Real-time monitoring of grinding efficiency in disc mills by acceleration measurement

Abstract

In this application note we introduce a novel approach for real-time measurement of the grinding efficiency in laboratory disc mills (patent pending). We demonstrate that efficient grinding is associated with a significant increase in the acceleration variability and decrease of the acceleration magnitude as measured by a 2-d acceleration sensor. This finding was consistent among various disc mills regardless of the mill type or grinding vessel volume. This smart-industry solution enables quantitative monitoring of grinding performance for improved analytical accuracy and reproducibility.

Key words

• **Sensory signal** • **Real time monitoring** • **Grinding** • **Disc mill**

Introduction

We have previously shown that acceleration measurement of the grinding vessel can be used to monitor the wear of the grinding set and the swing aggregate in disc mills. Furthermore, we demonstrated that the method is capable to predict the failure of anchor bolts connecting the drive motor to the swing aggregate. Accordingly, evaluation of the acceleration sensor signal turned out to be an easy and powerful approach for tool condition monitoring (TCM) and predictive maintenance (PdM) of disc mills.

In this application note, we present first data confirming that the acceleration signal can also be applied for monitoring the efficiency of the grinding process. Disc mills are used in the laboratory to comminute granular sample material reducing the grain size from usually 1 to 5 mm to 150 µm and below. The eccentric movement of the grinding vessel puts the grinding set inside into circular motion. The sample particles are ground based on shearing, impacting and compression of the material between grinding set, wall of the vessel and among each other. In many instances, the ground material is subsequently pelletized and analyzed by X-ray fluorescence. The grain size distribution following grinding has a significant impact on the XRF results. This so-called particle size effect may cause variances in elemental analysis of more than 30% due to different particle size distribution between samples [1]. It is therefore pivotal to minimize the variability of grain size distribution after grinding in order to decrease the bias of analytical results.

For many materials, the reproducibility of grain size distribution after grinding is very high. This is especially true for the use of automatic pulverizing mills compared to manual equipment. For some materials and applications, however, the grain size distribution may exhibit a high degree of variability due to variation in material properties or sampling. In the laboratory routine, it is practically unworkable to determine the particle size distribution after each grinding run. Therefore, it would be of great help if the grinding efficiency could be monitored in real time already during the grinding process.

Here, we show that begin and duration of the grinding process can be easily identified from the acceleration data. We provide first insights that the acceleration signal correlates with grinding efficiency and grain size distribution. Eventually, we elucidate the underlying mechanism for the change of the acceleration signal during milling.

Method

All tests were carried out on a manual (HSM 100P, tungsten carbide (TC) grinding vessel), semi-automatic (HP-M 500, chrome steel vessel) or automatic disc mill (model HP-MP, TC vessel). In each case, the acceleration sensor was mounted on the lower half of the swinging aggregate and connected to the PLC of the grinding mill for data acquisition. For analysis of the grinding vessel motion, the acceleration in x- and y-direction was assessed. For evaluation of grinding efficiency, the root mean square (RMS) of the x- and y-acceleration was calculated as previously described [2, 3]. The RMS values were plotted over time for evaluation. Furthermore, we calculated the standard deviation (SD) of the RMS values to determine the RMS variability.

In some instances, we also analyzed the grain size distribution of the ground material by using a vibratory sieve shaker.

Results

1. Acceleration signal of an empty grinding vessel, efficient and inefficient grinding

For this test series, we used the HSM 100P disc mill. First, we assessed acceleration during motion of an empty grinding vessel without sample material (only stone and ring) at a rotation speed of 1000 rpm. Second, we performed a grinding run with 50 g of silica sand at a grinding speed of 1000 rpm resulting in a significant grain size reduction (efficient grinding). Third, 50 g of the same material was ground at a lower speed of 600 rpm leading to only minor grain size reduction (inefficient grinding). The duration of each grinding run was 30 s.

