The effect of grinding media performance on milling and operational behaviour

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Synopsis

The effect of grinding media performance on milling and operational behaviour was demonstrated under different selected conditions of calcium carbonate slurry milling. A variety of grinding media materials and bead sizes, along with two different stirrer tip speeds, were used in the grinding process to generate a particle size reduction of the calcium carbonate ($CaCO_3$). To determine the optimum milling parameters the collected test data were used to calculate and evaluate specific energy as well as stress intensity under different milling conditions.

Keywords: Grinding, mill media, high energy mills, industrial minerals, precious metals.

Introduction

Nowadays, increasing energy costs and raw material prices make it important to look at the efficiency of the manufacturing process. Wet grinding and ultrafine wet grinding in stirred media mills are now a possible cost-effective production step for the processing of industrial minerals and precious metals. The generation of smaller particle sizes (down to micrometer scale), adjusted to specific particle size distribution, can be advantageous for further production steps—i.e. better liberation of precious metals or improved industrial mineral qualities—i.e. Titaniumdioxide or calcium carbonate—with better colour strength for fillers.

In the following paper the wet grinding process is investigated under different milling conditions of calcium carbonate slurry (milling product). Different grinding media materials varying in specific weight, bead size and stirrer tip speeds are used to determine an optimum of energy consumption for the milling process, based on the stress model of Kwade (2000, 2005).

The idea of A. Kwade´s stress model describing the phyical process in stirred media mills bases on a practical example of crushing a stone in small pieces. There are different possibilities of hitting a stone. A small or big hammer can be used. The hammer can be struck slow or fast the stone and the number of hits can be different. Kwade looked at two different views of the fracture of the stone in this example—first, what is the hammer doing? Second, what happens with the stone?

- The view of the hammer—mill related stress model—how high is the frequency of the strikes, independent of the number of the stones, and how strong are the blows, which represent the energy transferred to the particles of the hammer?
- The view of the stone—product related stress model—how often are the stone and parts of the stone hit? These are the number of hits to obtain a certain fineness. And, secondly, how high is the intensity of the stress, resulting in the specific energy, which is transferred to the stone at each hit?

Kwade transferred this model to the milling process in stirred media mills

In the stress model of the mill, the following aspects are involved:

- The crushing behaviour of the mill is defined by the kind of stresses (such as shear forces, impact, and compression), the frequency of the stress events, and the energy, which are supplied by the mill at each stress event, the so-called stress energy
- The total number of stresses and the crushing time determine the product quality
- The stress energy of all stresses is not constant; it corresponds to a distribution of the stress energy.

The product related stress model contains the following aspects:

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- ➤ The product quality like particle size in a crushing or dispersing process is defined by the kind of stresses (shear forces, impact, and compression), how often each particle and broken particles are stressed, and how high is the specific energy or the specifc force by each stress event
- ➤ The number of stress events and intensity are not constant for all particles and can only be characterized only by stress distribution
- ➤ The stress intensity and the material properties define the efficiency of the specific energy, which is transferred to the particle of the milling product and influence the product quality and fineness of the product.

A combination of both models leads to a relation between the parameters of specific energy, power input into the mill, and the production capacity. That means, in detail, that the total energy which is transferred to the product particles can be determined by the summation of all stress energies. The specific energy, which is actually transferred by the grinding media to the product particles, is obtained by relating the total energy to the total mass of the product.

The result of Kwade's investigations and work is that the milling efficiency is a product of stress intensity and stress numbers, and the best milling efficiency is achieved by selecting grinding media size, denisty of grinding media, and mill speed to approach an optimum stress intensity and maximize the stress number.

Due to Kwade´s investigations and modelling of grinding and dispersing with stirred media mills, the following milling tests with calcium carbonate and different grinding media were done to find out the optimum grinding conditions.

Description of test conditions and mill parameters

All tests were performed in a Drais laboratory perl mill PML H/V with an installed electrical motor power of 3 kW. The material of the mill chamber was silicon carbide whereas the stirrer and discs were made of yttria stabilized zirconia. The mill working volume was 0.9 l. A screen cartridge with a screen size of 0.2 mm was used to separate the beads and slurry at the outlet of the mill. All tests were performed with a grinding media filling grade of 80 volume-% (mill working volume). The stirrer tip speed was set at 6 m/s and 10 m/s.

