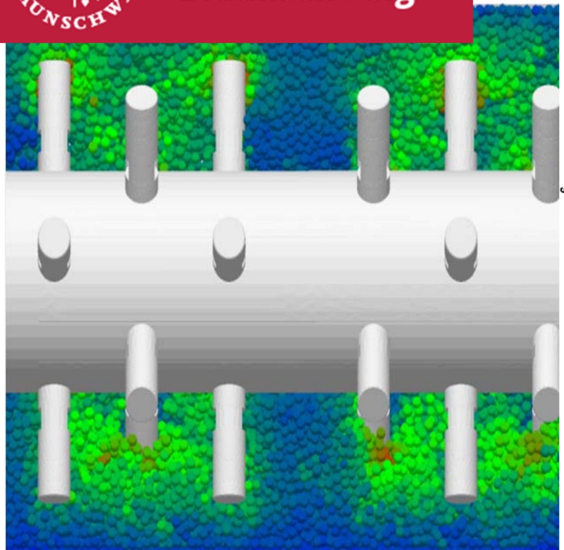

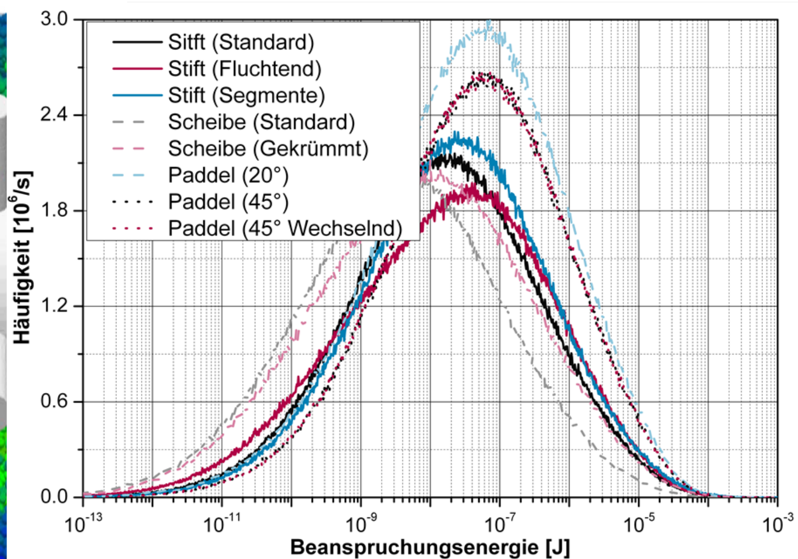

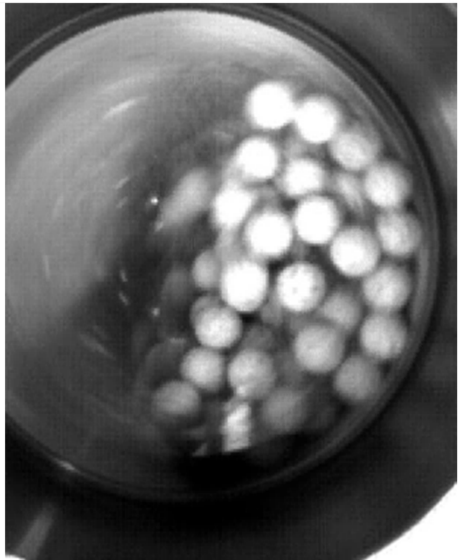

Comminution processes: Basics and application to energy efficiency

Arno Kwade, Institute for Particle Technology, Technische Universität Braunschweig

2. März 2015

Content

- Motivation
- Learnings from systematic investigation of single particle breakage
- From „Micro“ to „Macro“
- Examples of applying „Stressing energy approach“
- What can be the future?
- Conclusions

Motivation

- Basic of comminution in mills is the stressing and breakage of individual particles
- Knowledge of indivicual stressing events, especially with single particles, helps to learn about
  - **Minimum of specific energy requirement**
  - Effect of different particle arrangements on breakage behaviour and specific energy requirement (what can really be achieved)
  - Calculation of milling processes from „micro“ to „macro“
- A lot of knowledge on the breakage of particles in the micrometer size range was created by researches in the 20th century


Rumpf


Schönert


Schubert

What is the efficiency of a milling process?

- Different possibilities to define energy efficiency:
  1. Specific energy of mill compared to new created surface energy

     → not meaningful, efficiency much smaller that 1%
  2. Specific energy of mill compared to minimum specific energy requirement in so-called element tests. However, here at least two possibilities exist:
     a. breakage energy of single particle stressing by compression / by impact
     b. specific energy of an optimized stressing event occuring in the mill (measured in a element test)

- **Discuss possible definitions 2 a and 2 b based on basic research**

Importance of high energy efficiency

High energy efficiency and, thus, low specific energy requirement for demanded product fineness (quality) is important because

- Low energy costs
- High production capacity because
- Low contamination and wear costs pre ton of product
- Less cooling issues

$$\dot{m}_P = \frac{P_M - P_0}{E_m}$$

Content

- Tradition of comminution research
- Systematic investigation of single particle breakage
- Mill development from „Micro“ to „Macro“
- Examples of applying „Stressing energy approach“
- What can be the future?
- Conclusions

Factors affecting particle breakdown (according to Rumpf and Schoenert)

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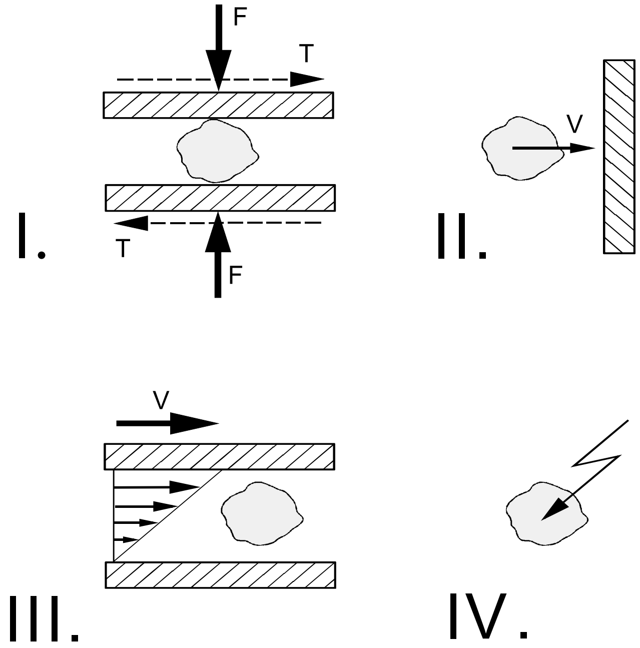
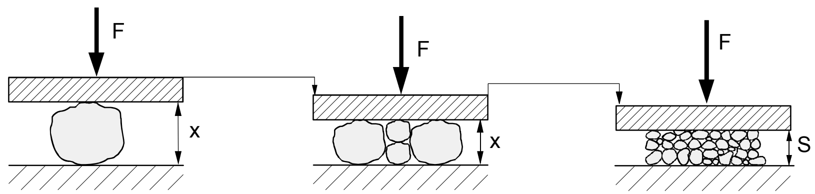
a) Type of stressing particles

   I. Compression and shear between two surfaces
   II. Impact at one surface
   III. Stress by a fluid
   IV. Non-mechanical stress



b) Arrangement of particles in a stress event

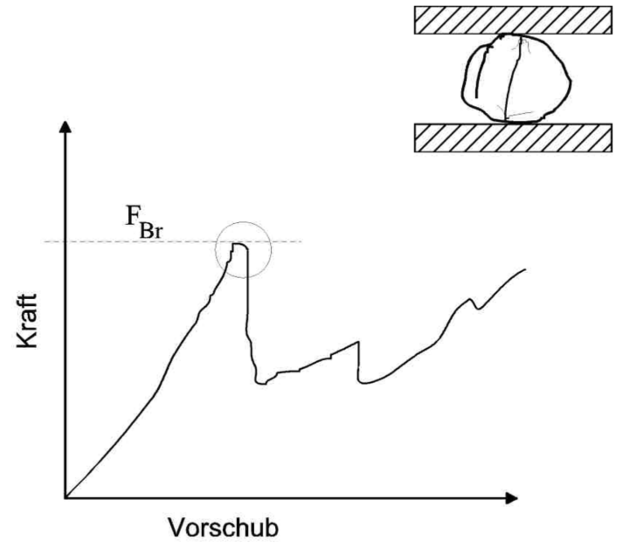
   1. Single particle
   2. Several single particles with direct contact to stressing tools
   3. Bed of particles



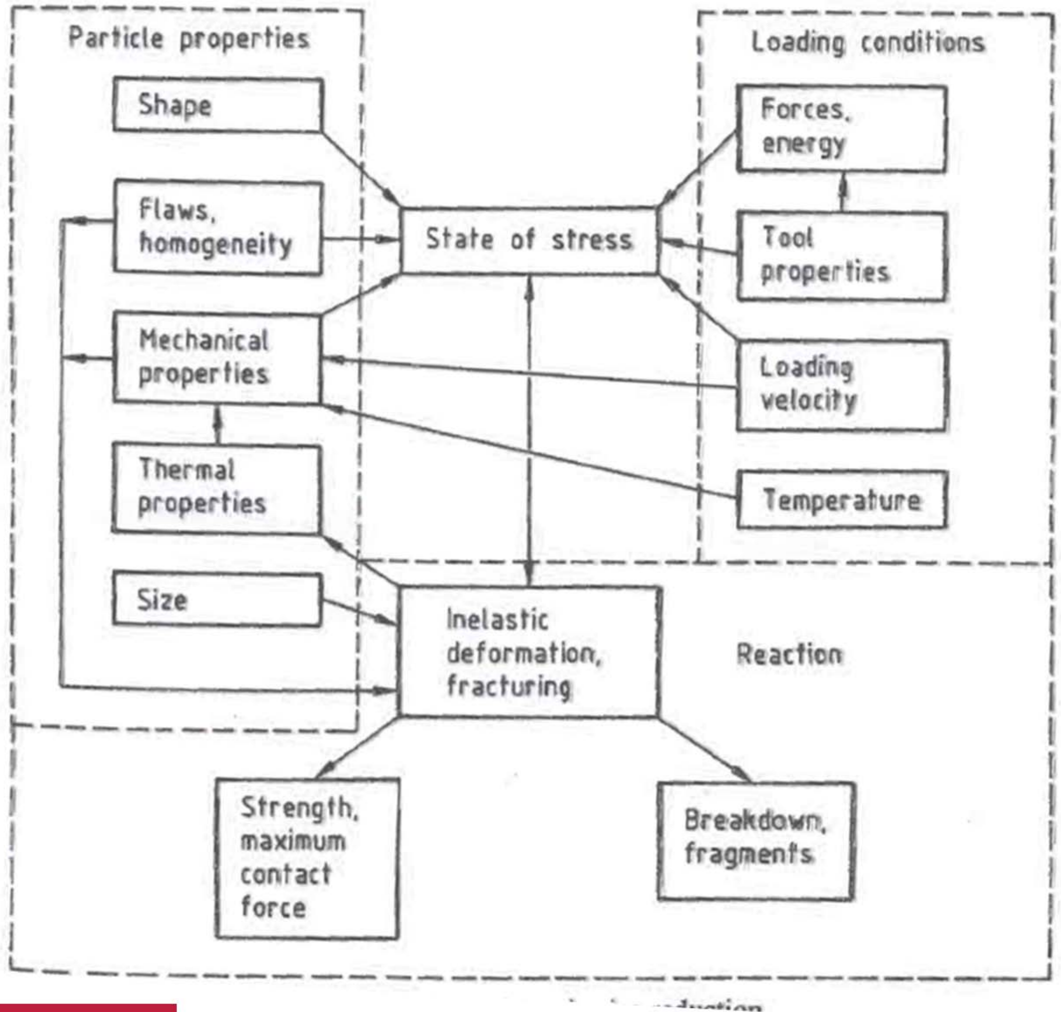
c) Force or energy of stress event

Basic processes to achieve particle fracture
Force or energy of particle breakage

- Deformation of particle by applied forces produce a three dimensional stress field with compression, tensile and shear stresses
- By deformation elastic energy is stored in the stress field
- **If stress value is sufficient high, fractures are initiated by tensile stresses. The energy required for the fracture has to be taken out of the stress field due to elastic deformation**
- First total fracture determines breakage
- If elastically stored energy is higher than energy required for breakage, a part of the energy is transferred into kinetic energy of fragments, thus reducing breakage efficiency
- Number and direction of fractures determine size and shape of fragments



Factors affecting particle breakdown (according to Schoenert)



All Figures out of Schoenert, Bernotat: Size reduction, in Ullmanns Encyclopedia of Chemical Technology

Effect of type of stress on particle breakage

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Fracturing of brittle glass spheres
- Zones of fine particles due to high tensile strength

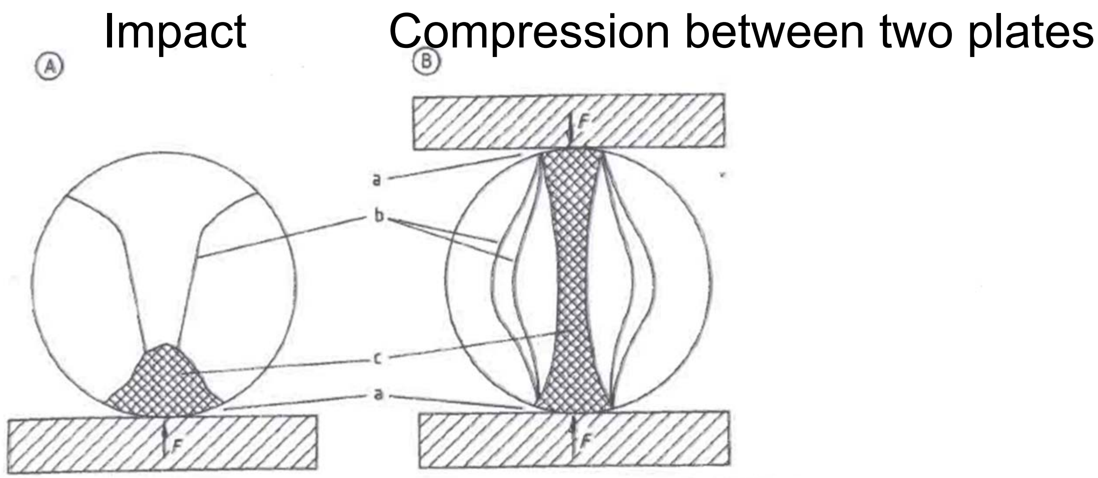


Figure 3. Fracturing in brittle glass spheres subjected to impact (A) and compression (B) loading
a) Contact surface at which stress is applied; b) Cracks; c) Fines

Fracturing of inelastically deforming PMMA spheres
- Meridian cracks
- Advantage of high velocities and low temperature due to viscous material behaviour