The empty grinding vessel (Figure 1, A) led to a very uniform signal without fluctuations over time. The mean RMS was 30.1 m/s^2, the mean standard deviation of the RMS was low at 1.4. During efficient grinding (Figure 1, B), the initial acceleration signal was relatively constant with a low variability (RMS 29.9 ± 2.8 m/s^2). After 8.5 s (red arrow in Figure 1, B), there was a significant change in the signal pattern with a constant increase of the variability (RMS 31.3 ± 5.1 m/s^2). During inefficient grinding (Figure 1, C), the acceleration signal remained unchanged with little variability throughout the entire period (RMS 11.8 ± 1.2 m/s^2).

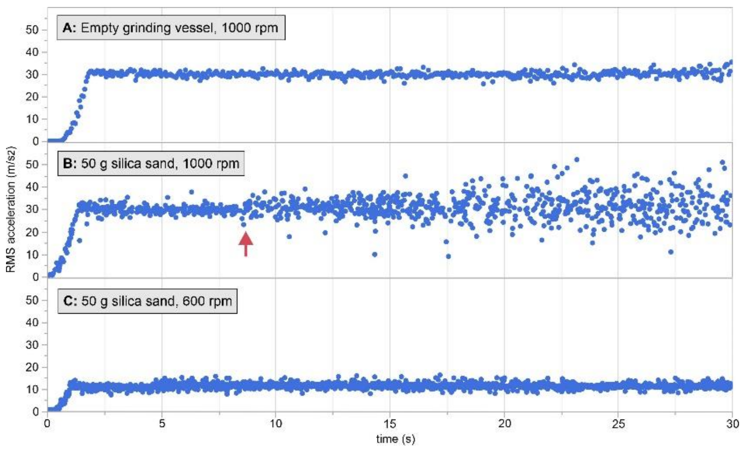

Figure 1: *RMS acceleration signal of an empty grinding vessel (A) and during efficient grinding (B) vs. inefficient grinding (C) of silica sand.*

2. Influence of the sample weight on the acceleration signal

In this test series, we assessed the influence of the sample weight on the acceleration pattern during grinding of silica sand and iron ore. For each material, we carried out five tests and increased the sample load from 50 to 90 g in steps of 10 g. In each run, we used the HSM 100P with a grinding time of 30 s and a rotation speed of 1200 rpm.

For silica sand, we found a characteristic change of the acceleration signal over time. In each run, the initial signal showed a uniform acceleration pattern without major fluctuations and then immediately changed displaying an increasing fluctuation and lowering of the RMS values (Figure 2). The time of the signal change depended on the sample weight and was delayed with increasing sample load. For 50 g, the signal change appeared already at 9 s. For 60, 70, 80 and 90 g the change took place later at 15 s, 26 s, 28 s and 31 s, respectively (red arrows in Figure 2). The RMS values were similar between trials. In the run with 60 g of silica sand, the mean RMS before the signal change was 49.4 ± 1.8 m/s^2, thereafter 32.5 ± 8.5 m/s^2.

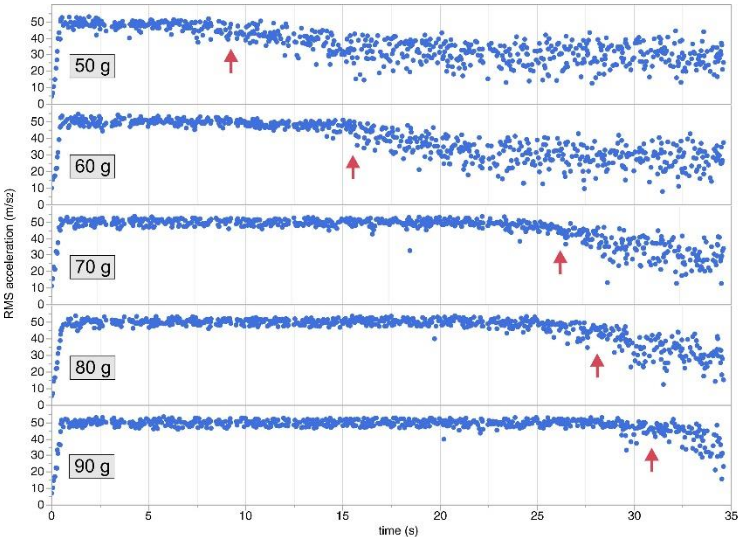

Figure 2: *RMS acceleration signal assessed during grinding of different amounts of silica sand in the manual disc mill of the type HSM 100P. The onset of the efficient grinding phase is characterized by an increase of the RMS variability (red arrow). The point of time when the signal changes depends on the sample weight.*

For iron ore, we observed a similar signal behavior like for silica sand (Figure 3). The time point of the signal change depended on the sample weight and increased from 12.5 s (50 g) to 25 s (90 g). However, the signal changes were smaller than for silica sand. For 60 g of iron ore, the mean RMS before the signal change was 50.1 ± 2.6 m/s^2, thereafter 46.6 ± 3.4 m/s^2.

