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Original Research Paper

Dry grinding in planetary ball mills: Evaluation of a stressing model

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ABSTRACT

Planetary ball mills at laboratory scale are widely used for grinding and alloying processes. However, in contrast to other mill types, no applicable mechanistic model exists to describe the stressing conditions and their effect on particle breakage, so that processes are empirically evaluated so far. Within this study, the stressing conditions are determined by simulations based on the discrete element method including the contact model of Hertz and Mindlin. The contact model parameters are carefully calibrated by a series of experiments, so that it is finally possible to validate the simulation results by comparison of measured and calculated power values. The correlation of stressing conditions and breakage rates of alumina powder demonstrates the effect of stressing on breakage kinetics and breakage mechanism. It allows calculating the active mass in dependence on process parameters by an extension of Schönert's active mass model.

Altogether, the presented stressing model features analytical functions for the mill-related stressing conditions and highlights the importance of stressing intensity as process determining parameter, which defines the required number of material-related stressing events and the specific energy.

1. Introduction

Planetary ball mills are used in several fields of fine and wet grinding, mechanical alloying and mechanochemical synthesis at laboratory scale [1–3]. Although usually limited to capacities of 2 L in total, the advantages of high energy densities and effective particle breakage accompanied by high reliability and easy handling makes them a widespread and successful tool. However, after years of usage in process technology the effect of process parameters and geometrical dimensions on stressing conditions and particle breakage are still not understood in detail and applicable process or stressing models are missing [4].

A planetary ball mill consists of a rotating sun disc (SUN), on which one up to four grinding chambers (GC) are located. The grinding chambers themselves rotate at higher speeds, normally in opposite direction to the sun disc to ensure high forces and a highly random motion and collision pattern of grinding media (see Fig. 1).

The powder particles are trapped between colliding media as shown schematically in Fig. 2 and fractured as a result of stressing. Within the collision event, a fraction of kinetic energy of the media is dissipated into deformation, friction and heat.

(1) The amount of dissipated energy is referred to as stressing energy, *SE*, and depends on the masses of the colliding bodies, so the mass of media and grinding chamber, as well as their relative velocity, $v_{\mathrm{rel,n}}$ (compare Eq. (6)). The relative colliding velocity is mainly affected by the process parameters of the mill. Additionally the stressing energy is influenced by the behavior of the powder particles themselves. The powder tends to form a layer on the media and grinding chamber surfaces, especially in case of small particle sizes, so that the particles are stressed as a particle bed [5].

(2) Within the particle bed, several micro processes including breakage, rearrangement and deformation take place. As these micro processes change with layer thickness and can hardly be characterized individually for the introduced system, the coefficient of restitution, *COR*, is used. It is defined as ratio of the final, $v_{\mathrm{rel,fin}}$, to the initial, $v_{\mathrm{rel,ini}}$, relative velocity of the bodies after they collide, and thus determines the fraction of kinetic energy which is dissipated.

$$COR = \frac{v_{\mathrm{rel,fin}}}{v_{\mathrm{rel,ini}}} \qquad (1)$$

(3) Within the particle bed, the strength of a single particle is not solely an indication for its tendency to break. Each particle receives only a part of the stressing energy, while its state of stress is affected by the number of neighbouring par-

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Nomenclature

Symbols

CF	collision frequency, s^{-1}
CF_0	normalized collision frequency (per media), s^{-1}
COR	coefficient of restitution, –
d_{GM}	grinding media diameter, mm
$E_{m,DEM,n}$	calculated specific energy based on normal collisions, kJ kg^{-1}
$E_{kin,GM}$	kinetic energy of a grinding media, J
h	fall height, m
h_0	bounce height, m
k	speed ratio, –
L	layer thickness, m
m_A	active mass, kg
m_{GC}	mass of grinding chamber, kg
m_{GM}	mass of a grinding media, kg
$m_{stressed}$	theoretical amount of stressed material, kg
m_P	mass of ground product (alumina), kg
M_{GC}	torque, Nm
n_{GC}	rotational speed of grinding chamber, rpm
n_{SUN}	rotational speed of sun disc, rpm
P_0	no-load power (experiment), W
P_{EXP}	measured power (experiment), W
$P_{EXP,total}$	total power (experiment), W
$P^*_{EXP,total}$	normalized total power (experiment), W L^{-1}
$P_{DEM,n}$	calculated power based on normal collisions (simulation), W
$P^*_{DEM,n}$	normalized power (simulation) based on normal collisions, W L^{-1}
$P^*_{DEM,total}$	normalized total power (simulation), W L^{-1}
R_{SUN}	radius of sun disc, mm
SE	stressing energy, J
$\overline{SE}_n$	mean normal stressing energy, J
$SE_{n,media}$	stressing energy of media-media collision, J
$SE_{n,chamber}$	stressing energy of media-chamber collision, J
$\overline{SE}_{total}$	mean total stressing energy, J
SI	stressing intensity, J kg^{-1}
$\overline{SI}_n$	mean normal stressing intensity, J kg^{-1}
SN_{mat}	material related stressing number, –
t_G	grinding time, s
$v_{rel,n}$	relative velocity in normal direction, m s^{-1}
V_{GC}	volume of grinding chamber, ml
V_{GM}	volume of grinding media, ml
$V_{GM,void}$	void volume of bulk grinding media, ml
V_P	volume of alumina particles, ml
$V_{P,bulk}$	volume of bulk alumina, ml
$\rho_{P,bulk}$	bulk powder density, kg m^{-3}
ρ_P	powder density, kg m^{-3}
ε	porosity of bulk grinding media, –
ε_P	porosity of bulk powder, –
φ_{GM}	grinding media filling ratio, –
φ_P	powder filling ratio, –
υ^*_E	energy transfer factor, –