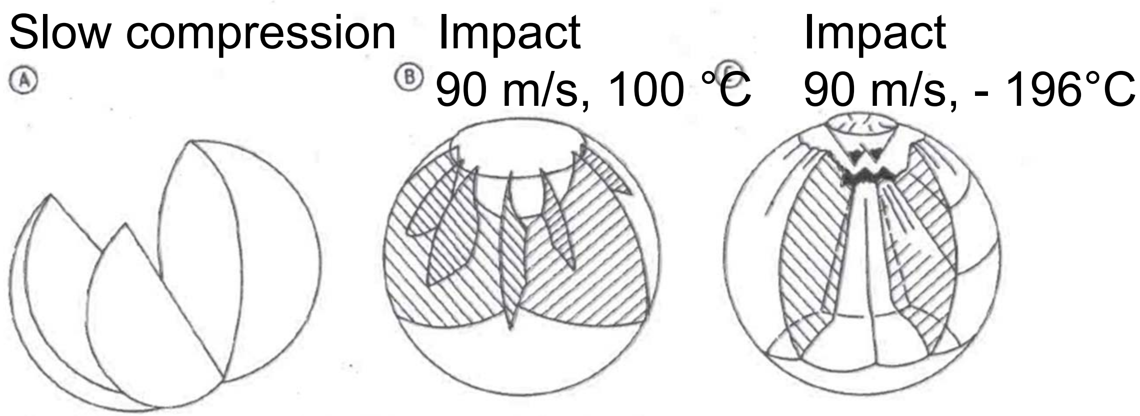
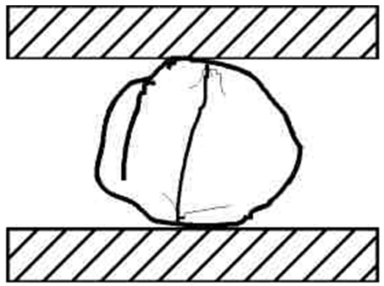
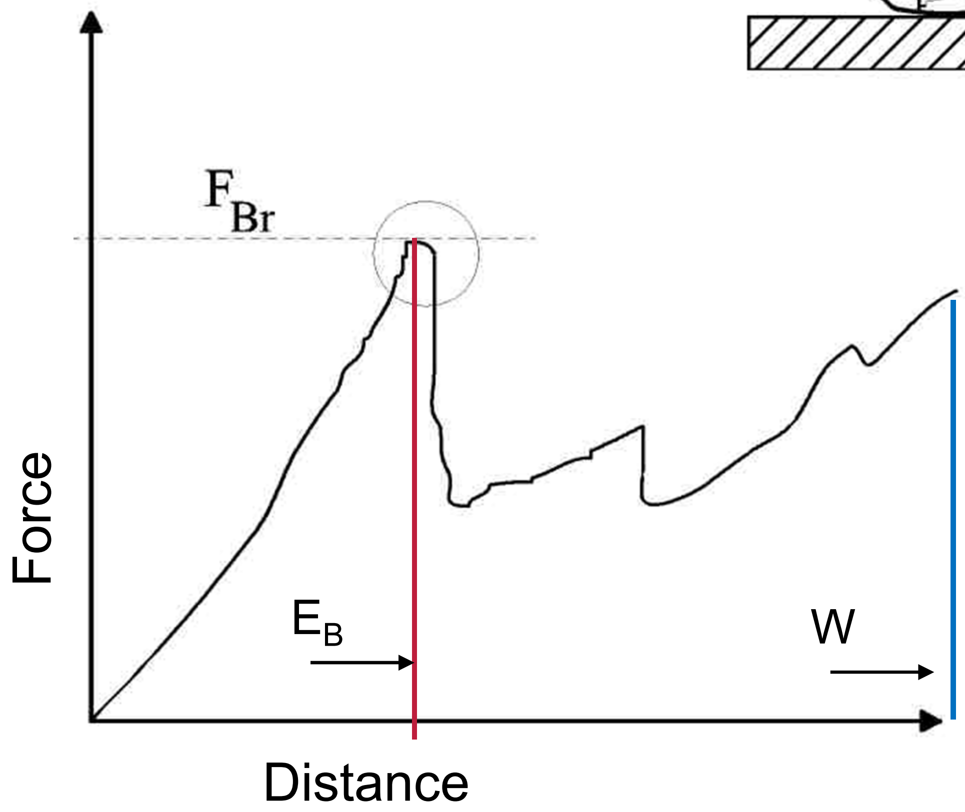


Figure 4. Meridian cracks in inelastically deforming poly(methyl methacrylate) spheres
A) Slow compression at 20 °C; B) Impacting at 90 m/s and 100 °C; C) Impacting at 90 m/s and −196 °C

Single particle stressing by compression



Observation of cracks with high speed cameras



Determination of

- Breakage strength F_{Br}/A
- Specific breakage energy $E_{B,m} = E / m_p$
- Specific work of comminution W_m

Particle strength as well as specific breakage energy/specific work of comminution

Particle strength by compression

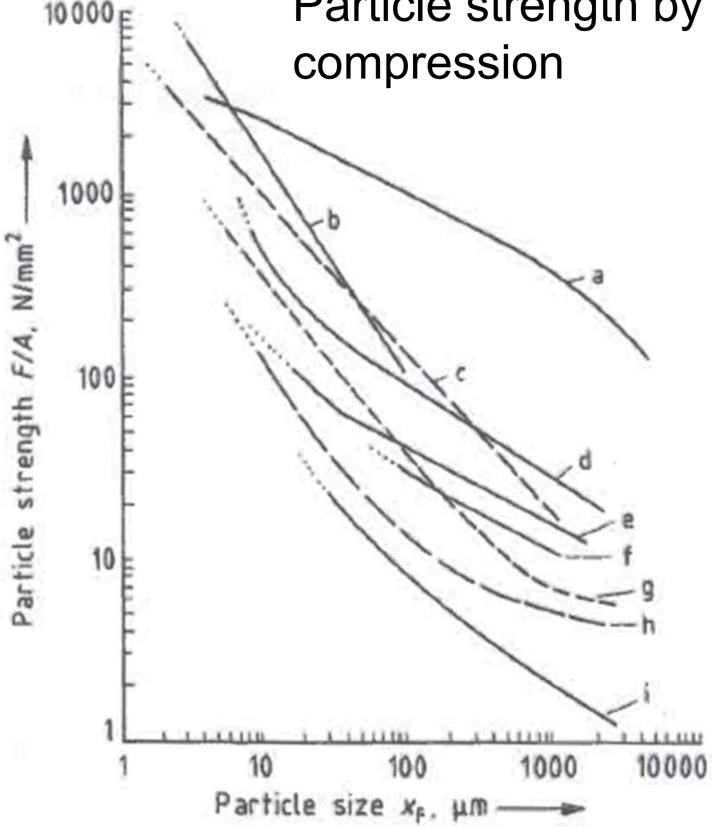
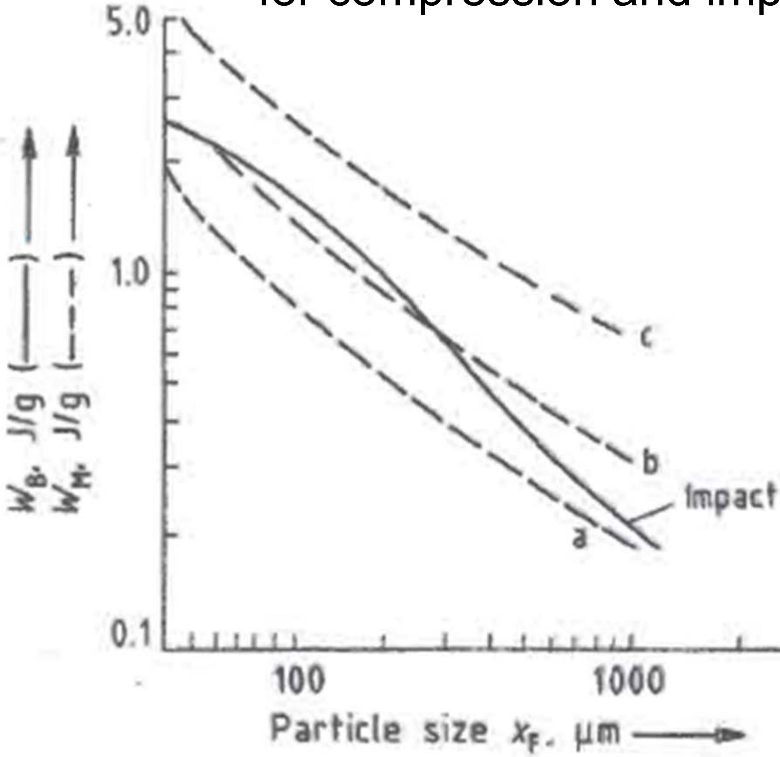


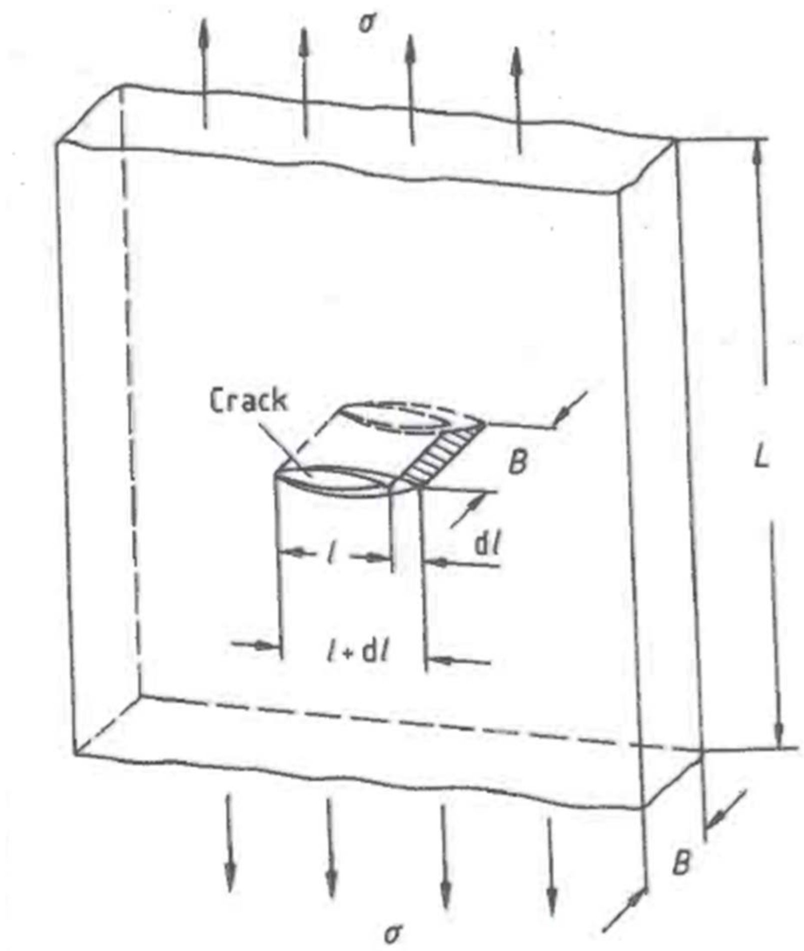
Figure 9. Particle strength of various materials as a function of particle size
a) Glass spheres; b) Boron carbide; c) Crystalline boron; d) Cement clinker; e) Marble; f) Cane sugar; g) Quartz; h) Limestone; i) Coal

Specific work of comminution for compression and impact



The finer the particle, the higher the strength and breakage energy

Increase of stress inside particles due to cracks



Maximum stress in particle

$$\sigma_{max} / \sigma_0 = 1 + 2\sqrt{a / r}$$

Breakage strength compared to molecular strength

$$\sigma_0 \approx \sigma_{mol} / 100$$

Effect of particle size on particle breakage by compression

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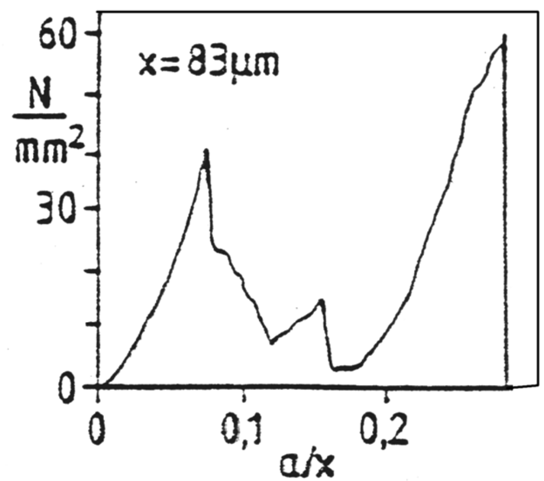
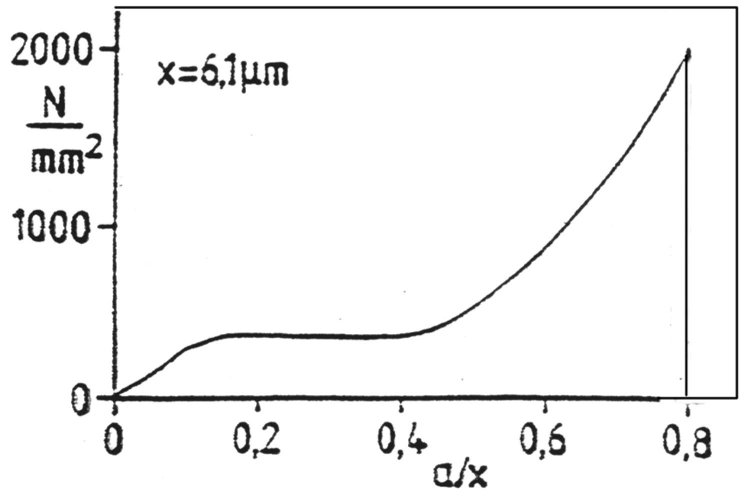
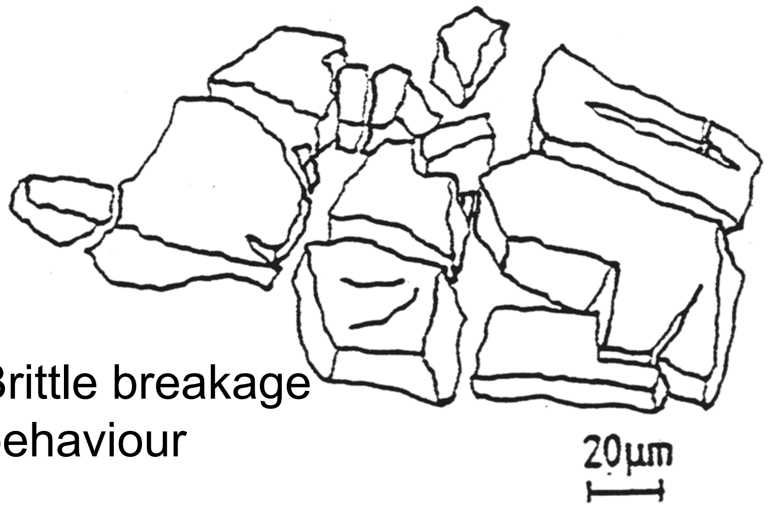
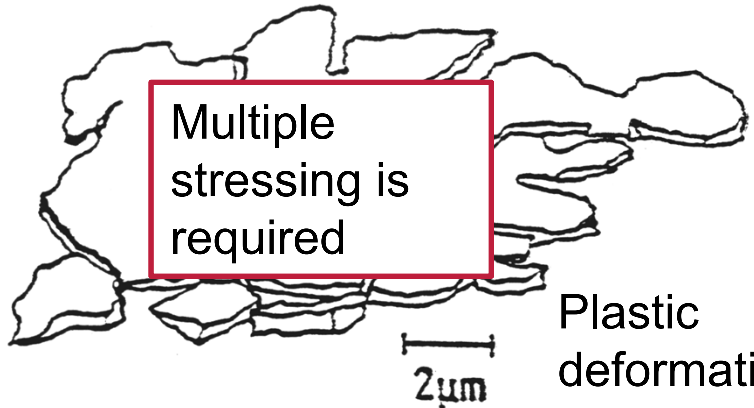