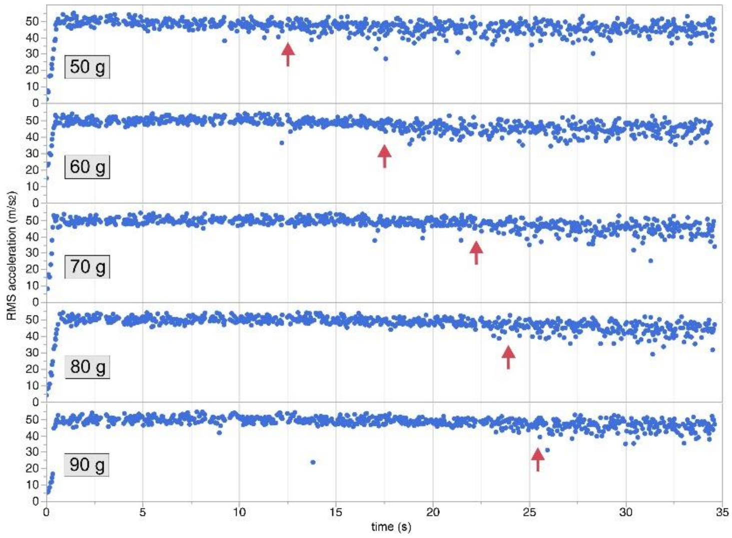

Figure 3: *RMS acceleration signal assessed during grinding of different amounts of iron ore in the manual disc mill of the type HSM 100P. Similarly to results for silica sand, the onset of the efficient grinding phase is characterized by an increase of the RMS variability (red arrow). Also here, the onset of the signal changes depends on the sample weight. Compared to silica sand, the RMS changes are less pronounced.*

3. Influence of the rotation speed on the acceleration signal and grain size distribution

In this test series, we examined the influence of the rotation speed on the acceleration signal. The test runs were carried out on the semiautomatic HP-M 500 during grinding of 200 g of iron ore for 60 s. The rotation speed was different in each run (900, 1000, 1100 rpm). After each run, we determined the grain size distribution of the ground material by using a vibratory sieve shaker.

For 900 rpm, the signal change occurred very late during the grinding process at 57 s. For 1000 and 1100 rpm, the signal change was earlier at 50 s and 38 s (Figure 4).

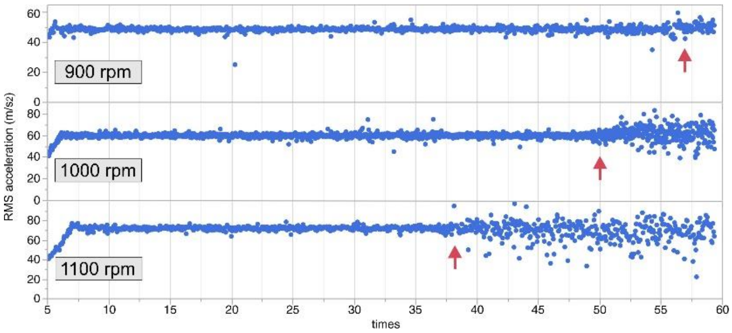

Figure 4: *RMS acceleration signal assessed during grinding of 200 g iron within the HP-M 500. The rotation speed varied from 900 to 1000 rpm. The grinding time in all trials was 60 s. The onset of the signal change (red arrow) depended on the rotation speed with earlier begin at a higher rpm value.*

In the grain size analysis, we found an increase of the fraction < 45 µm from 41.2 % at 900 rpm to 51.0 % at 1000 rpm and 59.6 % at 1100 rpm. At the same time, the fraction > 150 µm decreased from 31.2 % to 17.3 % and 6.4 %, respectively (Figure 5).

