Validating the Improved Energy Transfer Model in Stirred Media Mills with different Ores

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Abstract. In the past a range of mechanistic models have been developed to predict milling processes. A popular one for stirred media mills is the stress model for which recently the energy transfer was considered in greater depth. To better account for the effect of viscosity on the energy transfer coefficients a previous study was carried out using quartz. In contrast, most grinding processes involve more complex materials. In this work that further developed stress model is validated using ores as complex materials. Characterisation of the materials and their breakage behaviour is performed and a master curve for the prediction of the specific energy input established. The model's performance is evaluated by comparing experimental comminution data with model-based predictions of specific energy input.

1. Introduction

As energy costs rise, the energy optimization of industrial processes is becoming increasingly important. This is particularly true for energy-intensive comminution processes. In addition to numerical models, mechanistic models also offer the possibility of optimising comminution in large-scale plants based on a small number of Lab-scale experiments.

A well-known mechanistic model is Kwade's stress model [1], which has been further developed in the past [2, 3], to more accurately describe the behaviour of the mill. Energy transfer factors are a particular focus of their work. In the work of Sterling et. al. [3], the influence of viscosity on the energy transfer factors was reevaluated, and an improved master curve was established. This master curve can be used to determine the optimal operating conditions for multi-scale stirred media mills based on a limited number of experimental tests and knowledge of material properties.

Although these models have been well studied for homogeneous materials, heterogeneous materials are often encountered in practical applications. The study of multi-component comminution is gaining importance in context of sustainability concerns, such as recycling and the availability of critical raw materials. However, the stress model improvement by Sterling et. al. [3] is based on studies with silica as model material and will be validated using several copper and iron ores in this study.

2. Materials and methods

2.1. Experimental investigations

Laboratory-scale comminution studies are first conducted for each of the ores used. For this purpose, a horizontal stirred media mill with a polyurethane lining and agitator is used. The suspension is cooled via the feed tank. At least six different parameter combinations are tested for each ore, with variations in agitator tip speed and grinding media (GM) density and size. The range of parameters used is shown in Table 1.

Table 1. Parameter variation for grinding experiments

Parameter	Symbol	Variation
GM size	d_{GM}	1,01 – 3,05 mm
GM density	ρ_{GM}	3,8 – 6,05 kg/L
Stirrer tip speed	v_t	6 – 12 m/s
GM filling ratio	φ_{GM}	80 %
Volumetric solids content	c_V	20 %

According to Kwade and Schwedes [1], this results in maximum stress energies ranging from 0,15 to 8,73 mJ. The comminution time is 20–60 minutes in circuit operation. From the GM filling ratio results the suspension volume inside the mill and therefore an average residence time t_r can be determined. In order to enhance reproducibility, the feedstock is added to the tank over a period of three minutes, with one-third of the total feedstock added each minute. Throughout the test duration, several samples are taken and analysed for particle size. Selected samples are additionally analysed for solids content, throughput, and rheology. Based on this data, the viscosity can be correlated with the particle size distribution of the suspension. Furthermore, it is possible to determine grinding-specific parameters such as the specific energy input E_m or the stress number *SN*.

In addition, nanoindentation tests are performed on the ores used. The Young's modulus Y can be determined from the elastic force-displacement curves according to

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Portnikov [**4**] using Eqs. (1–2). Here, F corresponds to the applied force for a total deformation Δ of the loaded particle with diameter d and effective Young's modulus Y^*. To then calculate the Young's modulus Y, the Poisson's ratio ν must be known.

$$F = \frac{1}{3} Y^* \cdot \sqrt{d} \cdot \Delta^{3/2} \quad (1)$$

$$Y^* = \frac{Y}{(1-\nu^2)} \quad (2)$$

The compressive strength of the materials σ_{cs} can also be determined from nanoindentation tests, when stressed until breakage. It can be calculated using Eq. (3) with the applied force F and a cross-sectional area A of the stressed particle. The latter is calculated using the longest and the smallest chord of the unstressed particle to form an ellipse.

$$\sigma_{CS} = \frac{F}{A} \quad (3)$$

It determines the minimum particle size and thus influences the stress intensity SI. The Young's modulus, on the other hand, is used for the calculation of the particle-related energy transfer coefficient ν_P.

2.2. Modelling

The master curve is modelled in accordance with the work of Sterling et. al. [3] following the determination of material properties and the grinding behaviour, respectively. Based on the experimental investigations, the average optimal stress intensity (stress energy related to stress mass) of the product $\overline{SI_{P,opt}}$ and subsequently also the product-specific stress number SN_P can be determined. The master curve, plotted as a function of $\overline{SI_{P,opt}}$ times SN_P versus $\overline{SI_{P,opt}}$, enables a backward calculation and thus a prediction of the comminution time t_c and the specific energy input E_m.