Brittle breakage behaviour



Multiple stressing is required

Plastic deformation behaviour

Transition from brittle to plastic deformation behaviour

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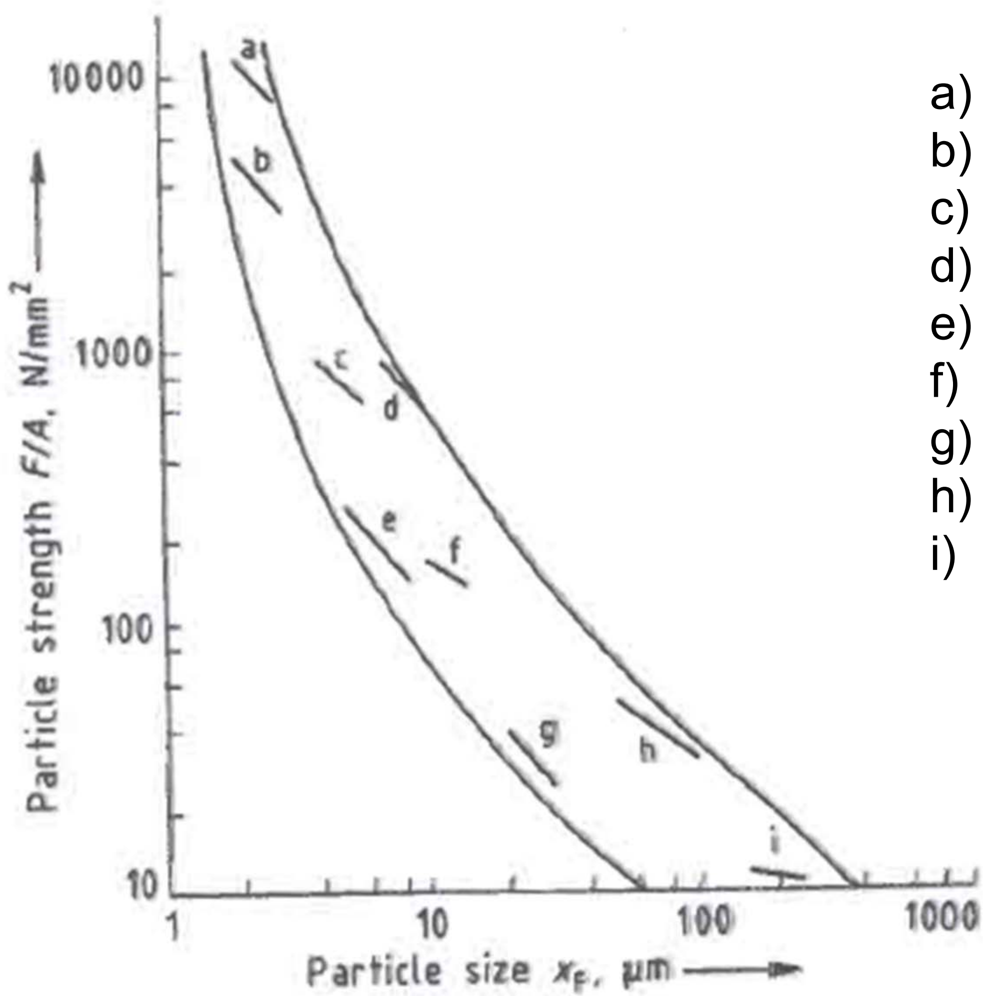


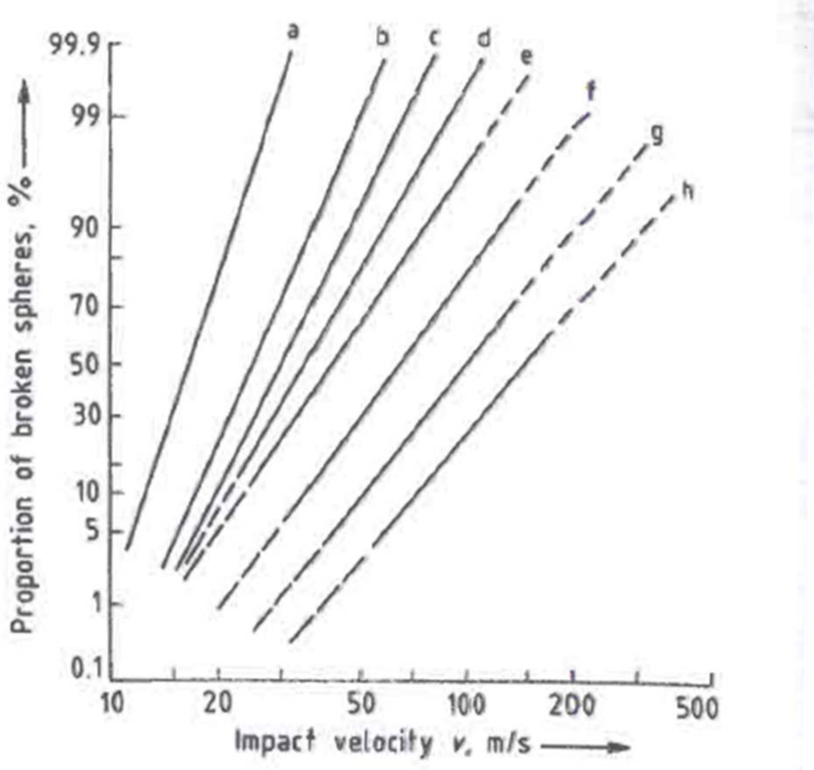
a) Boros carbide
b) Crystalline boron
c) Quartz
d) Cement clinker
e) Limestone
f) Marble
g) Coal
h) Cane sugar
i) Potash salts

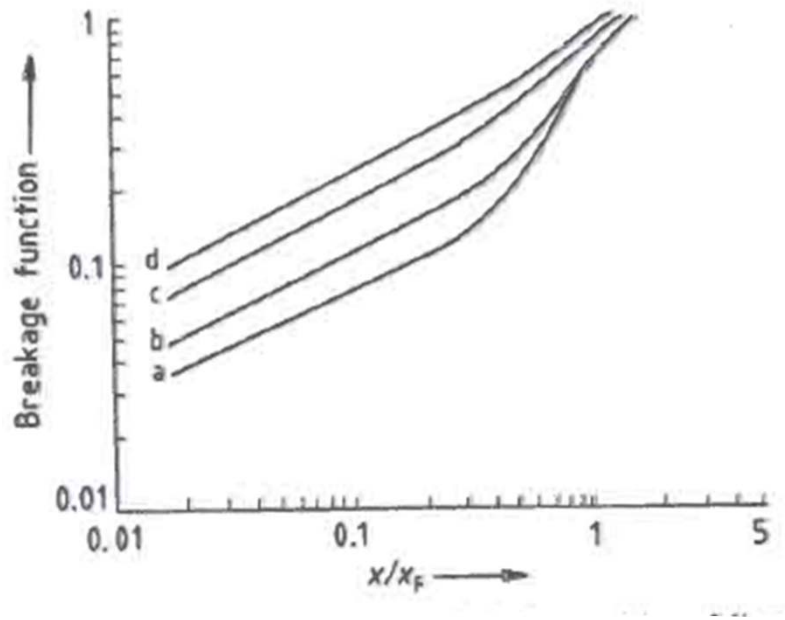
Probability of fracturing and breakage function

Probability of fracturing of glass spheres as function of impact velocity (stress energy)

➢ Selection function

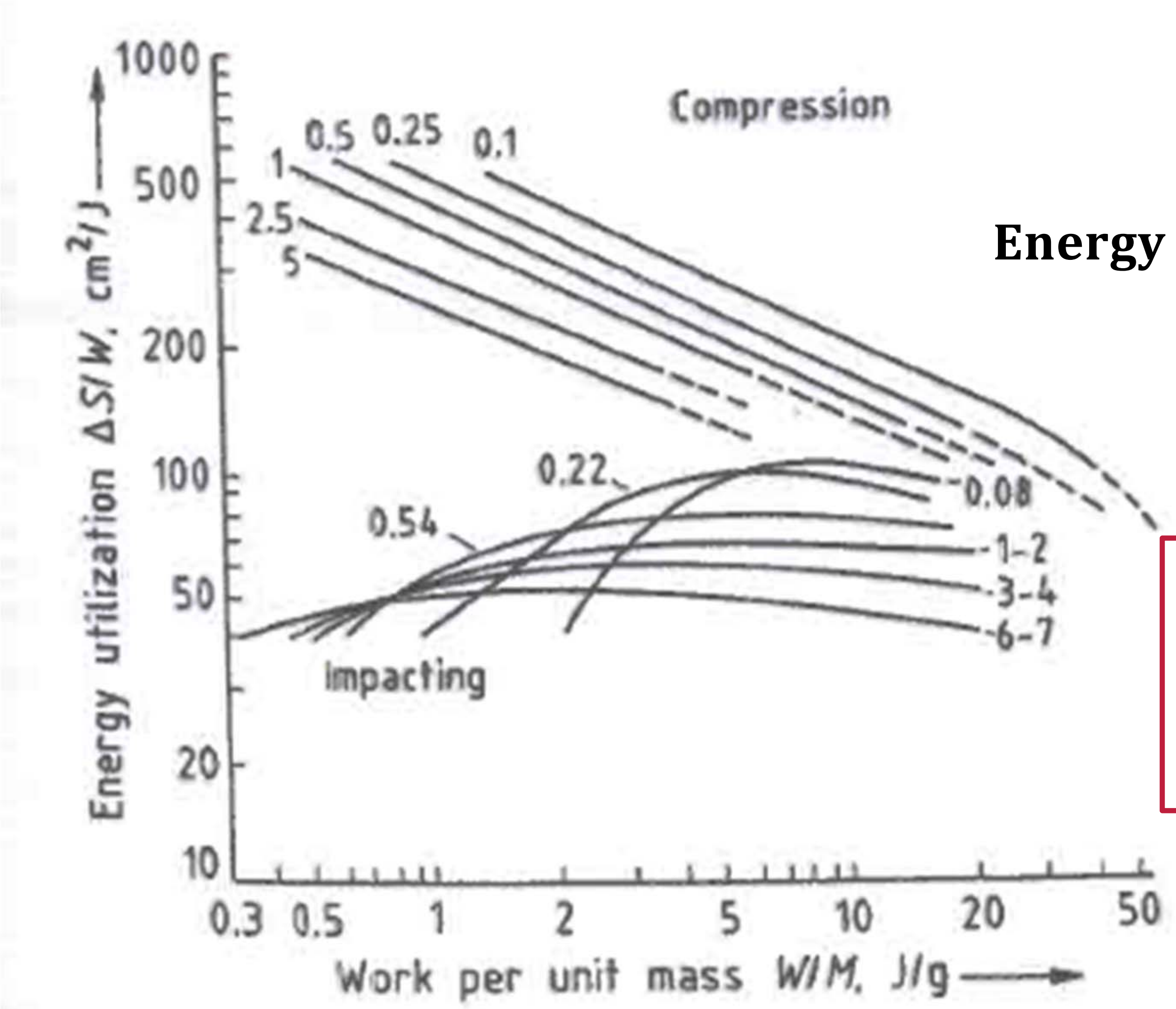
Breakage function of single limestone particles for different reduction ratios





Application of results of single particle tests on population balance calculations

Energy utilization for compression and impacting of limestone particles as function of specific work



$$\textbf{Energy utilization} = \frac{\Delta S_m}{W_m}$$

Energy utilization of compression is advantegeous against impact milling

Conclusions from „Micro“ tests

Energy efficiency of a certain mill depends at least on

- Type of stressing particles
- Specific work or specific force (= Stress intensity) of single particle stressing

Possible definitions for energy efficiency:

a) = Specific energy of single particle breakage / specific energy of mill for same product quality
- with optimized stress intensity or
- with stress intensity similar to mill

b) = Specific energy supplied to product particles / specific energy of mill for same product quality
- with optimized stress intensity or
- with stress intensity similar to mill

Conclusions from „Micro“ tests

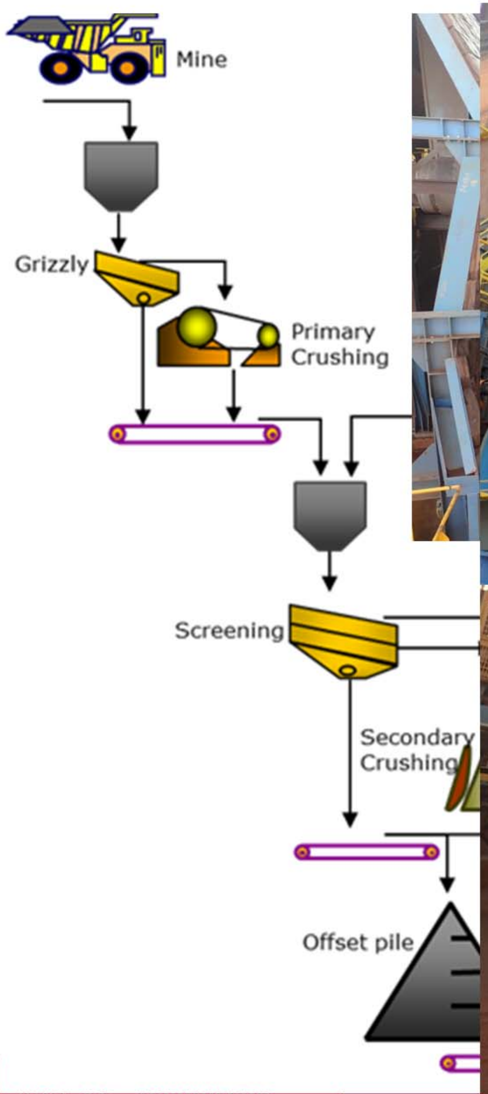
High energy efficiency can be achieved for

- Compression and shear between two surfaces or non-mechanical?
- Optimum specific work (= optimum stress intensity) resulting in highest energy utilization
- Multiple stressing with specific work (stress intensity) just sufficient for particle breakage, especially for plastic material behaviour at small particle sizes

Content

- Tradition of comminution research in Germany
- Systematic investigation of single particle breakage
- From „Micro“ to „Macro“
- Examples of applying „Stressing energy approach“
- What can be the future?
- Conclusions