Milling product and formulation

A ground calcium carbonate powder from IMERYS, mean particle size of D_{50} = 17 μm was used as the milling product. The slurry was a water base which included a dispersant aid 'Dispex N 40' (1 weight-% based on solids). The following formula properties were achieved: solid content 50 weight-% and specific slurry density 1.5 kg/ℓ.

Milling process mode

All milling tests were done in a recirculation mode with a slurry flow rate of 20 ℓ/h.

Tested grinding media 'SiLibeads'

Tests were run with five different grinding media types and two different bead sizes for each type. The grinding media were classified according to bead material as follows:

- ➤ Yttria stabilized zirconia (type ZY-premium, production method sintering process)
- ➤ Yttria stabilized zirconia (type ZY-standard like type ZY-premium, but different raw materials, production method sintering process)
- ➤ Zirconium silicate (type ZS, production method sintering process)
- ➤ Zirconium silicate (type Z, production method fused process)
- ➤ Doped glass-ceramic (Type GZ, which contains approx. 92% glass and 8% zirconia, production method fused process).

The bead types used and their properties are collated in Table I.

The specific weight of the Yttria stabilized zirconia beads varies from 6.00–6.06 kg/ℓ due to the differently used raw materials.

The variation of the specific weight from 3.8–4.1 kg/ℓ of the zirconium silicate bead qualities type Z and type ZS is caused by the production method. Bead porosity, which is the major reason for the lower specific weight of the type Z bead, is explained in the following.

The doped glass-ceramic type GZ bead specific weight is 2.8 kg/ℓ. The doped glass-ceramic bead has a much higher wear resistance and specific gravity than standard glass (2.5 kg/l).

For a better understanding of glass and ceramic grinding

Table I

Listing of grinding media 'SiLibeads' used in the milling tests

SiLi grinding media type	Material	Bead size (mm)	Micro-hardness HV 'Vickers'	Specific weight kg/ℓ	Symbols for tip speed 6 m/s	Symbols for tip speed 10 m/s
ZY premium	Yttria stabilized zirconia	0.4-0.5	1200	6.06	□	■
ZY premium	Yttria stabilized zirconia	1.0-1.2	1200	6.06	○	●
ZY standard	Yttria stabilized zirconia	0.4-0.5	1150	6.00		■
ZY standard	Yttria stabilized zirconia	1.0-1.2	1150	6.00		●
ZS	Zirconium silicate, sintered	0.4-0.5	1000	4.10		■
ZS	Zirconium silicate, sintered	1.0-1.2	1000	4.10		●
Z	Zirconium silicate, fused	0.4-0.5	700	3.80		■
Z	Zirconium silicate, fused	1.0-1.2	700	3.80		●
GZ	Glass, doped with zirconia	0.4-0.5	700	2.80	□	■
GZ	Glass, doped with zirconia	1.0-1.2	700	2.80	○	●

media, a general outlook of possible production methods and their influence on the bead quality is given in the next section.

Possible production methods of ceramic and glass beads

For the production method of ceramic grinding media as a matter of principle, two manufacturing processes can be distinguished. One method is the sintering process—the shape of the beads is formed in a previous step, for example by a sol-gel process, granulation process, or pressing process. Afterwards, the beads are densified by high temperatures in a furnace—called the sintering process, and get their final mechanical properties. The necessary temperature range and temperature schedule of the sintering process depends on the material formulation and can vary, for example, from 1350°C to 1700°C. During this heating treatment the densifiction of the beads takes place by material transport of diffusion at the grain boundaries linked with a shrinkage of the bead size—this process is like baking a cake.

The second possible production method of grinding media is the fused process. All necessary raw materials are smelted and homogenized in a kiln at high temperatures of more than 2000°C. The hot material smelt leaves the kiln and the bead forming process from the smelt takes place—droplets are generated and fly from a certain height to the bottom. Due to the the surface tensile of the hot liquid droplets, the shape changes to round spheres. During the flight through the atmosphere, the spheres cool down and become stable and solid before they reach the bottom.