In contrast to Sterling et. al.'s work [3], the equation for determining the improved product-specific stress number $SN_{P,imp}$ was adapted in this study as shown in Eq. (4). The respective calculation of these variables as well as the power factor k_{susp} can be found in the model [3].

$$SN_{P,imp} = v_t \cdot \frac{m_{GM} \cdot t_r}{\frac{\pi}{6} d_{GM}{}^3 \cdot \rho_{GM} \cdot \sqrt[3]{k_{susp}}} \cdot \left(\frac{\overline{SI_{P,imp}}}{\overline{SI_{P,opt,imp}}}\right)^{1-\alpha} \quad (4)$$

3. Results and discussion

The following section presents the results for one of the copper ores used, referred to hereafter as Sample 1. After characterizing the material using a nanoindenter and analysing its fracture behaviour based on comminution tests as shown in Section 2.1, the master curve depicted in Figure 1 was obtained. The two grinding media materials used — zirconium dioxide (ZrO_2) and an oxide mixture consisting primarily of aluminium oxide (Al_2O_3) — are color-coded. The combined master curve, plotted in dark blue, follows the equation given in Eq. (5).

$$\overline{SI_{P,opt,imp}} \cdot SN_{P,imp} = 5{,}4 \cdot 10^{-18} \cdot \overline{SI_{P,opt,imp}}^{4,2} \quad (5)$$

The R^2 value of 0.96 indicates a good fit.

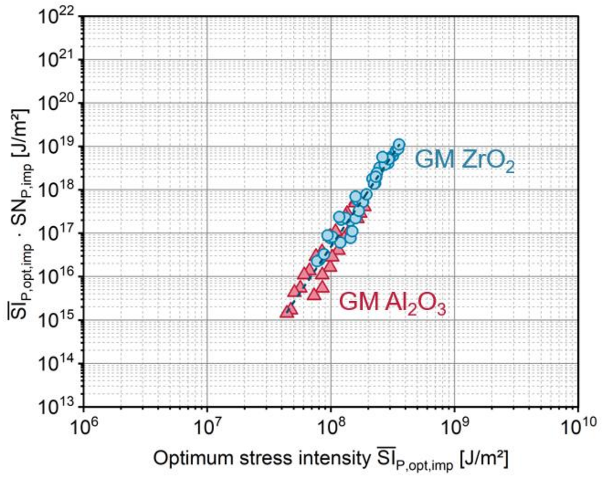

Figure 1. Master curve for Sample 1 with different grinding media (GM) materials used.

If the master curve is used to calculate the specific energy requirement for various target particle sizes for Sample 1 under given milling parameters, a model-based prediction of the grinding behavior can be made. A comparison with the experimentally collected data for a selected test is shown in Figure 2. This test was conducted using grinding media from the alumina mix at a stirrer peripheral speed of 6 m/s.

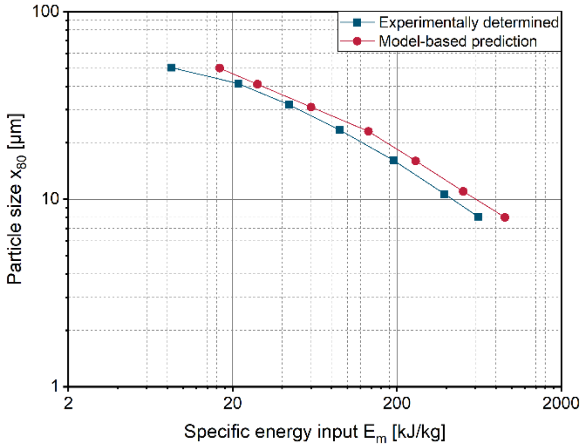

Figure 2. Comparison of comminution curves between experimental data and modelling approach for grinding of Sample 1 with GM size of 2,53 mm GM density of 3,8 kg/L and stirrer tip speed of 6 m/s.

The trends of the experimentally recorded and modelled comminution curves are generally similar. However, the model-based curve overestimates the specific energy input slightly compared to the experimental curve.

4. Conclusion

The model developed by Sterling et. al. provides a solid foundation for predicting the behaviour of real-world complex materials such as ores. However, the difference between the modelled specific energy input and the experimentally determined value makes it clear that there is still room to refine the model's predictions.

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