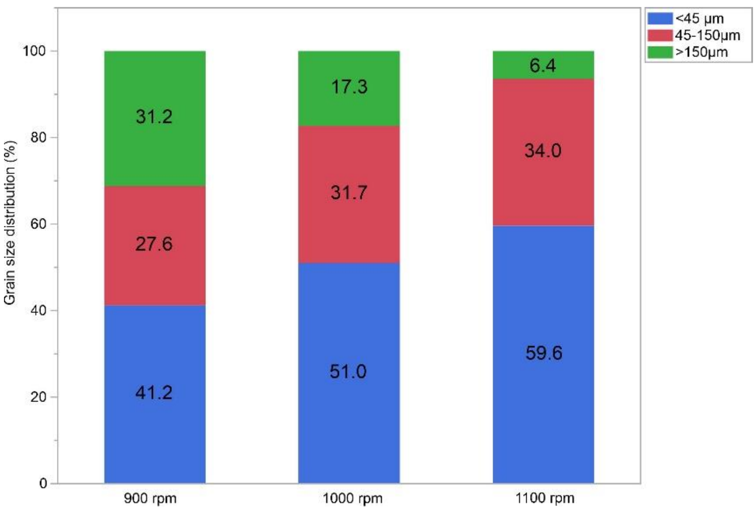

Figure 5: *Grain size distribution after grinding of 200 g iron ore in the HP-M 500 at different rotation speeds for 60 s.*

4. Oscillation analysis

In order to evaluate the underlying cause for the change of the acceleration signal during grinding we performed an oscillation analysis. We examined the signal during grinding of iron ore in an automatic mill (HP-MP) at a rotation speed of 1000 rpm. Similarly to the previous trial, we initially observed a uniform signal with little fluctuation which then changed to a signal with large fluctuations (Figure 6). We performed an oscillation analysis before the signal change (red box at 10 s, Figure 6) and thereafter (red box at 15 s, Figure 6).

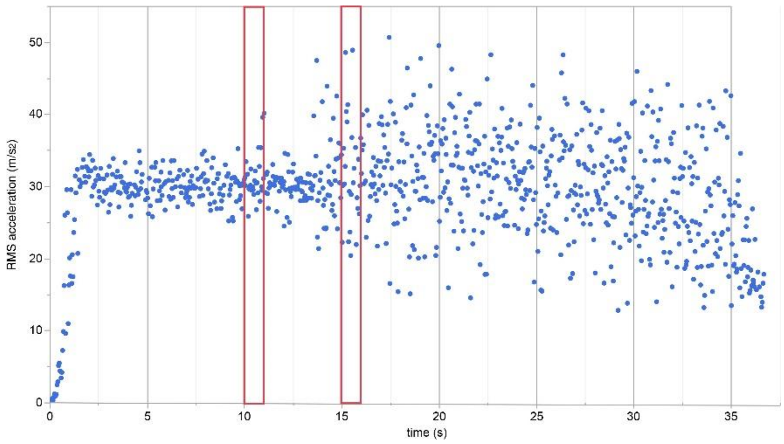

Figure 6: *RMS acceleration signal during grinding of 60 g iron ore in an automatic mill (combined mill and press of the type HP-MP). The recording was used to perform an oscillation analysis at two different points of time each covering 1 s (red boxes). First oscillation analysis was carried out before increase of the acceleration variability (at 10 s), second analysis thereafter (at 15 s).*

For this purpose we projected the acceleration values in the x- and y-direction on an ideal sinusoidal oscillation (Figure 7). When set in motion, the grinding vessel describes a circular path around its center. Therefore, the acceleration in the x- and y-direction shows a phase lag of 90° (Figure 7).

After 10 s the values for x- y- acceleration are located on their ideal sinusoidal curves (Figure 7, A). Also, the phase lag of x- and y-acceleration was quite constant at 90°. Accordingly, the resulting RMS values of x- and y- direction plotted in a relatively straight line with very little deviation. This corresponds to a situation when the grinding vessel can move relatively undisturbed along its ideal circular path. After 15 s we found that some of the x- and y acceleration values were lower than predicted by the ideal sinusoidal curve (Figure 7, B). These temporary decelerations led to an increased variability of the RMS values.

