Contribution to the analysis of grinder vibrations using condition monitoring procedures based on vibration measurements

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Abstract. The article deals with the vibration of the workpiece on the grinder using a cBN grinding wheel. The workpieces were made of hardened steel with a hardness of 62 HRC and ceramics: Al₂O₃, SiC, Si₃N₄, and ZrO₂/Y₂O₃. Grinding was performed at different infeed rates during 5 consecutive passes. Up and down grinding were also evaluated. Measured realizations of the acceleration of the workpiece during grinding were processed in the time and frequency domain and compared with each other. We consider acceleration patterns to be diagnostic signals that will help to understand the process of chip formation during grinding as well as the process of damaging parts made of the tested materials.

1. Introduction
With the development of non-metallic materials, the scope of their use in technical practice is also growing. This development requires knowledge of the relevant processes taking place in these materials. Processes are presented by specific symptoms. The relationship between symptoms and analysed processes may be ambiguous. However, even in this case, they can be helpful in recognizing and understanding the relevant processes. It is also a prerequisite for detecting anomalies arising in these processes.

Ceramic materials are widely employed for many industrial applications in which their specific mechanical and thermal properties are beneficial for specific purposes. Especially the low thermal conductivity, high hardness as well as outstanding corrosion resistance represents their advantages against steels (or other metal structures). Being so, components made of ceramics can meet the specific demands which cannot be fully filled by the use of other materials. On the other hand, production of the components made of ceramics is associated with specific difficulties. Especially high hardness of ceramics causes that high speed steels or cemented carbides cannot be employed for their machining. Being so, only limited types of cutting materials such as diamond or cBN can be successfully integrated into technological operations of machining. Ceramics components are usually produces via grinding (or other finishing methods). This topic is nowadays studied from many aspects such as surface roughness [1], material removal mechanism [2]. Furthermore, grinding process can remarkably affect functional properties of components [3-9].
Quality of ground components is usually expressed in such terms as surface roughness, precision of components, their shape deviations etc. Ceramics, as brittle structures, very often suffer from brittle cracking especially on the components edges. Being so, alternative concepts are developed for grinding process such as ultrasonic vibration [2, 9, 10] or new grinding wheels concepts. Being so, this paper is focused on measurement of vibration of workpiece and analysis of recorded signals. To refer grinding vibration against grinding conventional materials such as hardened steel or hardened bearing steel is also ground at the same grinding conditions.

2. Experimental conditions
In this paper we focus on monitoring the vibration of the workpiece during grinding and comparison of the obtained vibration values for selected materials and at different infeed rates (0.005mm, 0.010mm, 0.015mm, 0.020mm with abbreviations: 005, 010, 015, 020).

Samples with dimensions 22x22x5 mm were made of 4 types of non-metallic materials: Al₂O₃, SiC, Si₃N₄, ZrO₂/Y₂O₃. A sample of hardened bearing steel hardened to 61 HRC was also made. Their specifications (mechanical and thermal properties) are listed in table 1.

| Table 1. Hardness and thermal conductivity of studied materials. |
|---------------------------------------------------------------|
|                  | Al₂O₃ | SiC | Si₃N₄ | ZrO₂/Y₂O₃ | Hardened steel |
| Hardness (kg.mm⁻²) | 2100  | 2400 | 1800  | 1500      | 825           |
| Thermal conductivity (W.m⁻¹.K⁻¹) | 32    | 92   | 27    | 3/5       | 50            |

Grinding wheel: 175x10/2x32 K75 B-VII made of cBN. Grinding machine: BPH 20. Cutting conditions as follows: \( v_c = 25 \text{ m.s}^{-1}, v_w = 4 \text{ m.min}^{-1} \), infeed rates \( a_p = 0.005; 0.01; 0.015 \) and 0.02 mm (abbreviations: 005, 010, 015, 020) – 5 passes, coolant - Emulzin H of 2% concentration, 15 l.min⁻¹. One pass was consisted at first of mode A (up grinding) and at second of mode B (down grinding).