ticles and its location within the bed. Thus, the stressing intensity, *SI*, is considered, which is defined as ratio of stressing energy to the amount of captured mass, or active mass, m_A (compare Eq. (13)) [6,7].

High intensities applied by coarse media can lead to an overloading accompanied by low energy utilization [5,8]. However, low stressing intensities result in repeated stressing of particles with attrition or fracture. Attrition is the gradual breakage of particles, which leaves the original size of particles relatively unchanged [9]. Fracture at low intensities is then caused by the growth of defects after repeated stressing [9]. Thus, the breakage mechanism is based on fracture or attrition and is determined by the stressing intensity. For wet grinding in stirred media mills

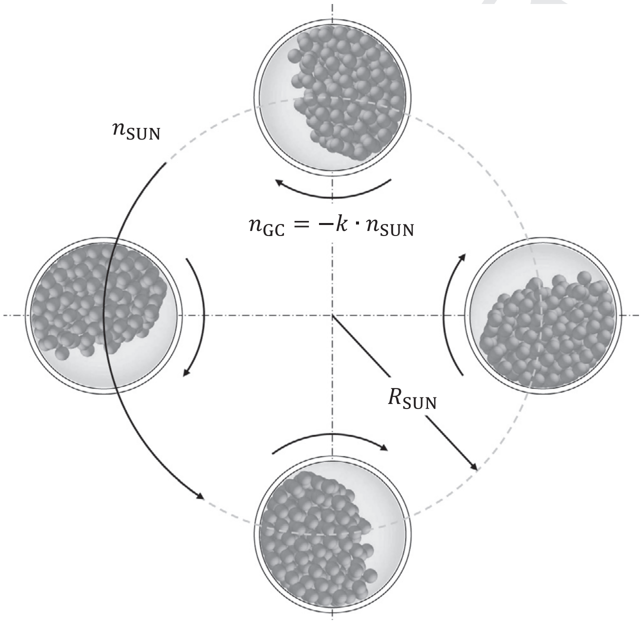

Fig. 1. Scheme of planetary ball mill with four grinding chambers rotating in opposite direction to sun disc.

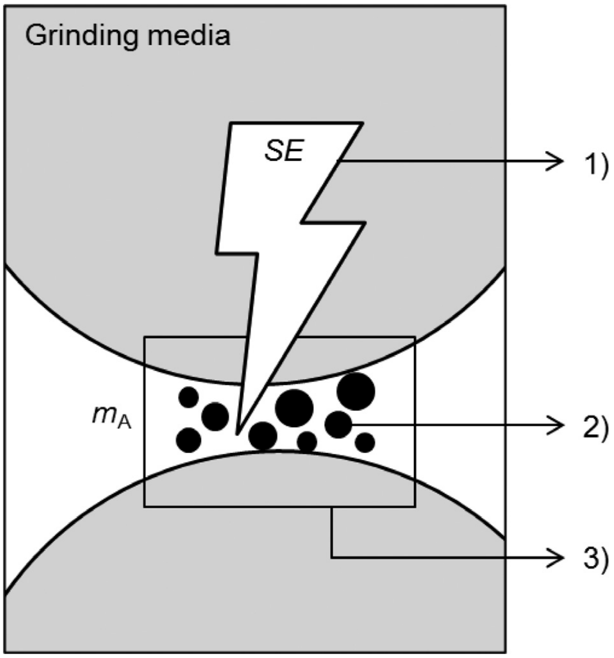

Fig. 2. Stressing of particles between colliding media.

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