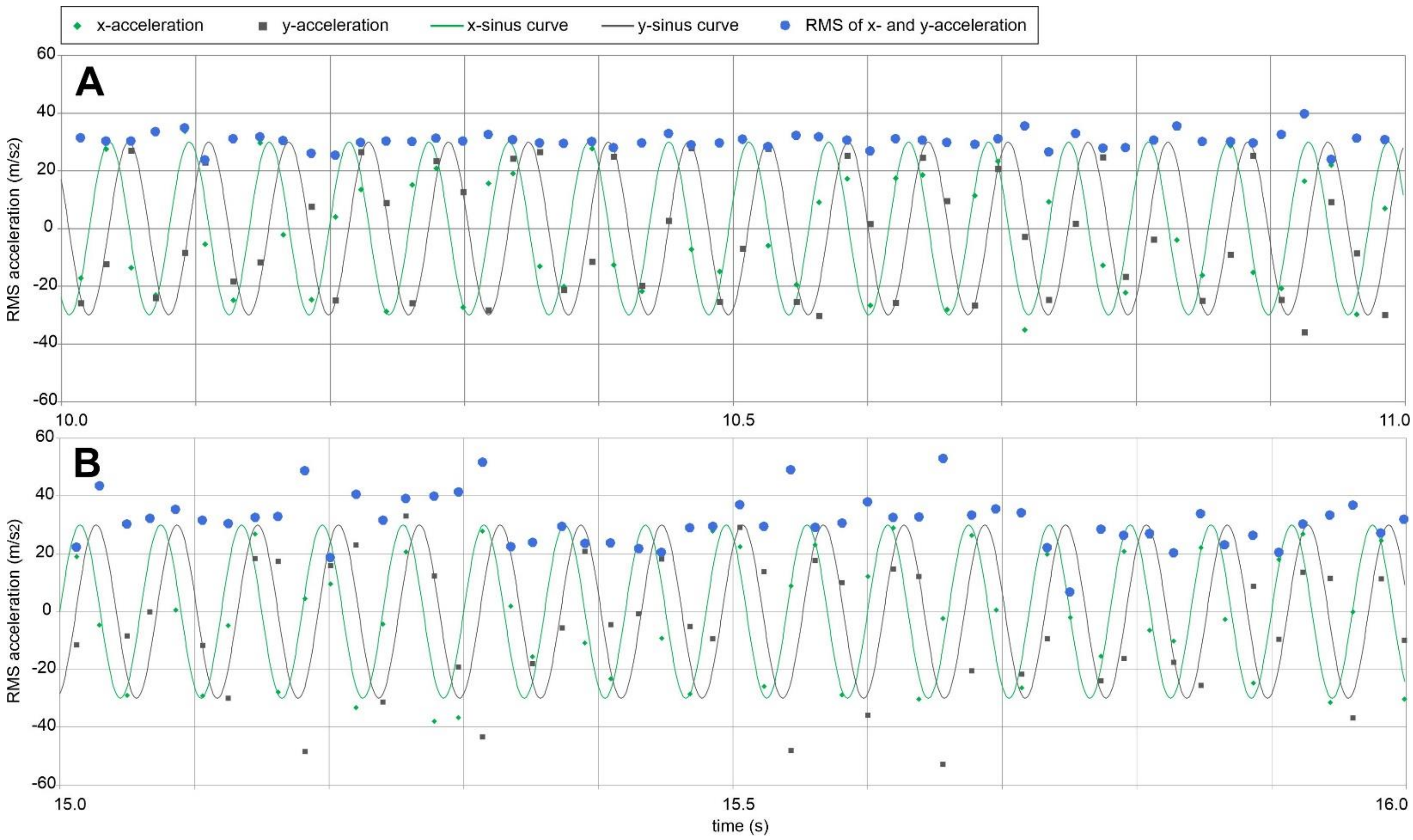

Figure 7: *Oscillation analysis of the grinding run shown in Figure 6 at two different points of time- before onset of variability increase at 10 s (A) and after increase at 15 s (B). If the grinding vessels shows a completely undisturbed circular motion x- and y-acceleration can be described as sinusoidal curves with a phase lag of 90° (green and black curves). (A) Before onset of efficient grinding measured x- and y-acceleration values lie along these curves resulting in constant RMS values. (B) After onset of efficient grinding x- and y-values show significant decelerations with deviations from the ideal curve resulting in a higher variability of RMS values.*