Plant for iron ore processing



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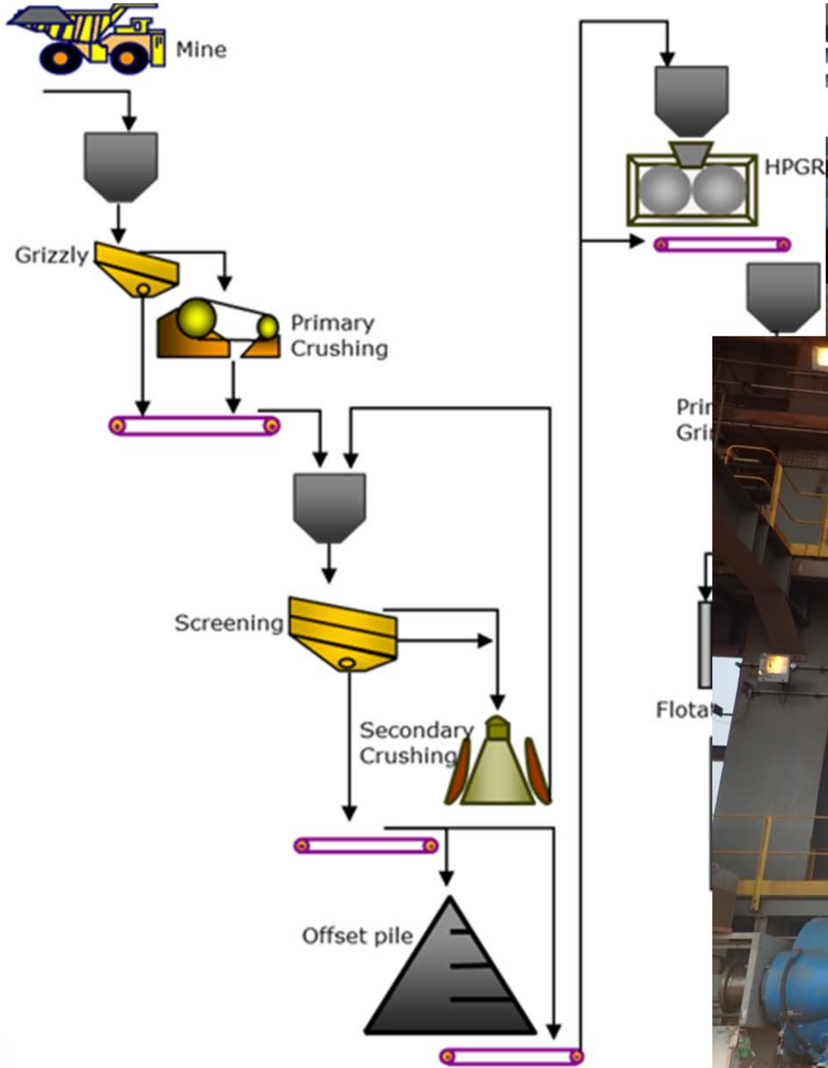
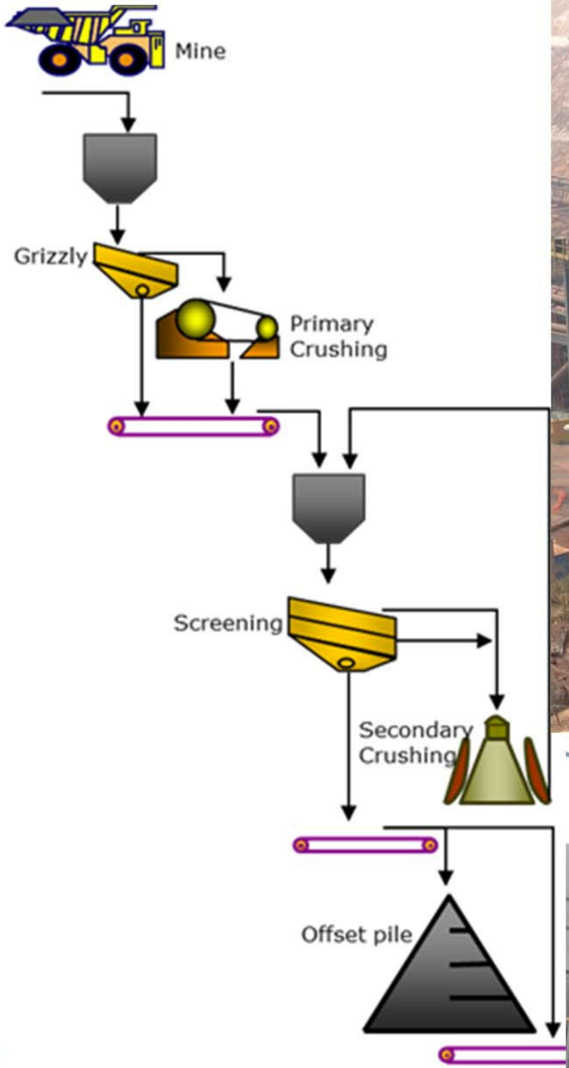
Plant for iron ore processing



Plant for iron ore



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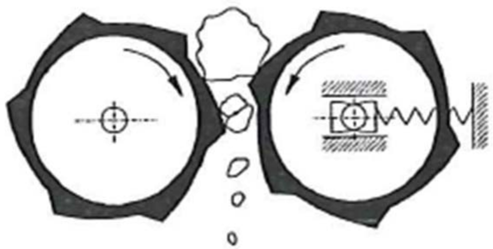
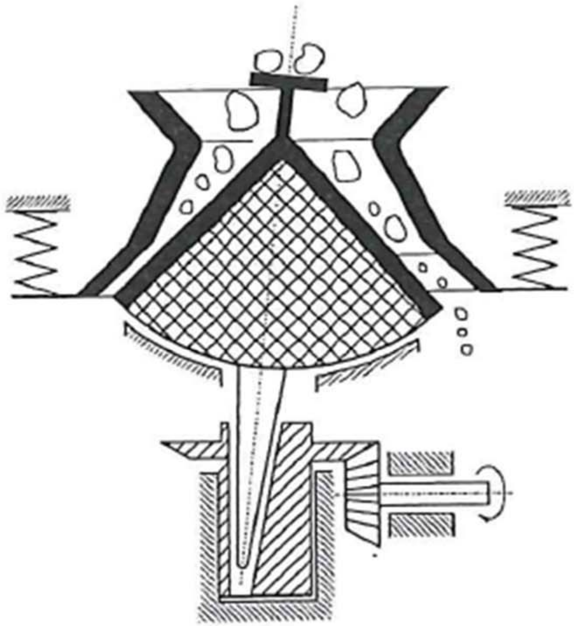
Overview crusher and mill types

Crushers (compression between two surfaces)



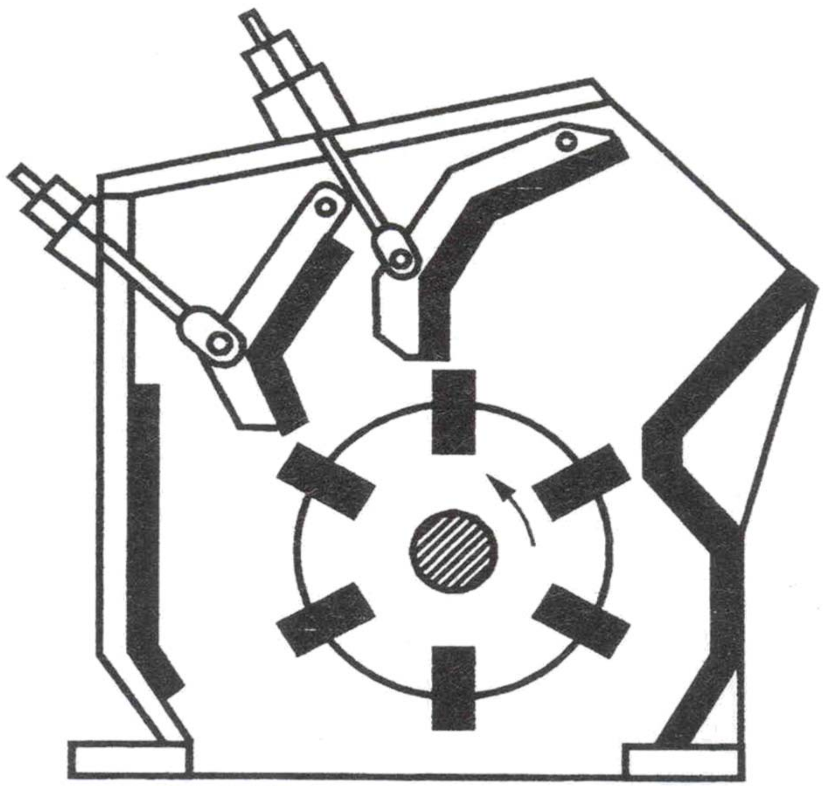
Double roll crusher

Eccentric jaw crusher



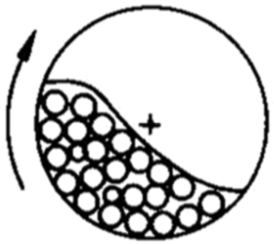
Shallow cone crusher

Impact crusher

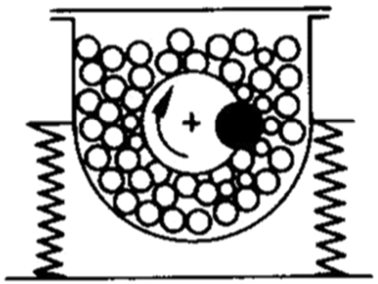


Overview crusher and mill types

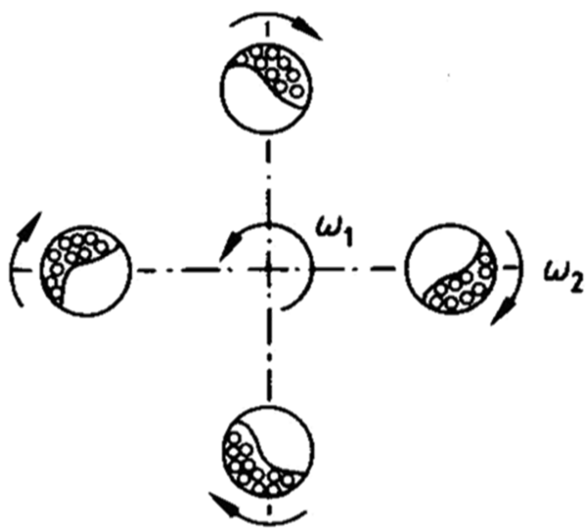
Mills with loose grinding media



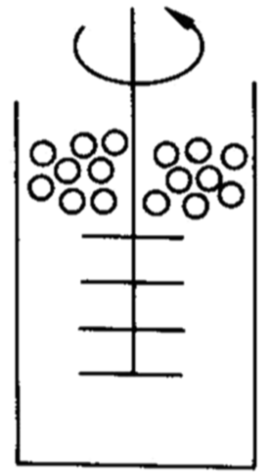
Tumbling mill



Vibrating mill



Planetary ball mill



Stirred ball mill

Overview crusher and mill types

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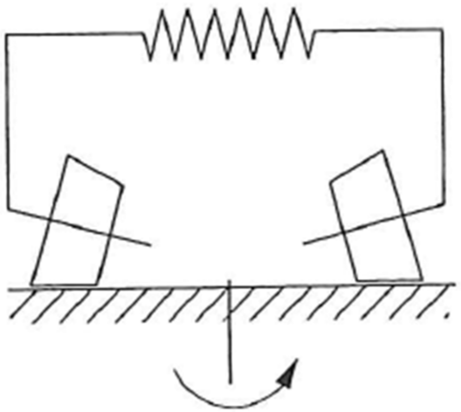
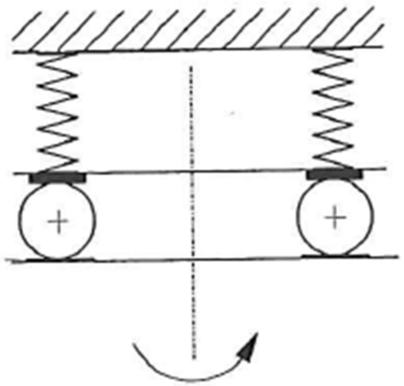
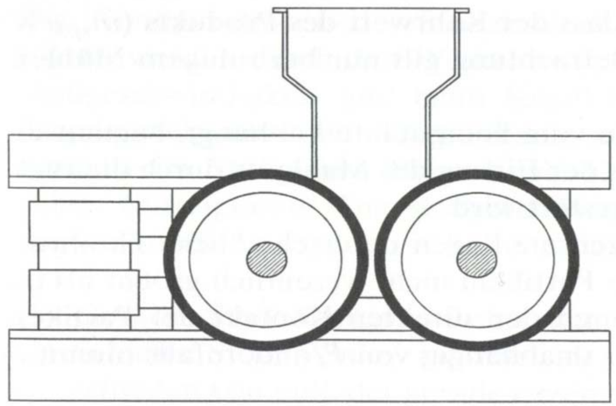
Roller and Ring-roller mills



Ring-roller mill



Ring ball mill



High pressure grinding roll

Overview crusher and mill types

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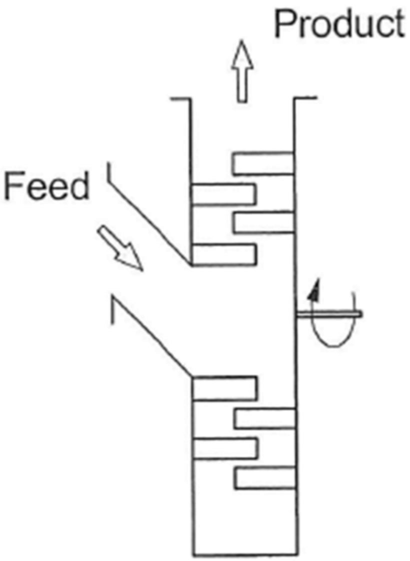
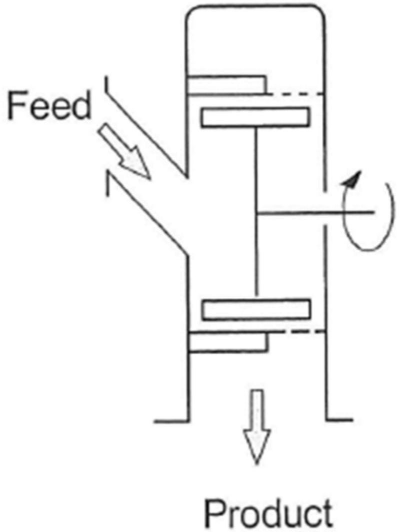
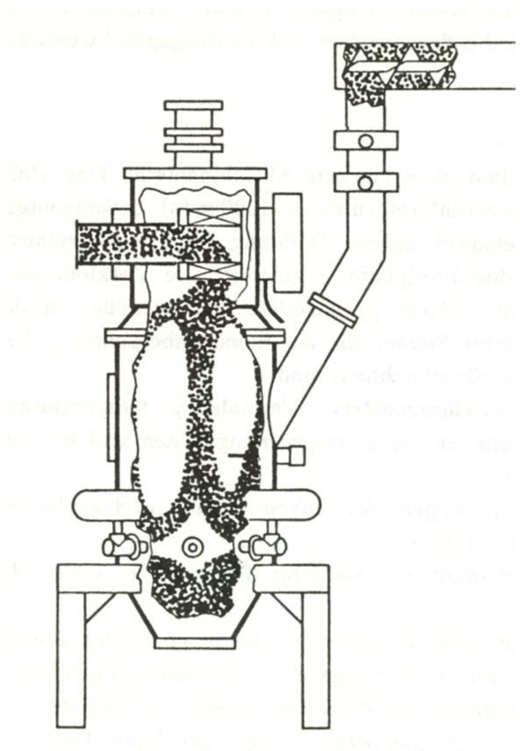
Impact Mills



Pin mill



Impact mill with screen

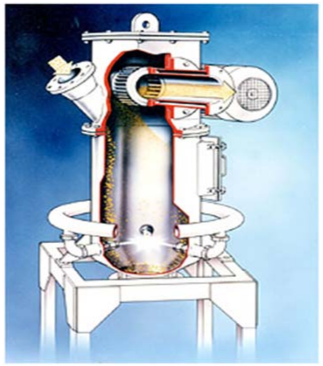


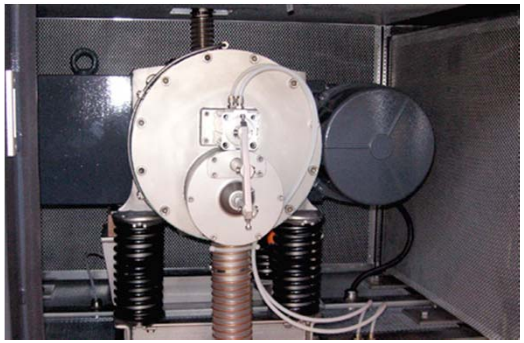
Fluidized bed mill

Question

What is the common micro process in all these mills?

In many individual stress events each time a certain amount of particles is stressed with a certain kind and intensity of stress





http://www.alpinehosokawa.com

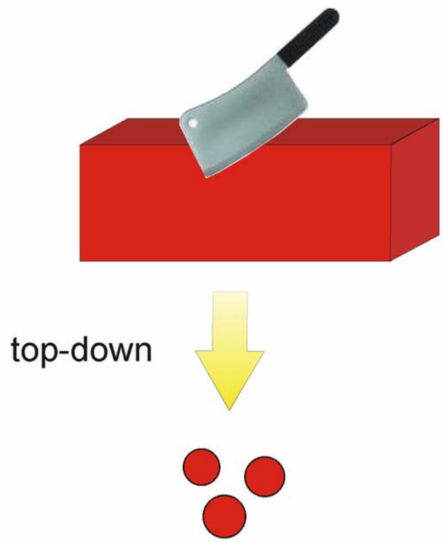
Basic idea of stress intensity model

Practical example for basic micro process

Smashing a stone or a sugar candy with a hammer into pieces

Different possibilities to hit the stone

- Small or large hammer
- Low or high speed
- One or more hits



Two different points of view

- What is the hammer doing?

I. How often does the hammer strike (independent on number of stones)?

→ Frequency of strokes

II. How strong are the strokes?

→ Energy of the hammer

→ Mill related stress model

- What happens with the stone?