Beads formed by the fused process have the following disadvantages:

- ➤ During the production, it cannot be avoided that air bubbles are included in the beads; therefore the specific weight is reduced. Such air bubbles form pores in the inner structure of the bead—as can be seen in Figure 1—and cause bead breakage during the milling process. Bead breakage contaminates the milling product and can clog the outlet of the mill, which leads to a stop in production
- ➤ During the forming process, bigger and smaller beads hit each other and stick together and so-called satellites come into existence—as is shown in Figure 2. At the later application of the milling process the satellites are separated from the bigger beads. The small satellites can contaminate the milling product or can clog the outlet of the mill and the grinding process cannot be continued
- ➤ After forming and cooling of the bead, material inhomogenization can take place, caused by destabilization of different material phases, which can initiate defects in the inner structure of the beads—shown in Figure 3. Such flaws can weaken the mechanical properties, which leads to some problems in the milling process such as beads with locked-in air bubbles.

All the mentioned negative influences and problems of a fused bead manufacturing process can largely be avoided when the beads are produced by the sintering process. The sintering manufacturing process needs more production steps, particularly material preparation and bead forming,

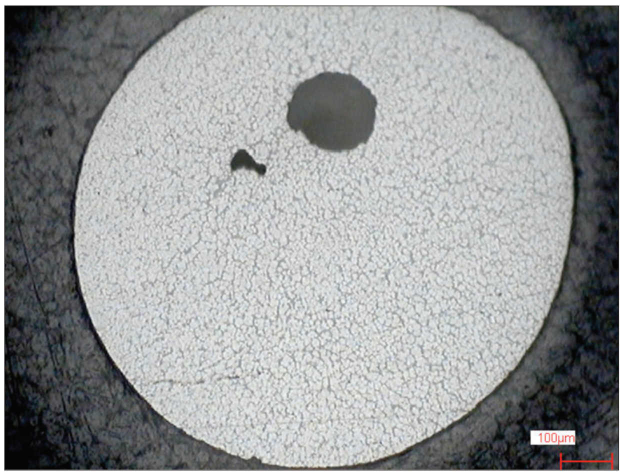

Figure 1—Polished section of a fused zirconium silicate bead, which shows the inner structure with two big air bubbles/pores (two black spots in the white-grey matrix)

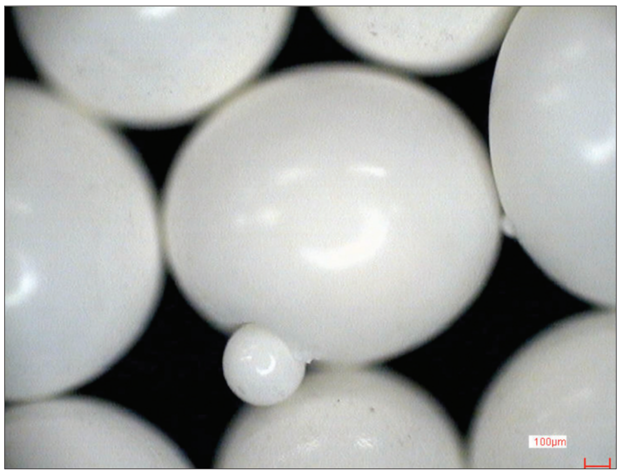

Figure 2—Fused zirconium silicate bead with a sticking 'satellite'

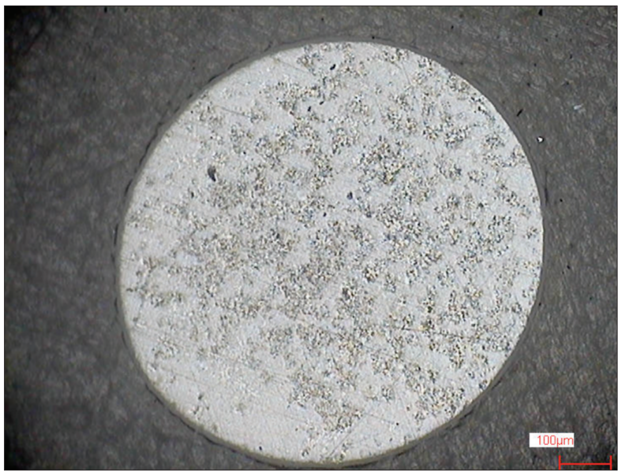

Figure 3—Polished section of a fused zirconium silicate bead, which shows different material phases and flaws in the inner structure

before the beads can be densified by sintering at high temperatures. Consequently, a higher technical expenditure is necessary, but beads with a very good inner structure—almost without any defects—can be produced, especially when the sol-gel-process for the bead forming is used.

Figure 4 shows the very dense inner structure of the sintered yttria stabilized zirconia grinding media 'SiLibeads type ZY' and in Figure 5 can be seen the inner structure of the sintered zirconiumsilicate grinding media 'SiLibeads type ZS'.