The vibration acceleration of the workpiece clamped on the grinder was measured with a B&K4517 accelerometer (frequency range up to 20kHz), NI 9234 NI dynamic signal acquisition module (up to 51.2 kS/s/ch), SW - LabVIEW SignalExpress and LabVIEW Diadem.

The grinding wheel, the clamped workpiece and glued accelerometer is in figure 1. Accelerometer was placed in the direction of longitudinal reciprocation motion of clamper with workpiece.

3. Results of experiments
The figure 2 shows the measured acceleration values as a function of time, \( a_p = 0.020 \text{ mm} \) (020). It is possible to recognize the non-stationary nature of the processes, the differences between A and B being observable. For some materials, there are also significantly high peak-to-peak values at the beginning and end of mode A, B. Let's neglect the mentioned high peak-to-peak values. If, in the case of hardened steel, the envelope curve of peak to peak values is monotonic (envelope curve is increasing or decreasing), then this is different for ceramic materials.
If we analyze the histogram of the acceleration amplitudes under the condition that this acceleration in absolute value exceeded $50 \text{m.s}^{-2}$, then the histograms of the vibration amplitudes are shown for modes A and B and for the minimum of $a_p$ in figure 3 and for the maximum of $a_p$ in figure 4. The histograms show the fact that higher acceleration values were measured for SiC, Si$_3$N$_4$ and Al$_2$O$_3$, while lower values were measured for ZrO$_2$/Y$_2$O$_3$ and hardened steel. Histograms also present the fact that with increasing value of $a_p$, the amplitudes of accelerations increase for hardened steel and ZrO$_2$/Y$_2$O$_3$ but for SiC, Si$_3$N$_4$ and Al$_2$O$_3$ these changes are almost negligible. To highlight the differences in the amplitudes, a difference graph for the lower and upper quartiles is plotted without distinguishing between modes A, B in figure 5.
Due to the analysis of vibration amplitudes in the time domain, ZrO$_2$/Y$_2$O$_3$ is “closer” to the hardener steel than to SiC, Si$_3$N$_4$ and Al$_2$O$_3$.

Because the histograms and quartiles provide summary information for all 5 passes, in figure 7 is a graph of the RMS (Root Mean Square) of the workpiece acceleration, which was determined for a time step of 0.005s. If, based on the analysis in the time domain (figure 1), we hypothesized a similar character of acceleration for hardened steel and ZrO$_2$/Y$_2$O$_3$, then based on figure 6, we could add Si$_3$N$_4$ to this group as well.

The results of the Fourier transform of time realizations (for figure 1) are shown in figure 7. The analysis in the frequency domain is shown only for 256 frequency components in order to make the graphs clearer. We can notice (figure 7) that in the SiC and Al$_2$O$_3$ and spectra higher frequencies are represented, while in the ZrO$_2$ spectrum lower ones. In this method of processing the measured signal, the spectra were determined for all 5 passes and did not take into account mode A and B or time. In figure 7 and figure 8 are the acceleration values processed by STFT (Short Time Fourier Transformation). The results are displayed using the color maps and the waterfalls.
Figure 6. RMS values of vibration acceleration for time step 0.005s.

Figure 7. Fourier transform of measured vibration amplitudes.
Figure 8. STFT of measured vibration amplitudes, colormaps.

Figure 9. STFT of measured vibration amplitudes, waterfalls.
4. Conclusions
This paper was based on the assumption that if grinding involves the interaction of a grinding wheel and a workpiece and the workpiece is made of a different material, then we can expect to generate symptoms of the material separation process and these symptoms may be different for different types of materials under the same grinding conditions. By measuring the acceleration of the workpiece, we wanted to know the grinding process and possibly point out the similar or different nature of the specified parameters. We assume that this procedure will lead to the categorization of the material separation process using the selected symptoms / parameters.
Based on the performed measurements and analysis of the determined parameters, we assume that the process of material separation can be divided into at least two groups. If one group consists of SiC and Al2O3 and then ceramic materials of the Si3N4 and ZrO2/Y2O3 also approach the other group (based on hardened steel).
We do not consider the above statements and research to be closed and we do not consider the selection of measured quantities to be closed either.

5. References
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