I. How often are the stone and the resulting fragments hit?

→ Number of hits

II. What are the intensities of the hits?

→ Specific energy supply

→ Product related stress model

Mill related stress model

The grinding behaviour of a mill is determined by

- the **type of stress** (e.g. impact or compression and shear)
- frequency of strokes or stress events
  → **stress frequency, SF_M**
- the energy made available at each stress event
  → **stress energy, SE**

- From stress frequency the total number of stress events can be determined:

$$SN_M = SF_M \cdot t_c$$

where t_c is comminution time for a certain product quality

- Stress energy is not constant for all stress events
  → **Frequency distribution of the stress energy**

Density function of stress energy

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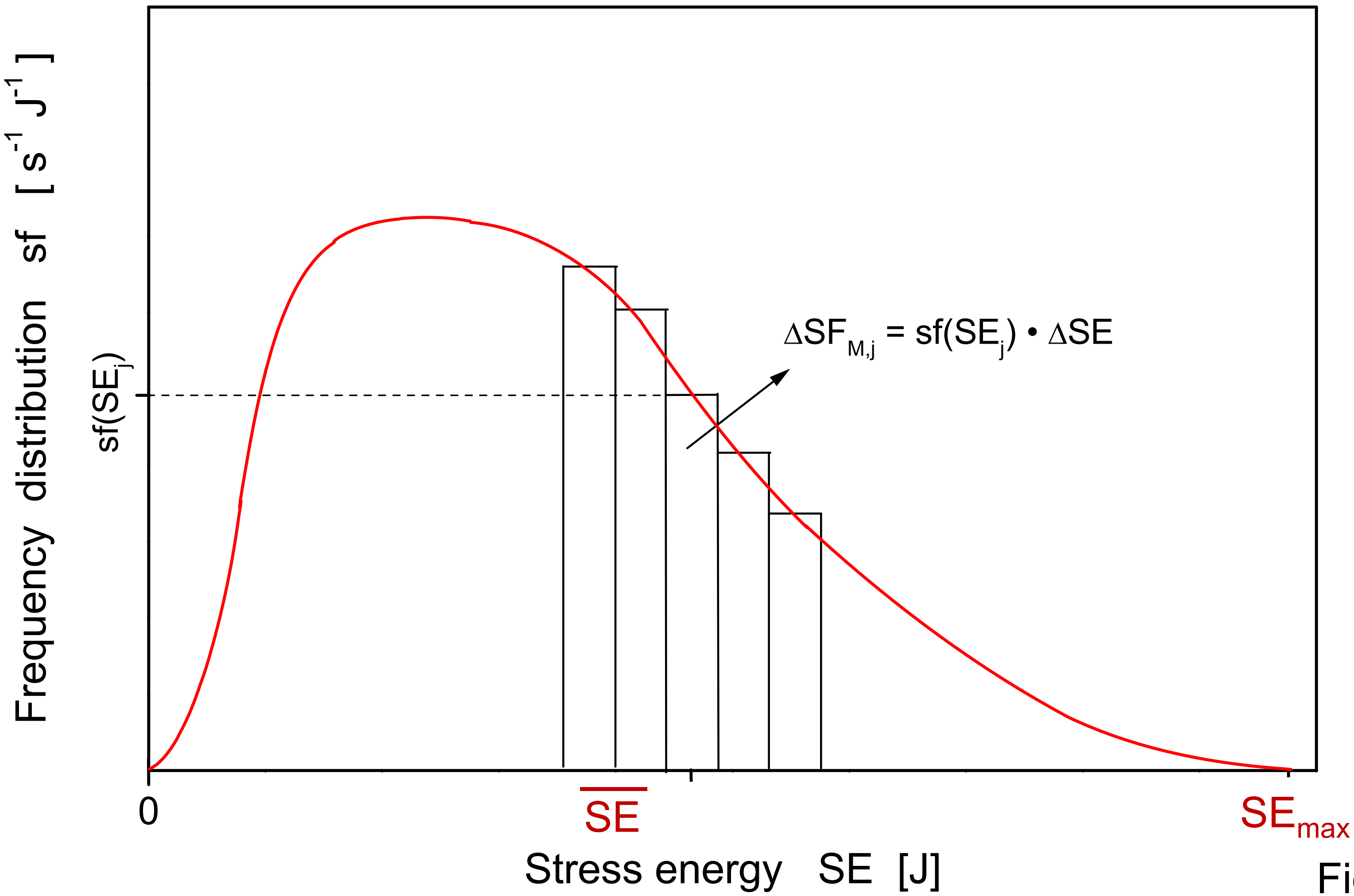
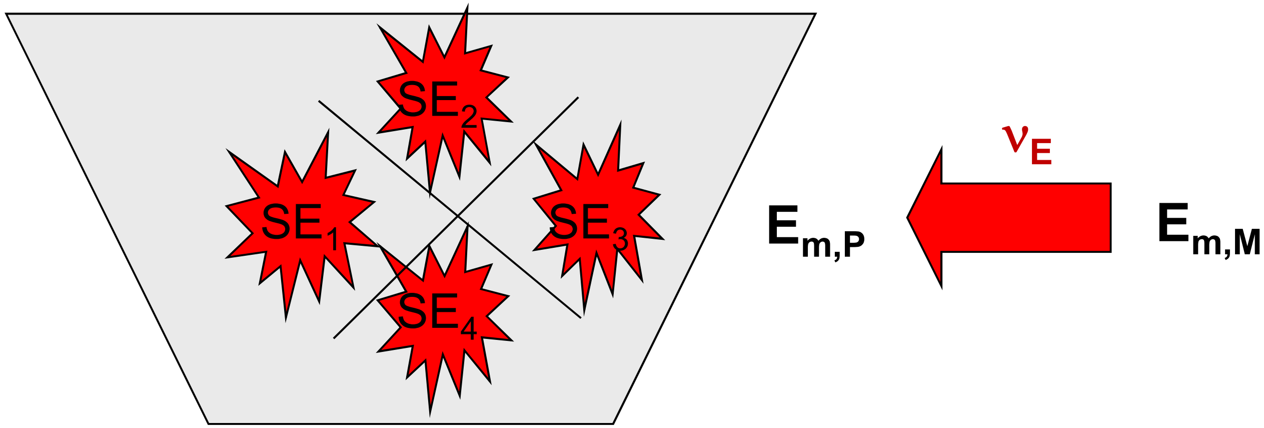


Fig. 3.17

Mirco to macro process – Relation of stress energy to specific energy input



$$E_{m,P} = \frac{E_{P,total}}{m_{P,tot}} = \frac{\sum_{i=1}^{SN_t} SE_i}{m_{P,tot}} = \frac{SN_t \cdot \overline{SE}}{m_{P,tot}} = \nu_E \cdot E_{m,M}$$

where $E_{m,M}$:= Specific energy input into grinding chamber

$E_{m,P}$:= Specific energy transferred to product particles

ν_E := Energy transfer factor (→ kind of energy efficiency)

Qualitative comparison of energy transfer coefficient

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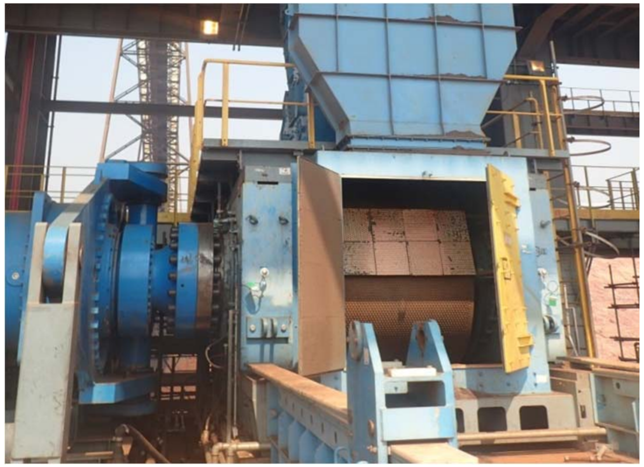
Tumbling ball mill

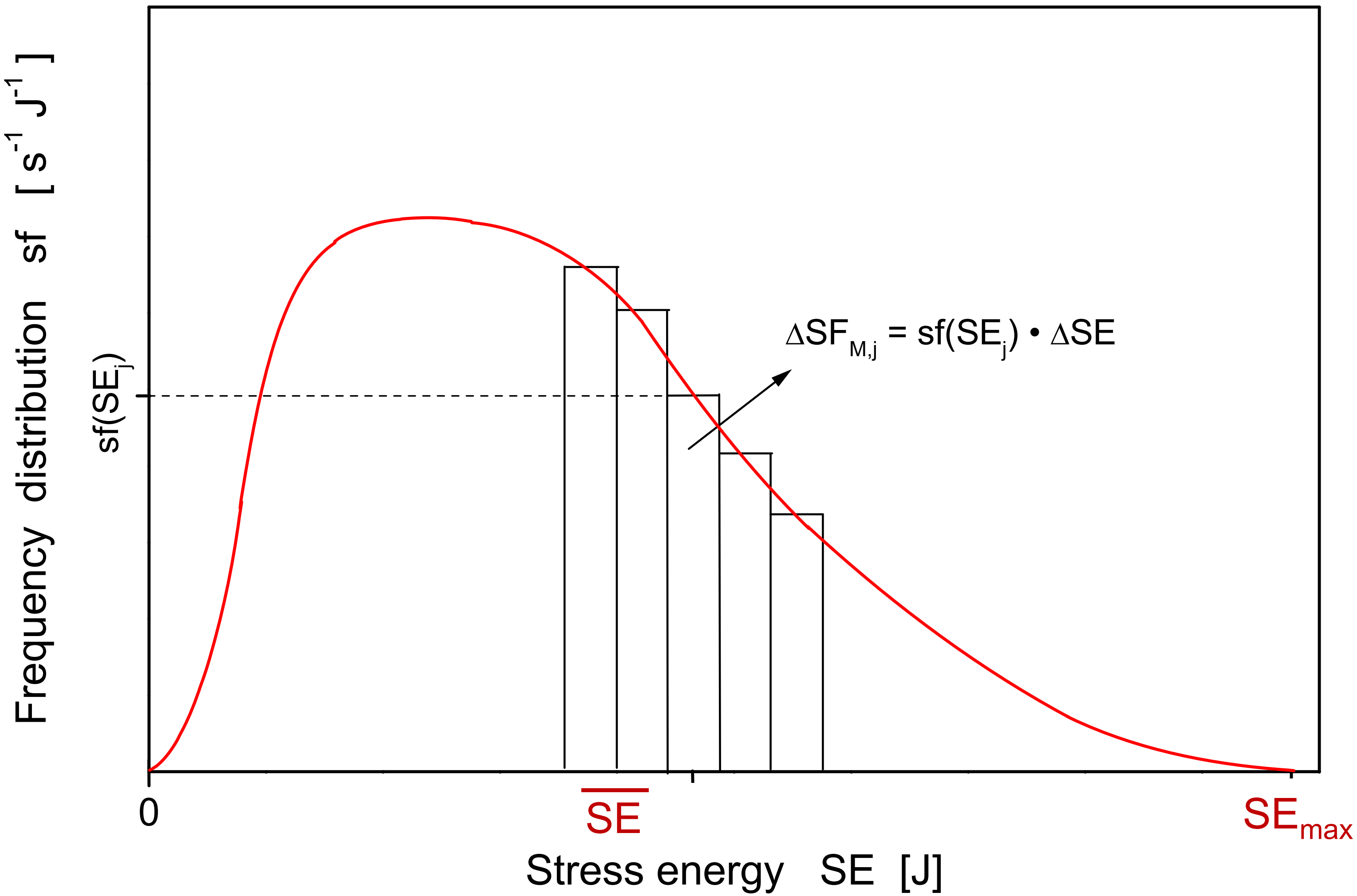
- High energy dissipations due to transport and friction inside material and ball deformation
- However, probably better energy utilization in each stressing event due to smaller stress intensity

High pressure grinding roll



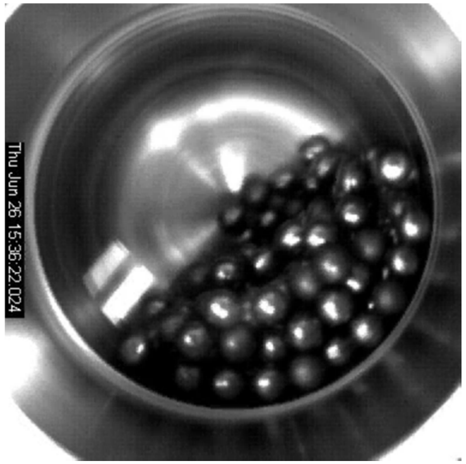
- Lower energy dissipations due to transport and friction inside material
- However, probably smaller energy utilization in each stressing event due to very high stress intensity in particle bed

How to determine stress energy distributions?

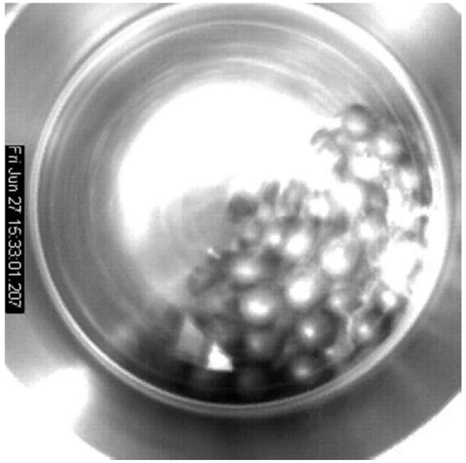


Experimental determination of stress energy distribution by ball motion tracking

Planetary ball mill under different conditions



no powder



limestone

α-Al_2O_3

parameters:

mill:

$k = -3$, $\omega_S = 20.9\ s^{-1}$

product:

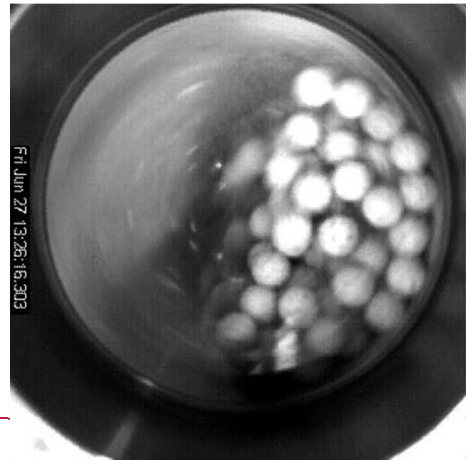
$\varphi_P = 0.5$, $x_{50,P} \approx 60\ \mu m$

grinding balls:

