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Empirical and scale-up modeling in stirred ball mills

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ABSTRACT

Stirred ball mills are frequently used for ultrafine- and nanogrinding in food, pharmaceutical and chemical industry, but only few investigations have been published on empirical or scale-up modeling of stirred ball mills. Experiments have been carried out with a laboratory scale stirred ball mill. During the experiments the main technical parameters such as stirrer speed, grinding media, filling ratio, grinding time and the solid mass concentration have been systematically adjusted. The particle size distribution of mill products can be well estimated by empirical functions, so an empirical model has been prepared for the laboratory mill. The relation between the grinding fineness, grinding time and specific grinding work was represented for several materials such as pumice, andesite, limestone and tailings of ore mining industry. The power consumption of the stirred ball mill for scale-up was determined by a method based on the dimensional analysis. A new scale-up model has been presented as well by with industrial size stirred ball mills can be designed on the basis of the laboratory measurements.

Keywords: Ultrafine grinding; Laboratory stirred ball mill; Empirical modeling; Scale-up

1. Introduction

Producing of disperse systems, comminution and grinding are two of the most often applied technological processes. Nowadays it has already been proved that grinding besides decreasing of particle size causes structural and chemical changes too in the grinding material. With respect to structural changes and mechanochemical reactions in fine grinding, plastic deformation has an important role where the particle becomes practically “free of dislocation”. The properties of products produced by fine grinding depend on the speed and the degree of the primary and secondary mechanochemical processes. The grinding process can be directed by helping of primary processes and reducing of secondary processes.

Stirred ball mills are used successfully for processing a great number of different very fine products in the ceramic, chemical, pharmaceutical, food, lacquer and paint industries. Recently, a variety of stirred ball mills have been developed and applied worldwide. Wet grinding with stirred ball mills has a wide range of applications. Owing to their high efficiency, stirred ball mills have greatly replaced traditional systems.

The requirements for raw materials with regard to quality and reliability are constantly growing. An important step in production is the ultrafine grinding of the raw materials into the achievable final particle size. The achievable particle size distribution can in principle be influenced by design parameters (geometry of the stirrer and the grinding chamber), by operating parameters (throughput, peripherial speed, method of operation), by grinding media (especially diameter, density, hardness and filling ratio) and by the feed material itself (hardness, concentration, density) (Karbstein et al., 1996). Fineness of the ground products, most of the particles below 5 μm is required as one of the most important specifications for the industrial applications. When grinding raw materials in stirred ball mills, the selection of grinding beads is of special significance. Besides the specific energy, properties of grinding beads strongly affect the grinding result. The choice of grinding beads depends on the type of the grinding material to be ground and the required fineness. As grinding media, usually beads made of glass, steel or ceramic materials are used (Becker and Kwade, 1997; Karbstein et al., 1996).

2. Methods and materials

The experiments were procedured by a vertical laboratory stirred ball mill (see Fig. 1). The experimental equipment (at the University of Miskolc, Institute of Raw Material Processing and Environment Process Engineering) was operated

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Nomenclature

c_m	solid mass concentration (–)
c_V	solid volume concentration (–)
C_{mix}	grindability index number (–)
D_m	diameter of mill (m)
d_g	diameter of grinding beads (m)
d_k	diameter of stirrer disks (m)
Eu	stirrer Euler number (–)
Fr	Froude number (–)
g	acceleration of gravity ($m\,s^{-2}$)
n	stirrer speed ($1\,min^{-1}$)
P_m	power consumption (kW)
Re	stirrer Reynolds number (–)
t	grinding time (min)
x	actual particle size (μm)
x_{50}	median (μm)
v_k	circumferential speed of stirrer ($m\,s^{-1}$)
w_k	width of stirrer disks (m)
W_f	specific grinding work ($kJ\,kg^{-1}$)
μ	dynamic viscosity of susp. (Pas)
μ_0	absolute dyn. viscosity of susp. (Pas)
ξ	relative particle size (–)
ρ	density of suspension ($kg\,m^{-3}$)
σ/R	scattering/correlation index (–)
φ_m	filling ratio of the mill (–)
a, b	constants (–)
a, c, e, f, h, i, m, n	exponents (–)
A, K_1, K_2	constants (–)