The better the inner structure of the beads, the better the property of wear and tear resistance in the later application of the milling process. Naturally, some other parameters such as the quality of the used raw materials (chemistry, particle size, specific surface area), necessary additives, material composition, and firing schedule of the sintering influence the bead quality in term of the milling efficiency and bead life time. The specific weight of grinding media is characterized by the material compositon, but can be influenced by the production method.

Figure 4—Polished section of sintered Yttria stabilized zirconia 'SiLibeads type ZY', very dense inner structure

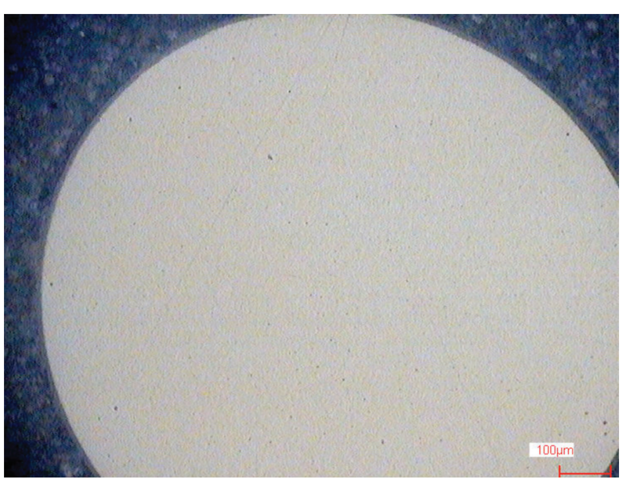

Figure 5—Polished section of sintered zirconium silicate 'SiLibeads type ZS', dense inner structure

Possible production methods of glass beads

Glass grinding media can be produced by different methods.

One possible method is the smelting process—all raw materials are fused in a glass furnace. The smelting temperature depends on the glass composition and temperatures up to 1400–1600°C are partly necessary. This method is comparable with the mentioned fused production process of ceramic beads, but additionally, it is possible to manufacture the viscose glass smelt into beads using moulds and press technologies.

Another posssible method for producing glass grinding media is the processing of glass granules in rotary kilns. The glass granules are transported to the rotary kiln and, due to the high temperature (range 800–1100°C depending on the glass formulation), the surface of the glass granules soften and, by the rotation of the kiln, the granules are formed to spheres.

All the common glass grinding media have an amorphous inner structure and are transparent. The colour of the beads depends on the glass compositon and the atmosphere in the kiln.

Data collection and measurements during the milling tests

The following parameters were collected and measured during the tests:

- ➤ The slurry flow rate was controlled and fixed at 20 ℓ/h
- ➤ The stirrer tip speed was measured in revolutions per minute (rpm) and calculated in m/s. The tests were performed with tip speeds of 6 and 10 m/s
- ➤ The real active electrical motor power input (kW) was measured
- ➤ The milling time was registered and calcium carbonate particle size measurements were taken at time: 0; 5; 10; 15; 20; 30 and 60 minutes. The particle size measurements in the suspenion were done by the 'Cilas-1064' particle size analyser, which works according to the laser light scattering method.

Calculations and evaluations of the collected data during the test

Based on Kwade's model of the grinding process, the measured and collected test data could be analysed. The specific energy input E_m was calculated, using the following Equation [1], in dependence of the generated particle size of the wet milled calcium carbonate:

$$Em = \frac{N - N_0}{\dot{m}} (J / kg) \quad [1]$$

E_m : Specific energy [J/kg]
N : Necessary electrical power running the filled mill with beads and slurry [W]
N_o : Necessary electrical power running the empty mill —idling [W]
$N–N_O$: Active electrical power [W]
m : Slurry flow rate [kg/s]
1 [J] = 1 [Ws]

Based on the data collection during the milling tests the stress intensity of the grinding media SI_{GM} could be calculated using Equation [2].

$$SI_{GM} = d^3 * \rho * v_T^2 (\text{Nm}) \quad [2]$$

SI_{GM} : Stress intensity of the grinding media (Nm)
d : Bead diameter (m)
ρ : Specific weight of grinding media (kg/m³)
v_T : Stirrer tip speed (m/s)

Using the calculated required specific energy E_m of the particle size reduction of the calcium carbonate for each test, a specific energy to particle size reduction relationship can be plotted.