$d_{GB} = 10\ mm$

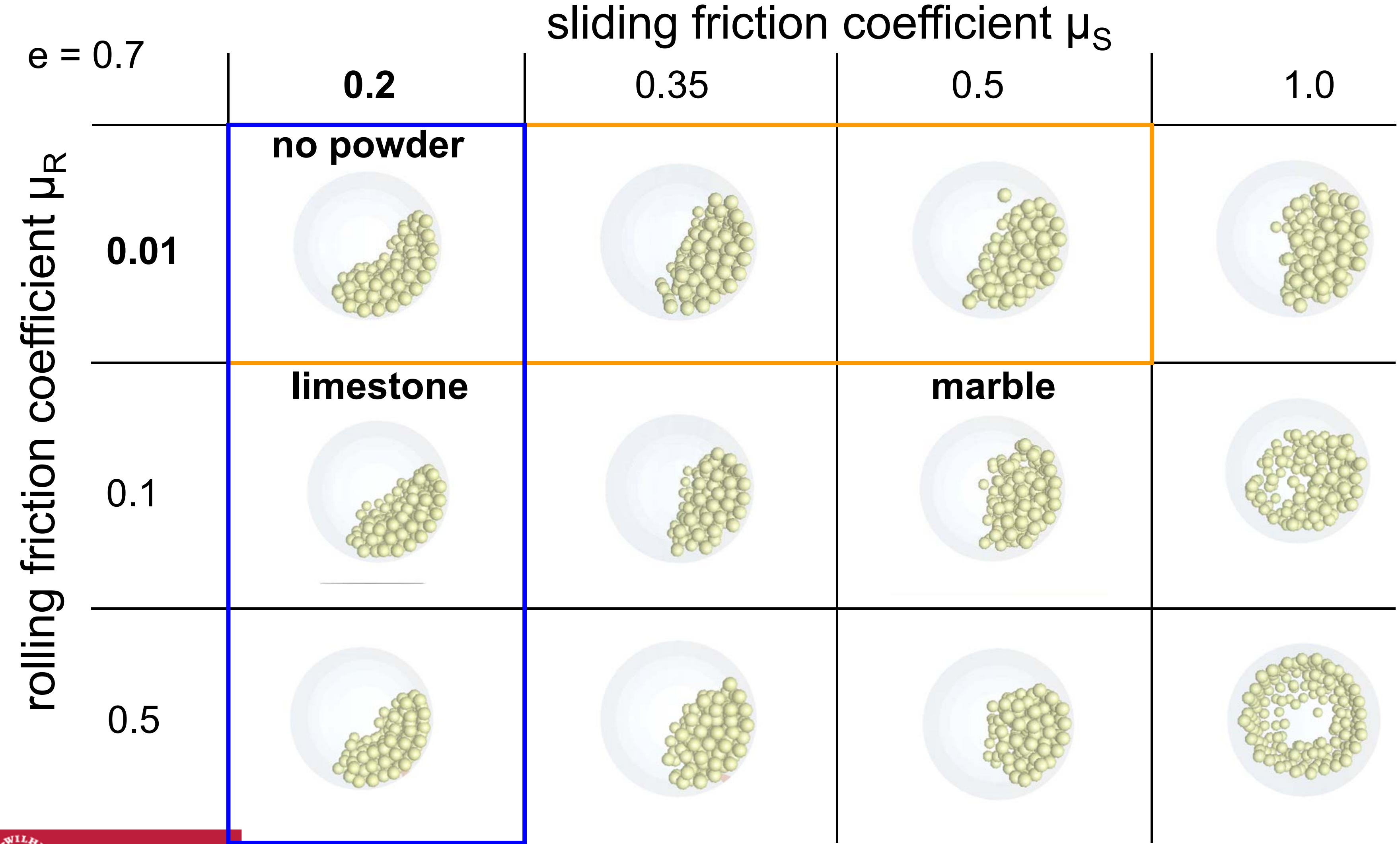
steel

$\varphi_{GB} = 0.3$



marble

Discrete element simulation –
Effect of friction coefficients on grinding ball motion



Comparison of media velocity distribution – measurement and DEM - simulation

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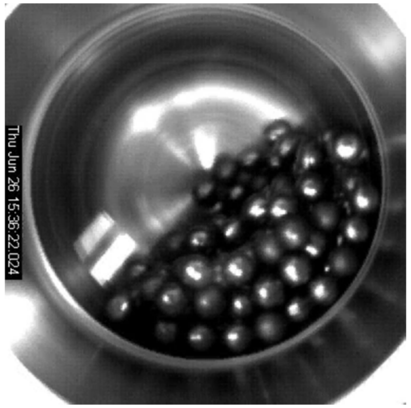
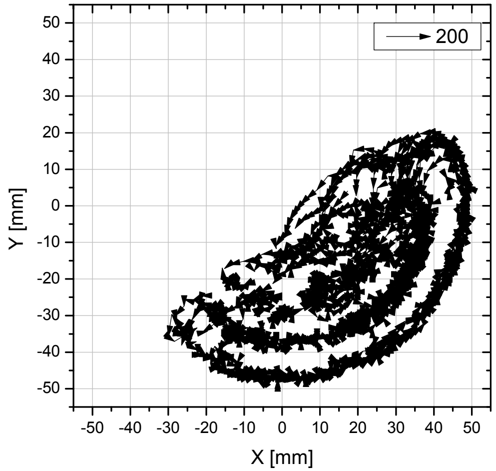
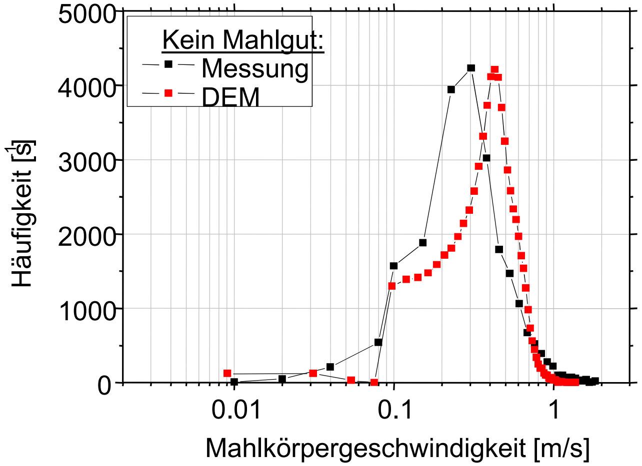
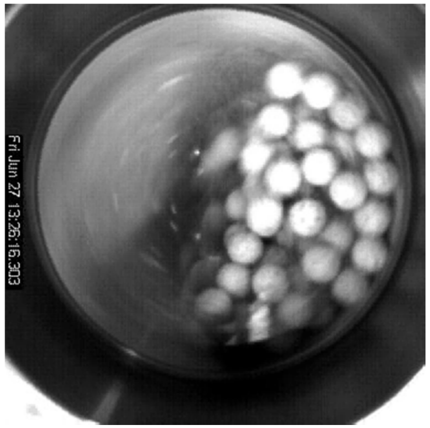
ohne Mahlgut

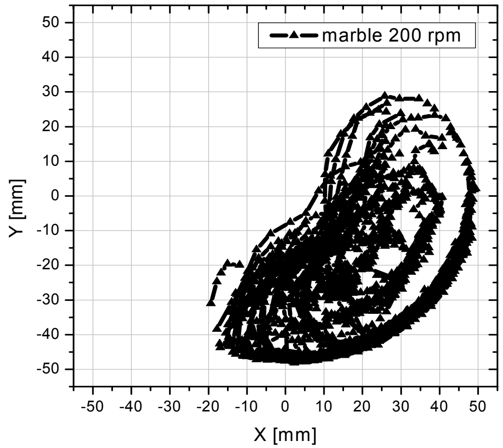


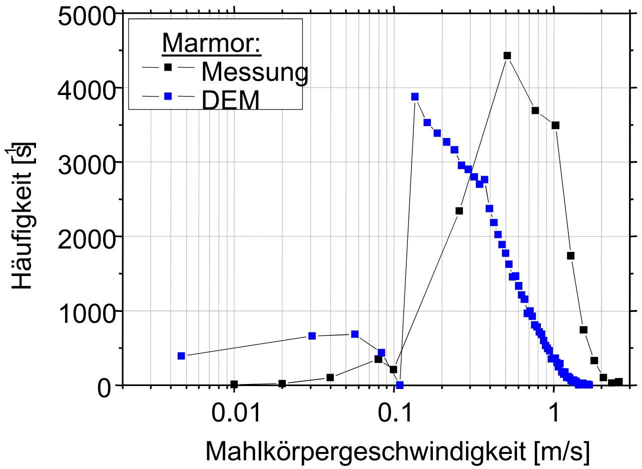




Marmor







Determination of stress energy distribution of dry operated stirred media mill by DEM-simulation

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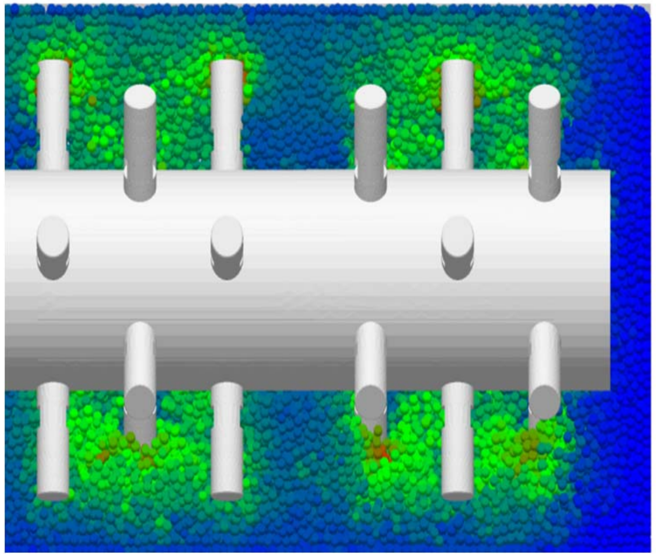
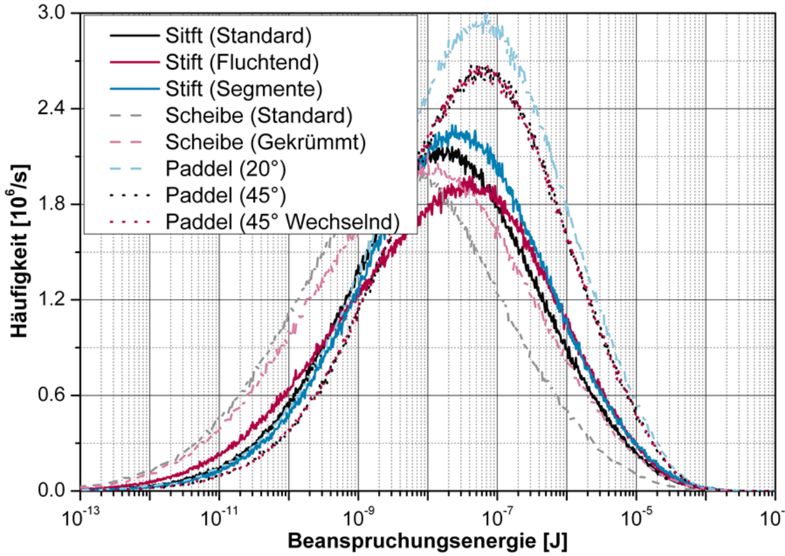


DEM - Simulation

Stress energy distribution



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Conclusions regarding energy efficiency

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- Energy transfer factor is important to characterize the mill beside
  - Type of stress
  - Stress energy distribution
  - Absolute stress frequency

- However, for the specific energy requirement and overall energy efficiency of a milling process the choice of the stress energy is also crucial

- How does stress energy SE and with that stress number SN determine the result, since there are an infinitive number of possibilities to achieve the same specific energy input?

Product related stress model for constant product qualities

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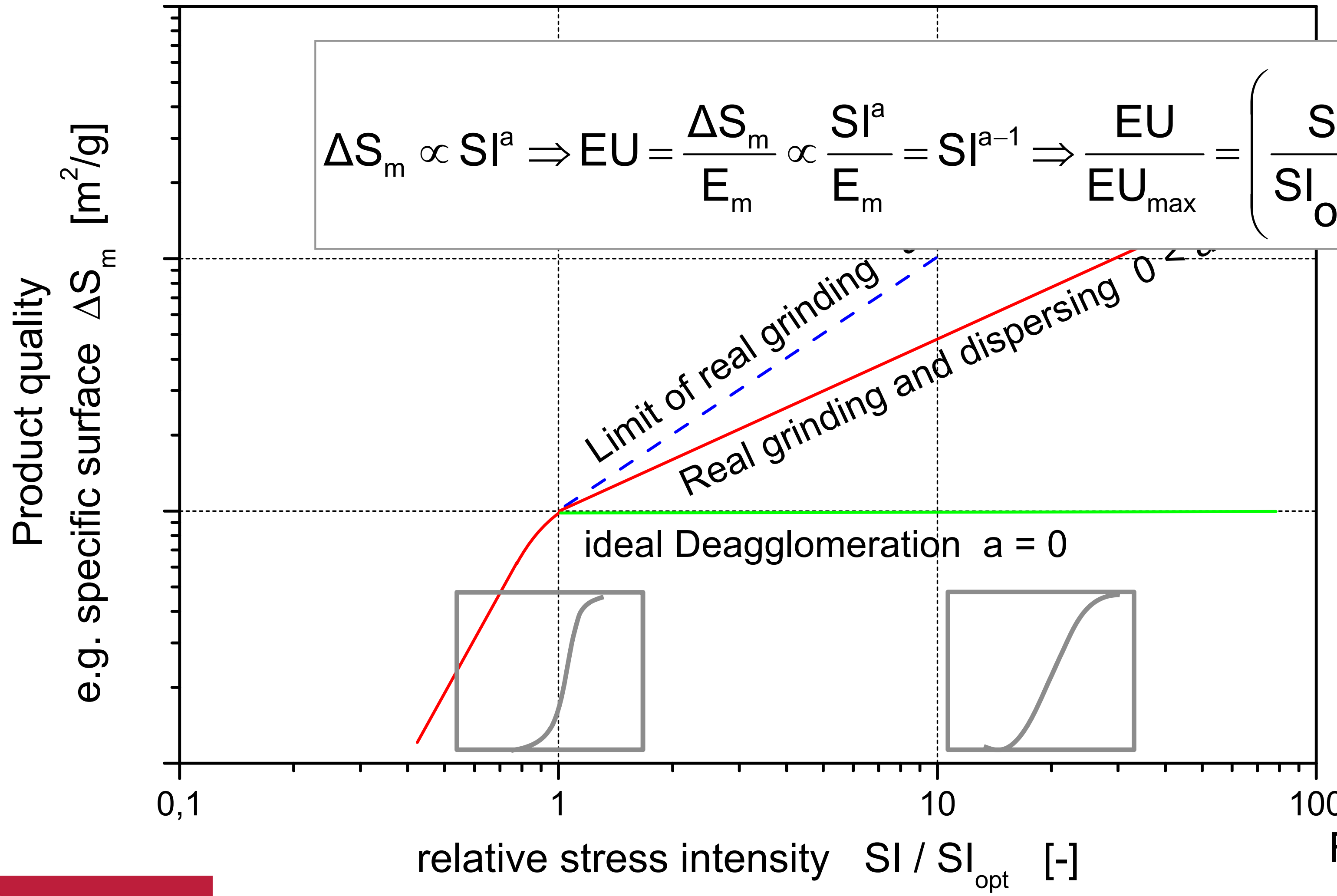
The product quality and fineness achieved in a grinding or dispersion process is constant if

- the feed particles and the resulting fragments are stressed similar
  → **type of stress** (e.g. impact or compression and shear)
- each feed particle and the resulting fragments are stressed equally often
  → **stress number per feed particle, SN_F**
- the specific energy at each stress event, i.e. the ratio of stress energy to stressed product mass or also specific force is equal
  → **stress intensity, SI**

- The stress intensity determines, how effective the specific energy transferred to the product is transposed into product quality and product fineness.