by grinding beads in a wet process. The effective chamber volume is 0.7 l. On the stirrer in the grinding chamber there are five fill disks with diameter of 70 mm. The grinding media consisted of steel balls, 3.175 mm in diameter, with a solid density of 7800 $kg\,m^{-3}$. Water was used as carrier liquid. As grinding material, tailings of ore mining industry (from Gyöngyösoroszi, Hungary) with maximum particle size of 150 μm was used. The density of solid material was 2580 $kg\,m^{-3}$. The experiments were conducted by the variation of several main parameters such as filling ratio, stirrer speed, solid mass concentration and the grinding time (see Table 1). The vertical orientation and geometry of the grinding chamber were not changed.

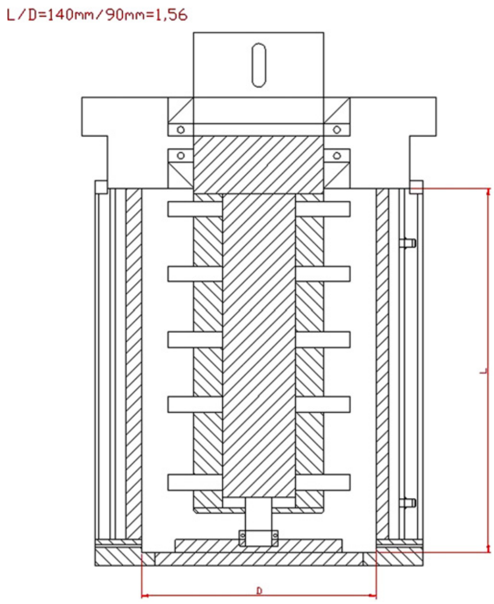

Fig. 1 – Laboratory stirred ball mill.

Table 1 – The variation of several main parameters by pre-grinding in the laboratory stirred ball mill (Mannheim, 2005).

Filling ratio	$\varphi_m = 0.7–0.8$
Stirrer speed	$n = 1440–2880\,min^{-1}$
Solid mass concentration	$c_m = 0.2–0.4$
Grinding time	$t = 1–20\,min$

The product fineness was described by the characteristic particle sizes which were measured by a laser doppler sizer (Sympatec Helos). Investigations showed that due to the high centrifugal forces, the particle size distribution of the ground product of the laboratory stirred ball mill was very fine. The average particle size (x_{50}, median) was 2.47 μm (by the grinding of 20 min) (Mannheim, 2005, 2006).

3. Results and analyses

3.1. *Empirical modeling*

Non-linear solutions endeavours to help process industries improve their products, materials and processes through

- better process operation, better process control
- reduced raw material consumption or energy consumption
- improved quality, reduced variations, reduced rejects
- easier product development
- improved measurement systems, software sensors

According to non-linear parameter estimations the empirical failure function can be approached. For determining the empirical failure functions, our work hypothesis is that the equipment of comminution (grinding) is firstly characterized by the shape of the breakage function. The parameters of the characteristic breakage function for given equipment depend on the main technical parameters of the mill (Csőke and Rácz, 1998).

Good non-linear models will take into account quantitative or heuristic knowledge of the process and materials, or parts of physical models, or knowledge of some of the nonlinearities in the relations. By empirical modeling we should select the breakage function which correctly follows the particle size distribution of the product, which determines the relationship between the parameters of this function and the physical parameters of the machine: An empirical model for the estimation of particle size distributions of product has been prepared for the laboratory stirred ball mill (from pilot-scale measurements). The experiments were achieved by the optimal values of the main parameters (see Table 2).

The characteristics and the inner structure of the particle size distribution can be detected by the so-called characteristic or relative particle size distribution curves (these are also known as empirical failure functions) (Csőke and Rácz, 1998).

Table 2 – The main optimal parameters by empirical modeling in the stirred ball mill (Mannheim, 2005).

Filling ratio	$\varphi_m = 0.7$
Stirring speed	$n = 1440\,min^{-1}$
Solid mass concentration	$c_m = 0.2$