When the evaluated data, as in Figure 6, are plotted in a double log scale, the relationship between the particle size and the specific energy can be presented as a linear function.

From this relationship, it is easy to determine the required specific energy for a defined particle size—for the calcium carbonate product with a mean particle size D_{50}= 2 μm prepared with SiLibeads type ZY premium 0.4–0.5 mm and tip speed of 6 m/s a specific energy of 426 kJ/kg is necessary.

This specific energy to particle size relationship, as in Figure 6, was determined for all tests listed in Table I.

With the calculation of the stress intensity of the grinding media SI_{GM} according to Equation [2] and the previously determined specific energy it is possible to generate an optimized energy consumption curve for the milling process of calcium carbonate prepared with different grinding media.

Results

The results of an optimized energy consumption curve for all tests are shown in Figure 7, where the required specific energy for a D_{50}=2 μm product is plotted versus the stress intensity of the different grinding media.

In this diagram, the square symbols represent the grinding media size 0.4–0.5 mm and the circles 1.0–1.2 mm. The different colours stand for the different bead materials and specific weights. Fully coloured dots and squares mark the tests run with tip speeds of 10 m/s and not fully coloured dots and squares 6 m/s.

The optimized energy consumption curve (minimum energy required) is given when the high density type ZY, yttria stabilized zirconia grinding media and small bead size is used at tip speeds of 10m/s:

- ➤ Type ZY Premium, 0.4–0.5 mm, specific weight 6.06 kg/ℓ (fully coloured black square)
- ➤ Type ZY standard, 0.4-0.5 mm, specific weight 6.00

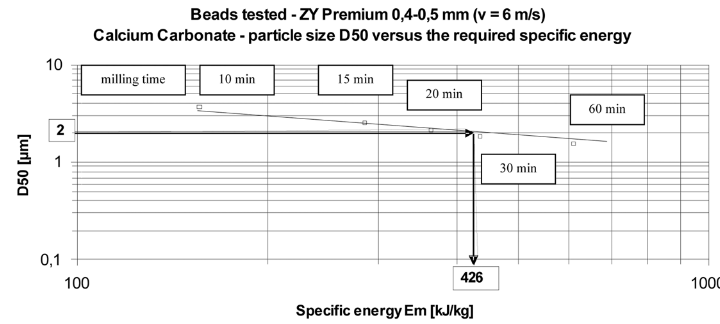

Figure 6—Relationship between the mean particle size D_{50} and the specific energy E_m—tested beads 'Type ZY-premium yttria stabilized zirconia, size 0.4–0.5 mm, tip speed 6 m/s'

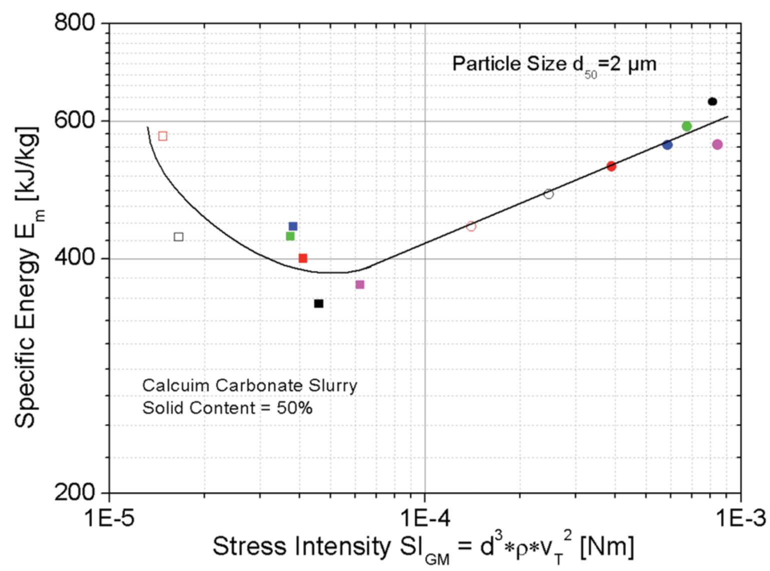

Figure 7—Optimum energy consumption curve in dependence of the grinding media material, bead size and tip speed