Effect of stress intensity on product quality for one stress event



$$\Delta S_m \propto SI^a \Rightarrow EU = \frac{\Delta S_m}{E_m} \propto \frac{SI^a}{E_m} = SI^{a-1} \Rightarrow \frac{EU}{EU_{max}} = \left(\frac{SI}{SI_{opt}}\right)^{a-1}$$

Fig. 3.19

Effect of stress energy on energy utilization

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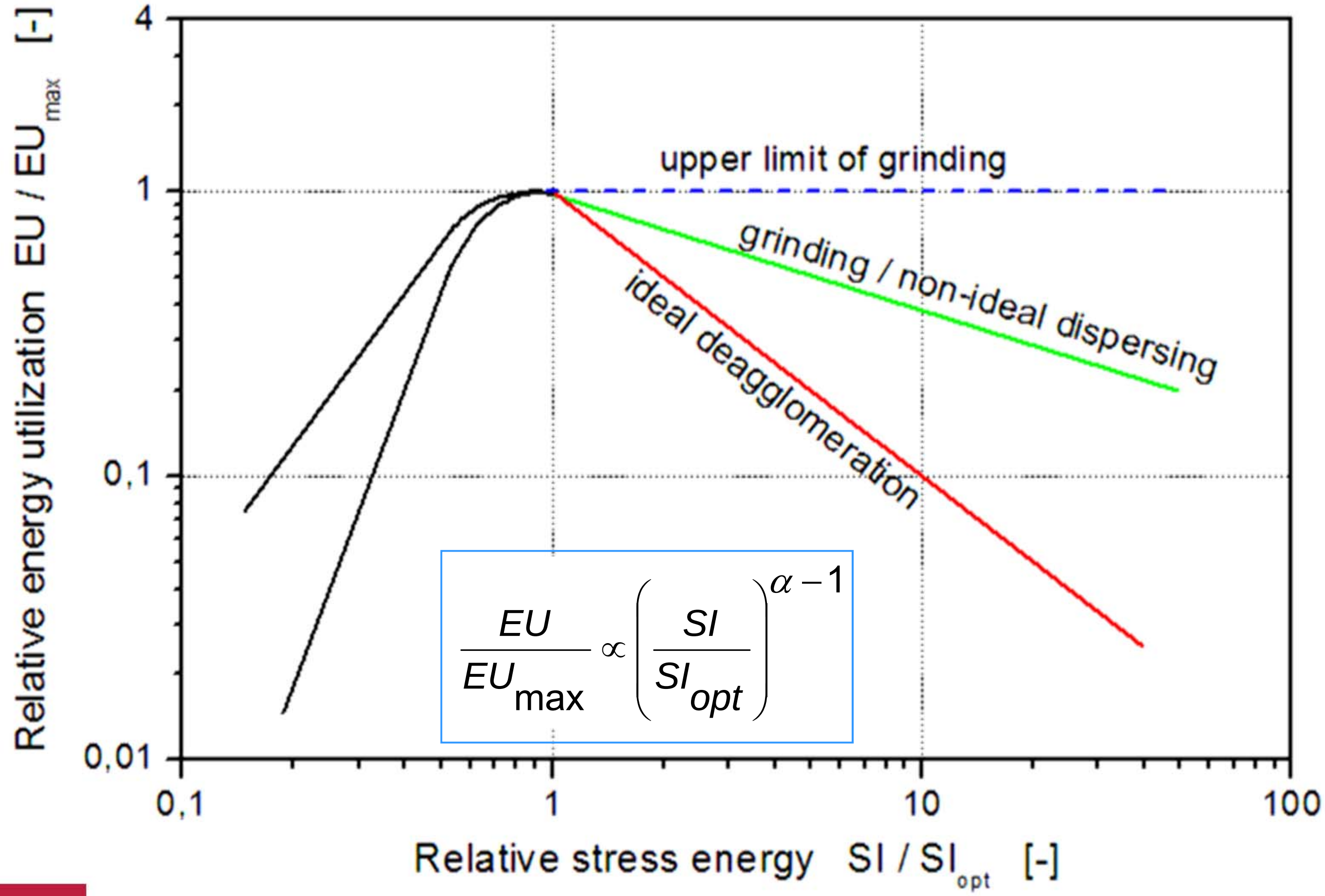
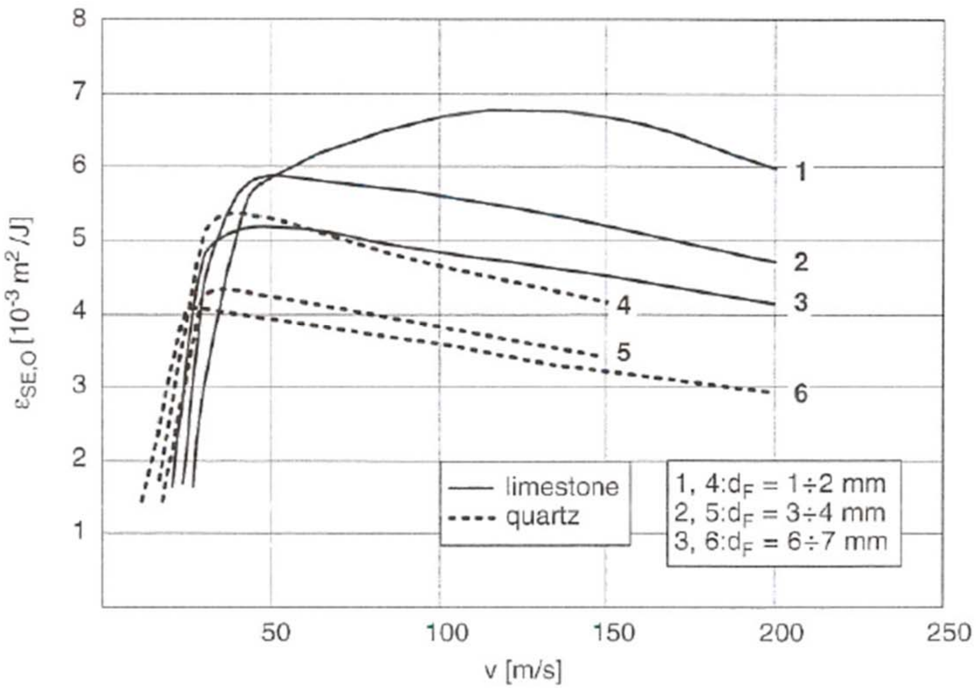
Energy utilization $EU = \Delta S / \Delta E = \Delta S / SE = \Delta S_m / \Delta SI$



$$\frac{EU}{EU_{max}} \propto \left(\frac{SI}{SI_{opt}}\right)^{\alpha - 1}$$

Effect of stress energy on energy utilization
Measurements by Rumpf, Schönert and Unland



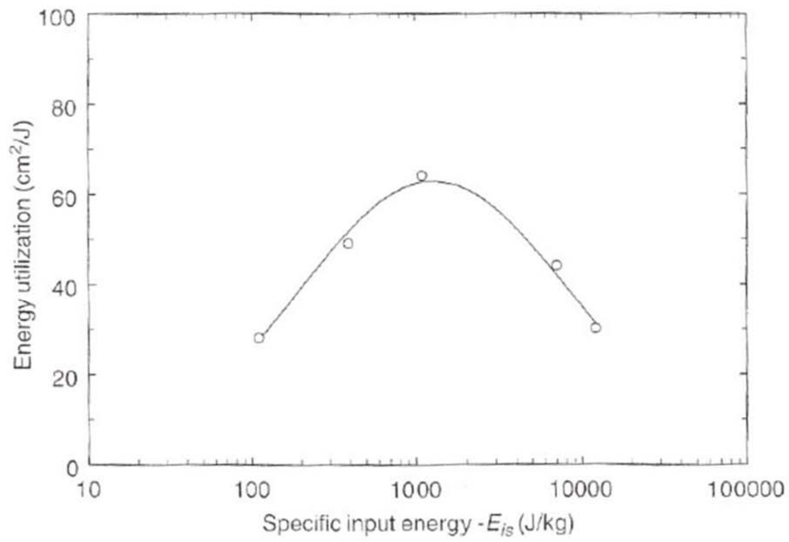


Fig. out of Handbook of Powder Technology – Particle Breakage

- Highest energy utilization was found to be close to the breakage point, i.e. the specific energy at which the particle just breakes (= specific breakage energy)
- The specific breakage energy can be taken as value for the optimum stress intensity SI_{opt}

Conclusions from principal considerations

Conclusions regarding definition of energy efficiency:

In general specific energy consumption of mill (without no-load power) should be compared to minimum specific energy requirement in optimized lab element tests (ideally slow compression or other type of stress if more favorite) at optimum stress intensity

Two factors determine energy efficiency:

- energy transfer coefficient (including friction inside particle beds)
- effect of stress intensity on specific energy requirement for particle breakage

$$\eta_E = \frac{E_{m,P,min}}{E_{m,M}} = \frac{E_{m,P,min}}{E_{m,P}} \cdot \nu_E$$

Content

- Tradition of comminution research
- Systematic investigation of single particle breakage
- Mill development from „Micro“ to „Macro“
- Examples of applying „Stressing energy approach“
- Conclusions

- Stress energy just sufficient, stress number as high as possible
- Advantages:
  - Speicific Energy is low and with that
    - Low energy costs
    - High production capacity because $\dot{m}_P = \frac{P_M - P_0}{E_m}$
    - Low contamination and wear costs pre ton of product
    - Less cooling issurs
  - Narrow product particle size distribution
  - Less mechanochemical surface changes or
  - Application of stress energy consideration on mass balances

Product fineness as function of specific energy for different grinding media sizes (stirred media mill)

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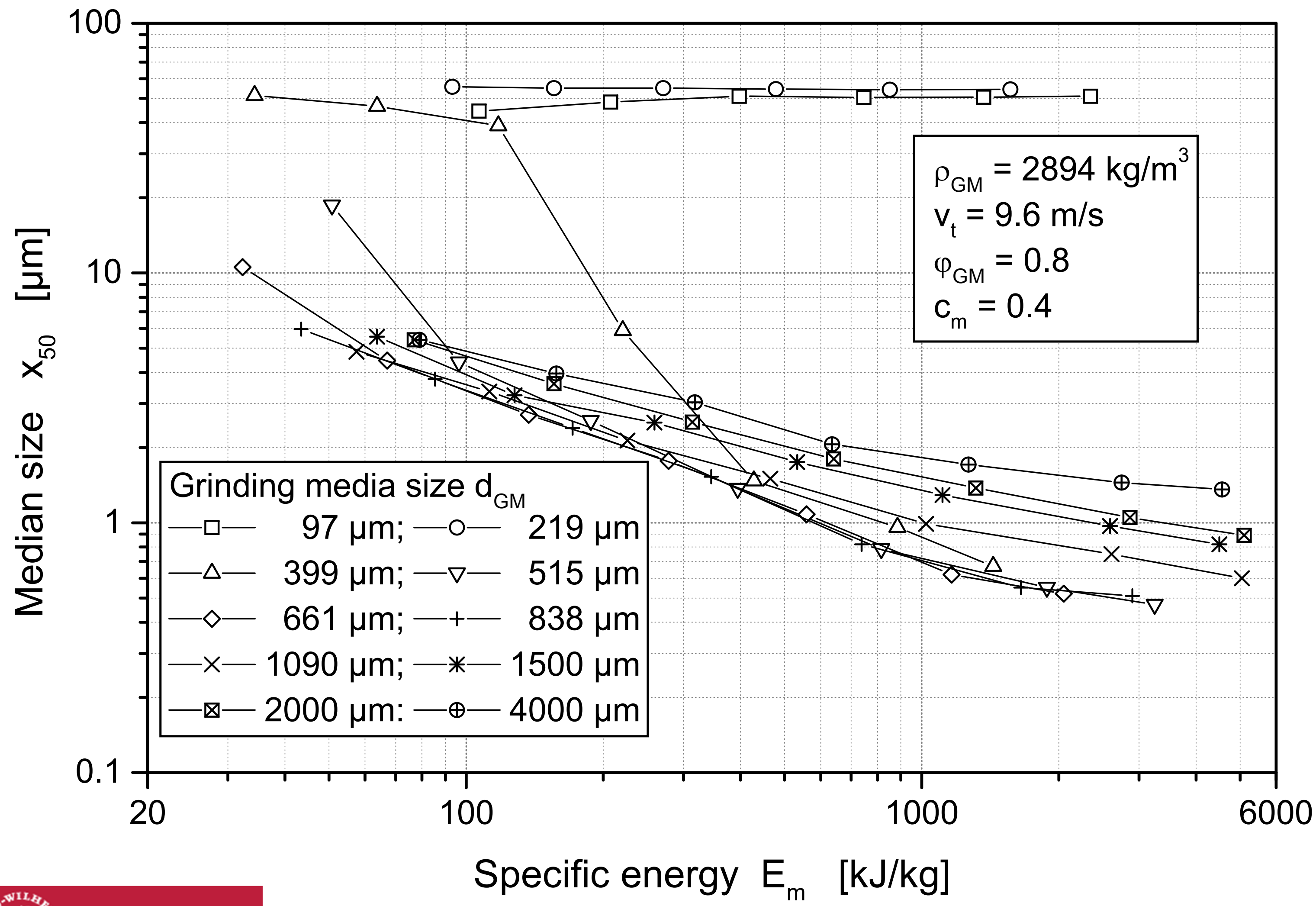

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Application of the stress model
Stirred media mill

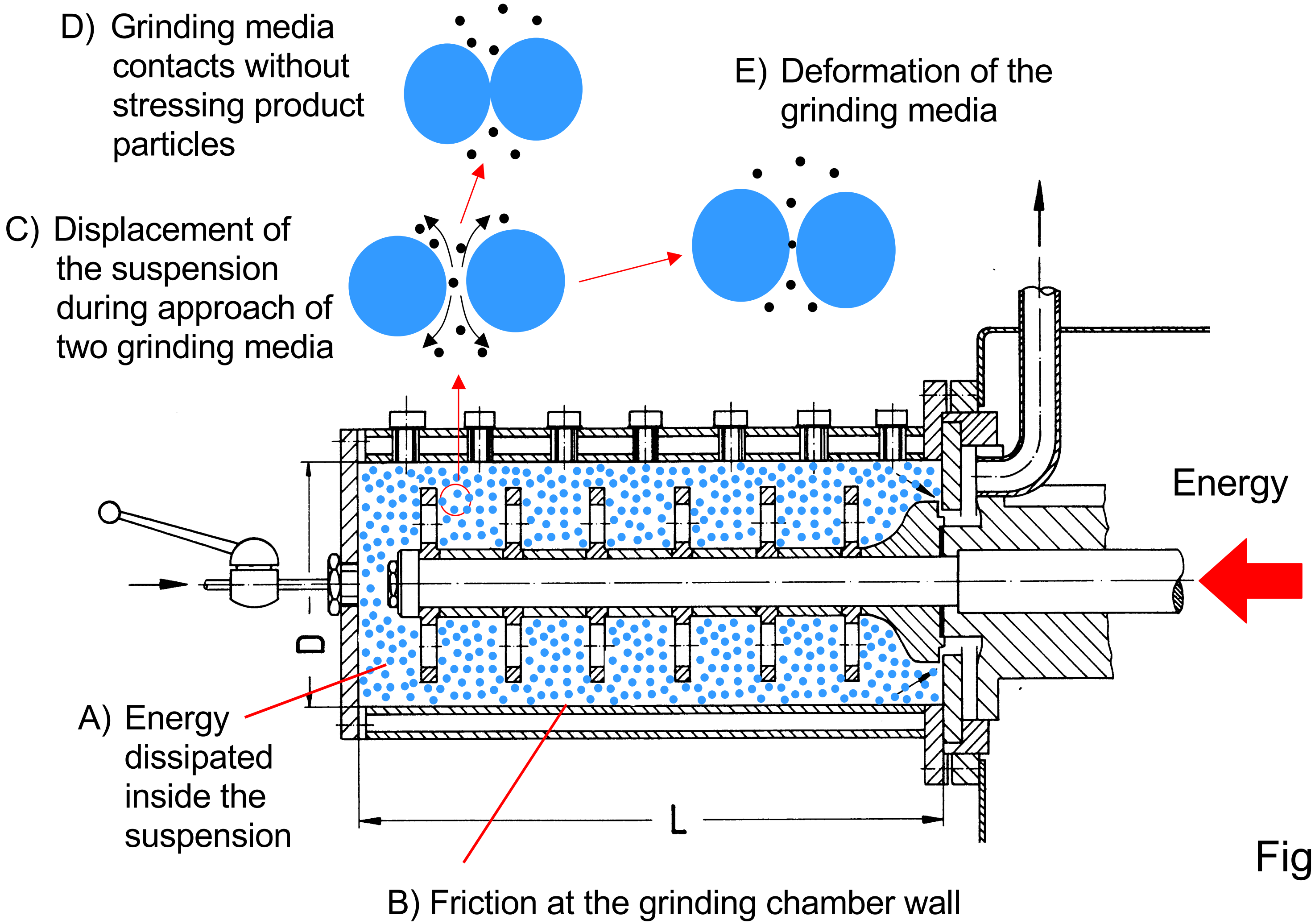

Fig. 3.62

Inclusion of viscous damping due to suspension displacement in stress model

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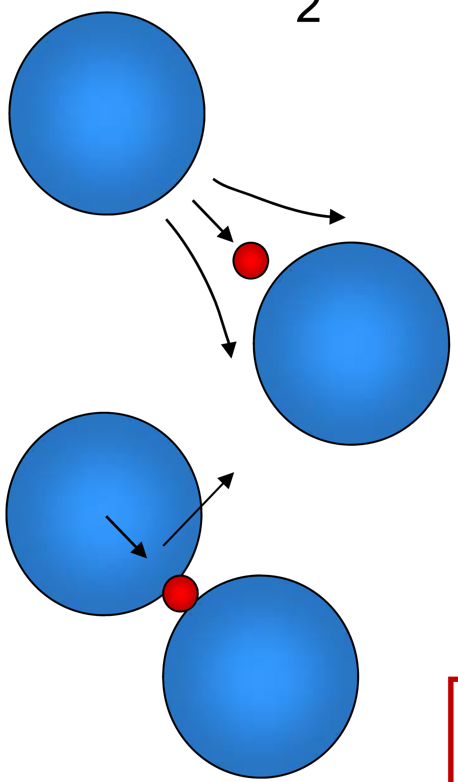
$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2$$