Discussion

In this application note, we introduce a new method for real-time monitoring of the grinding efficiency in disc mills. We demonstrate that the increase in acceleration variability and decrease of acceleration magnitude is a marker for efficient grinding. This finding is corroborated by the following observations: 1. Motion of an empty grinding vessel only leads to a uniform acceleration signal with low variability. 2. Inefficient grinding due to slow rotation speed or high sample volume is characterized by absence or late onset of the acceleration variability. 3. By contrast, efficient grinding is correlated with an early and swift increase in variability of acceleration. At the same time the mean magnitude of acceleration is decreased.

The above described signal pattern was observable in all disc mills used in this study including manual and automatic mills with a 100 ccm tungsten carbide grinding vessel as well as a semi-automatic mill with a 500 ccm chrome steel vessel. This shows that the signal pattern is a general phenomenon that can be utilized in a wide range of different discs mills and applications.

The underlying reason for the signal pattern change is not yet fully understood. In the oscillation analysis we showed that increased variability is attributable to brief decelerations of the grinding vessel in x- or y-direction. We reckon that these interruptions of acceleration are due to short blockages of the motion of the grinding set (ring and stone) in the material. The impeded motion of ring or stone most probably leads to a momentary deceleration of the entire grinding vessel which can be measured by the acceleration sensor.

What is the reason for the increasing motion blockage of the grinding set within the vessel during efficient grinding? The flowability and “viscosity” of powders strongly depends on the particle size and shape [4, 5]. At small average particle sizes and therefore high interparticular forces, stable bridges are formed between particles. Moreover, these bridges are not only stable but also quickly reforms. At the beginning of the grinding process, the average particle size is large and hardly any interparticular briges are built. This means that flowability of the sample is high and viscosity is low. Therefore, the grinding set can move relatively unhindered through the powder within the grinding vessel.

If efficient grinding takes place, the average particle size decreases. This leads to interparticular bridges resulting in lower flowability and higher viscosity of the powder. This in turn causes increasing blockage of the grinding set as measured by the increased acceleration variability.

What is the reason for the decreased acceleration amplitude during efficient grinding? The increased variability during efficient grinding is accompanied by a general decrease of the acceleration magnitude. This phenomenon is probably due to the transfer of the kinetic energy into energy used for comminution of the sample material.

Our approach opens up numerous opportunities for an easy and real-time monitoring of the grinding process. In subsequent reports we will show in detail that this technology allows the quantitative assessment of the grinding process and its different stages. This smart-industry solution offers significant benefits in application development and condition monitoring of routine processes.

References

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Germany

HERZOG Maschinenfabrik
GmbH & Co.KG
Auf dem Gehren 1
49086 Osnabrück
Germany
Phone +49 541 93320
info@herzog-maschinenfarbik.de
www.herzog-maschinenfabrik.de

USA

HERZOG Automation Corp.
16600 Sprague Road, Suite 400
Cleveland, Ohio 44130
USA
Phone +1 440 891 9777
info@herzogautomation.com
www.herzogautomation.com

Japan

HERZOG Japan Co., Ltd.
3-7, Komagome 2-chome
Toshima-ku
Tokio 170-0003
Japan
Phone +81 3 5907 1771
info@herzog.co.jp
www.herzog.co.jp

China

HERZOG (Shanghai) Automation
Equipment Co., Ltd.
Section A2, 2/F, Building 6
No. 473, West Fute 1st Road,
Waigaoqiao F.T.Z., Shagnhai,
200131
P.R.China
Phone +86 21 50375915
info@herzog-automation.com.cn
www.herzog-automation.com.cn