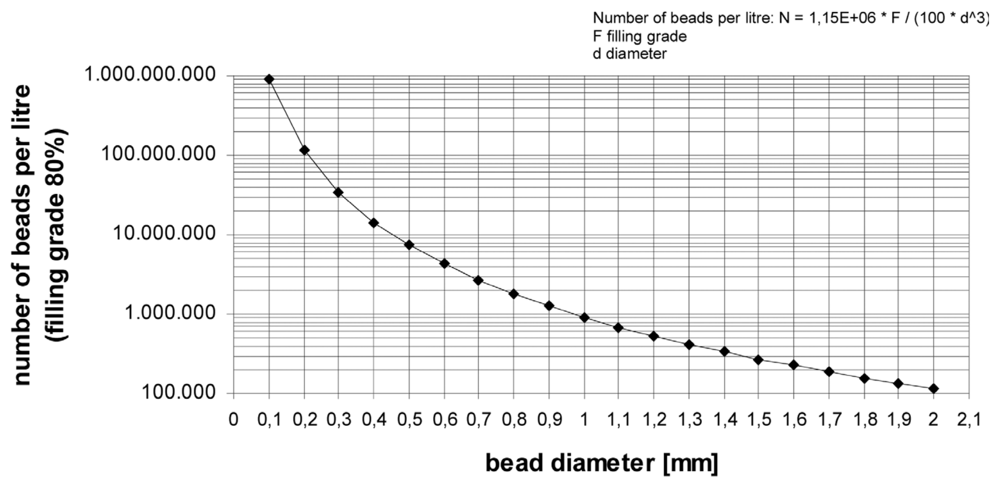

Figure 8—Number of beads per litre with an 80 volume-% filling grade in dependence of bead diameter

kg/ℓ (fully coloured purple square).

Using grinding media of the same size, 0.4–0.5 mm and tip speed 10 m/s, but with less specific weight (zirconium silicate type ZS 4.1 kg/ℓ—green square; zirconium silicate type Z 3.8 kg/ℓ—blue square or glass-ceramic type GZ 2.8 kg/ℓ—red square) a higher specific energy is necessary to generate a calcium carbonate product with mean particle size D_{50}=2 μm.

An increased specific energy is necessary to achieve a mean particle size D_{50}=2 μm, when the tip speed is reduced from 10 m/s to 6 m/s and small grinding media are used—not fully coloured squares:

- Black for the yttria stabilized zirconia bead type ZY premium, 0.4-0.5 mm, specific weight 6.06 kg/ℓ
- Red for the glass-ceramic bead type GZ, 0.4–0.5 mm, specific weight 2.8 kg/ℓ.

When larger sized grinding media 1.0–1.2 mm are used the required specific energy increases with higher specific weight of the grinding media and faster tip speed. All these results—circle and dot symbols—are seen right of the optimum of the energy consumption curve in Figure 7.

The comminution of the calcium carbonate product D_{50}= 2 μm is least expensive when the grinding process works at the minimum of the specific energy consumption. This is guaranteed when small sized grinding media with high specific weight are used at fast tip speed in the mill.

When larger sized grinding media 1.0–1.2 mm with lower specific weight can be replaced by smaller sized beads 0.4–0.5 mm with higher specific weight at the same volume level of bead filling grade, the number of beads per litre of the mill working volume raises dramatically. Additionally, the kinetic energy of the grinding media is increased by the ratio of the specific weight of the bead material by equal stirrer tip speed in the mill. Both aspects, bead size reduction and using beads with higher specific weight, improve the milling efficiency, because a higher number of beads achieve more contact points, impacts, compression, and shear forces between the beads and the product particles, and the higher mass of the grinding media in the mill generates much more kinetic energy.

The effect of bead size reduction and the number of beads per litre for an 80% filling grade in dependence of the bead diameter is shown in Figure 8.

In the case represented, the average number of beads per litre for bead size 1.0–1.2 mm is 700,000 and for bead size 0.4–0.5 mm 10,000,000. This means the number of beads per litre is more than 14 times higher when using 0.4–0.5 mm bead sizes rather than 1.0–1.2 mm.

Conclusions

In the wet grinding process of a stirred media mill the bead size, the specific weight of the grinding media, and the mill speed influence the milling efficiency. When using grinding media with a higher specific weight, it is possible to reduce the bead size without losing milling energy by equal bead filling volume. So, it is possible to improve the milling process by selecting the right bead material, bead size and mill speed in dependence of the milling product to achieve an optimum grinding result—quality wise and cost wise. If the milling process is not optimized, a lot of energy is wasted. Further, mill parts and grinding media wear increase, which lead to higher production costs.

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