process Monitoring System Based on Audible Energy Sound*, Journal of Intelligent Manufacturing, 20/1, 4354.

[13] LU M.C., KANNATEY-ASIBU JR., E., 2004, *Flank Wear and Process Characteristic Effect on System Dynamics in Turning,* Journal of Manufacturing Science and Engineering – Transactions of the ASME, 126/1, 131–140.

[14] SALGADO D.R., ALONSO F.J., 2007, *An Approach Based on Current and Sound Signals for in-Process Tool Wear Monitoring,* International Journal of Machine Tools and Manufacture, 47/14, 2140–2152.

[15] DEJA M., LICOW R., 2021, *A Pilot Study to Assess Manufacturing Processes Using Selected Point Measures of Vibroacoustic Signals Generated on a Multitasking Machine,* The International Journal of Advanced Manufacturing Technology, 115/3, 8078–22.

[16] DEJA M., 2014, *Vertical Vibration Reduction and Audible Sound Analysis in Surface Grinding with Electroplated Tools,* Journal of Measurements in Engineering, 2/2, 80–85.

[17] SHI Z., MALKIN S., 2006, *Wear of Electroplated CBN Wheels,* ASME J. Manufacturing Science and Engineering, 128/1, 110–118.

[18] LIPINSKI D., KACALAK W., 2016, *Metrological Aspects of Abrasive Tool Active Surface Topography Evaluation,* Metrology and Measurement Systems, 23/4, 567–577.

[19] HWANG T.W., EVANS C.J., WHITENTON E.P., MALKIN S., 2000, *High Speed Grinding of Silicon Nitride with Electroplated Diamond Wheels, Part 1: Wear and Wheel Life,* J. Manufacturing Science and Engineering, 122/1, 32–41.

[20] UPADHYAYA R.P., FIECOAT J.H., 2007, *Factors Affecting Grinding Performance with Electroplated CBN Wheels*, CIRP Annals – Manufacturing Technology, 56/1, 339–342.

[21] ZAWADA-TOMKIEWICZ A., SCIEGIENKA R., 2011, *Monitoring of a Micro-Smoothing Process with the Use of Machined Surface Images,* Metrology and Measurement Systems, 18/3, 419–428.

[22] SUTOWSKI P., NADOLNY K., KAPLONEK W., 2012, *Monitoring of Cylindrical Grinding Processes by Use of a Non-Contact AE System,* Int. J. Precis. Eng. Manuf. 13/10, 1737.

[23] SUTOWSKI P., 2012, *Surface Evaluation During the Grinding Process Using Acoustic Emission Signal*, Journal of Machine Engineering, 12/4, 23–34.

[24] DEJA M., 2013, *Selected Problems of Grinding with Lapping Kinematics,* Publishing House of Gdansk University of Technology, Monography 143.

[25] DEJA M., ZIELINSKI D., 2020), *Wear of Electroplated Diamond Tools in Lap-Grinding of* Al_2O_3 *Ceramic Materials,* Wear, 460, 203461.

[26] KORZYNSKI M., 2018, *Methodology of the Experiment. Planning, Implementation and Statistical Analysis of the Results of Technological Experiments*, Publisher House: Wydawnictwo WNT, 277, (in Polish).

MOST WIEDZY Downloaded from mostwiedzy.pl