- Kinetic energy determines stress energy → SE_{GM}
- Kinetic energy is used for:
  - Displacement of suspension during approach of grinding media → r_η
  - Deformation of grinding media while stressing product particles → r_Y
  - Deformation and stressing of product particles → SE_P

$$SE_{max} \propto SE_P = r_\eta \cdot r_Y \cdot SE_{GM} = r_\eta \cdot r_Y \cdot d_{GM}^3 \cdot \rho_{GM} \cdot v_t^2$$

Assume a certain signature plot
fineness = f(specific energy)

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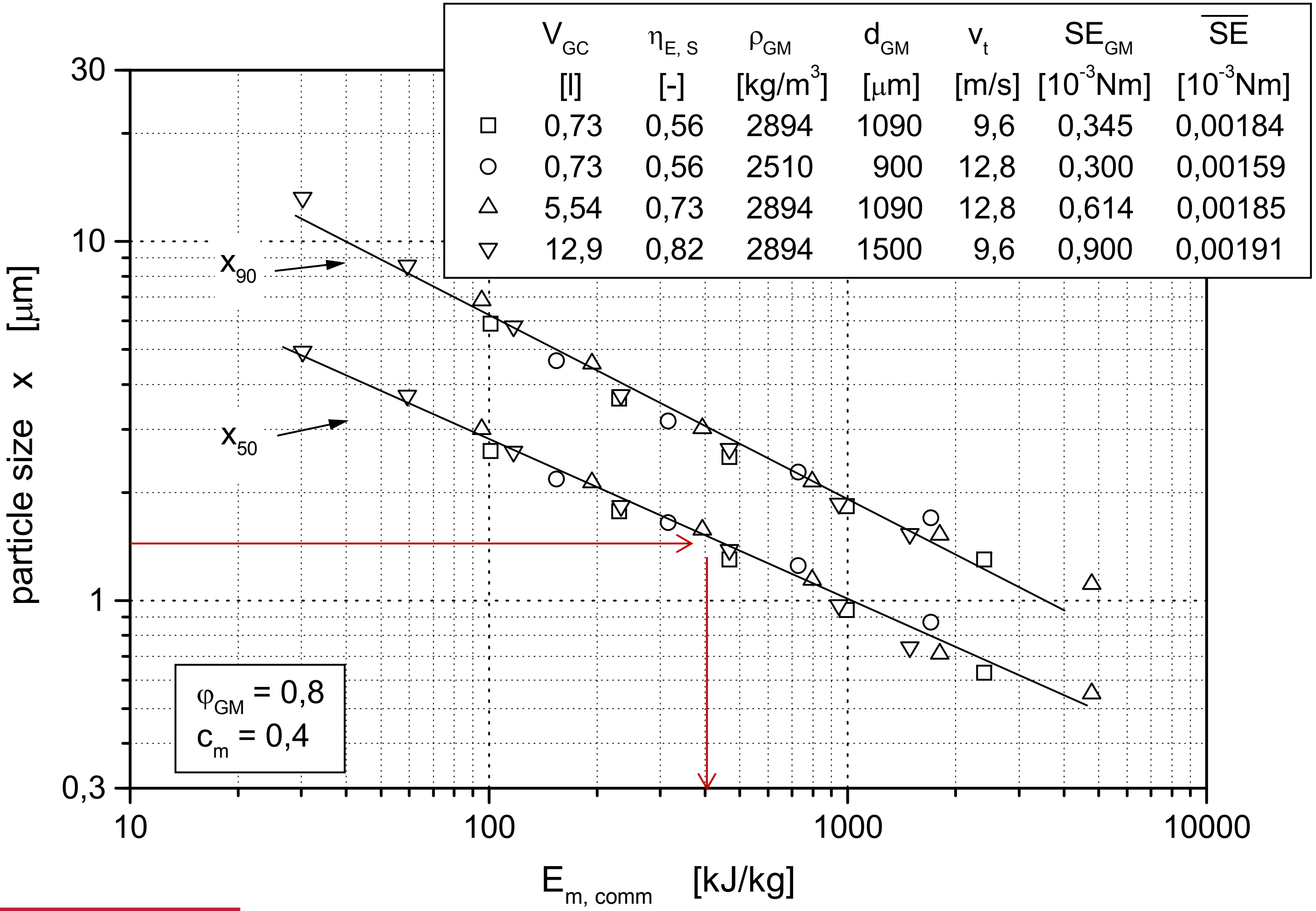

	V_{GC} [l]	$\eta_{E,\,S}$ [-]	ρ_{GM} [kg/m³]	d_{GM} [µm]	v_t [m/s]	SE_{GM} [10^{-3}Nm]	$\overline{SE}$ [10^{-3}Nm]
□	0,73	0,56	2894	1090	9,6	0,345	0,00184
○	0,73	0,56	2510	900	12,8	0,300	0,00159
△	5,54	0,73	2894	1090	12,8	0,614	0,00185
▽	12,9	0,82	2894	1500	9,6	0,900	0,00191

Specific energy required for a median size of 2 µm as function of stress energy

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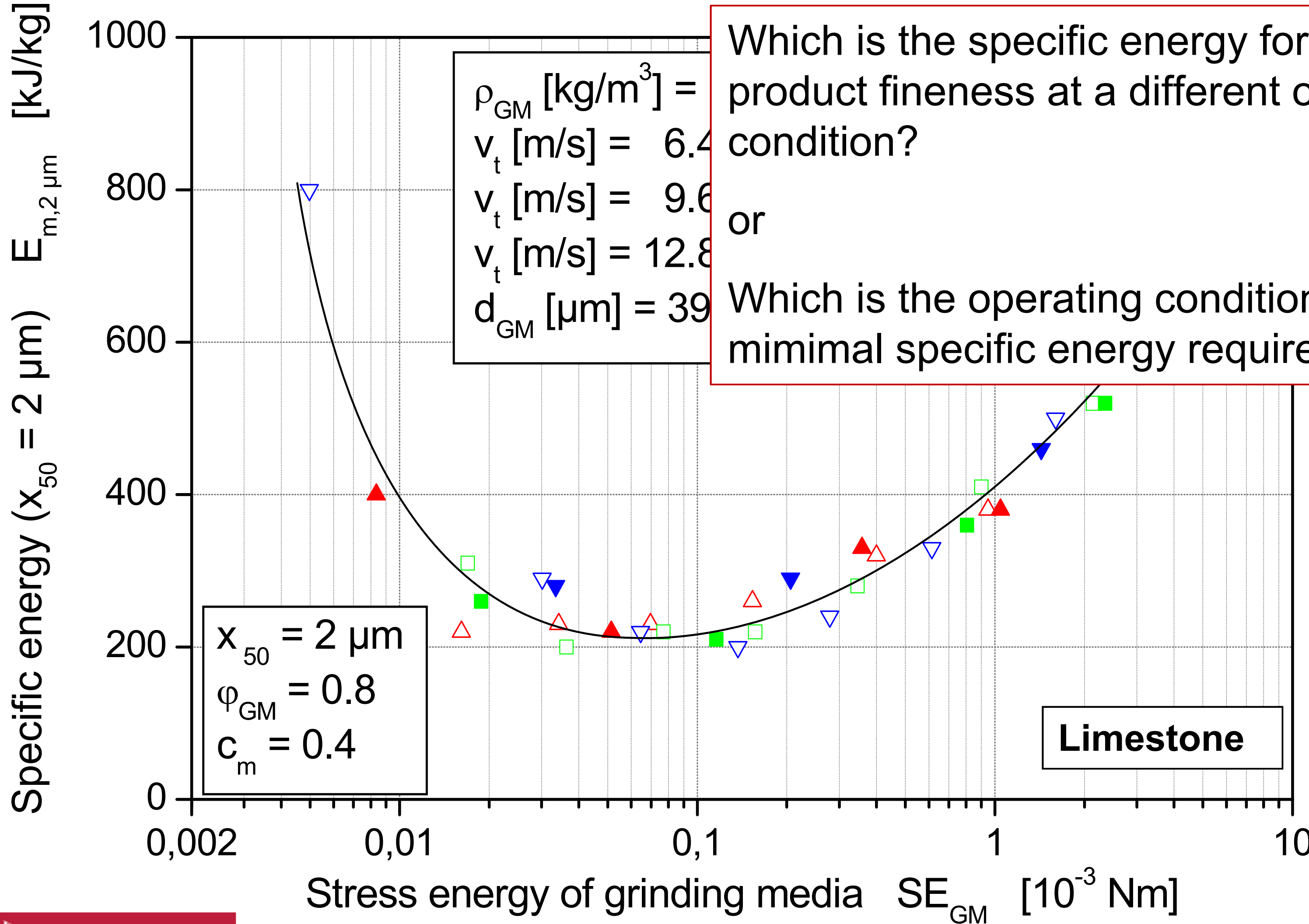

Which is the specific energy for a certain product fineness at a different operating condition?

or

Which is the operating condition to get the mimimal specific energy requirement?

Fig. 3.32

1. Calculation of actual and new stress energy based on relationship shown before if energy transfer factor stays constant and stress energy is sufficient higher than optimum stress energy

$$\frac{E_m}{E_{m,min}} = \left(\frac{SI}{SI_{opt}}\right)^{1-a} \Rightarrow E_{m,2} = E_{m,1} \cdot \left(\frac{SI_2}{SI_1}\right)^{1-a}$$

For example for stirred media mills as characteristic parameter for the stress intensity can be taken as long as the mill is not changed

$$SE \propto SE_{GM} = d_{GM}^3 \cdot \rho_{GM} \cdot v_t^2$$

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   For example for stirred media mills as characteristic parameter for the stress intensity can be taken as long as the mill is not changed

$$SE \propto SE_{GM} = d_{GM}^3 \cdot \rho_{GM} \cdot v_t^2$$

2. If a model for power draw is known the production capacity can be calculated

$$\dot{m}_P = \frac{P_M - P_0}{E_m} = \frac{f(D,n,...)}{f(D,n,...)}$$

- Based on this equation for scale up of a mill the two following parameters have to be kept constant:
  - Utilized specific energy
  - Stress energy distribution or, for simplification, the mean stress energy

- Scale-up rule based on stress model:

$$\left(E_{m,Lab} \cdot \nu_{E,1,Lab}\right)_{\overline{SE}} = \left(E_{m,Prod} \cdot \nu_{E,1,Prod}\right)_{\overline{SE}}$$

- For calculation of specific energy of production scale mill
  - the mean stress energy of lab and production scale mill should be similar and
  - the energy transfer coefficient should be determined for lab and production scale

Influence of grinding chamber size on the specific energy needed to produce a product fineness of x_{50} = 1,5 µm

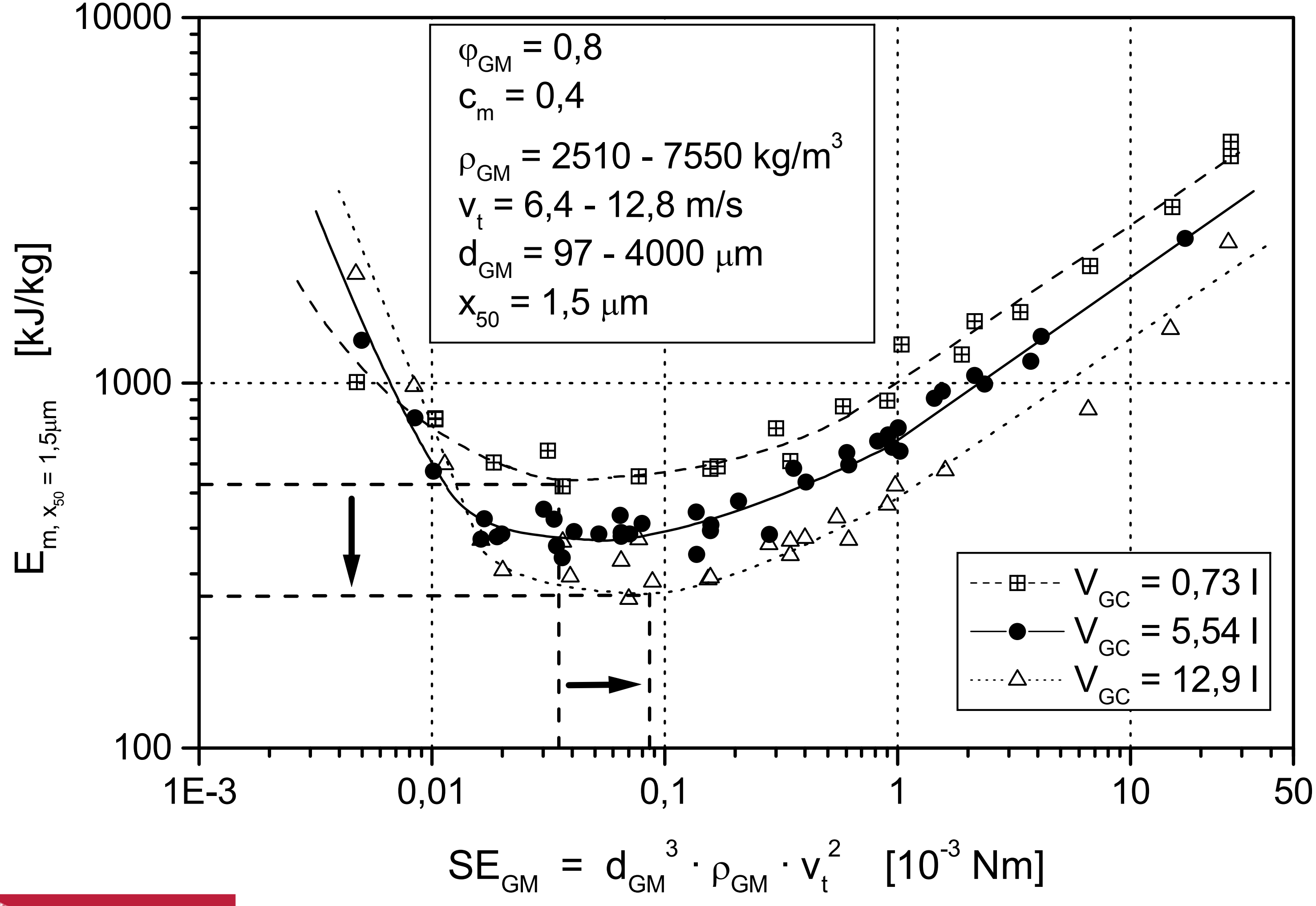
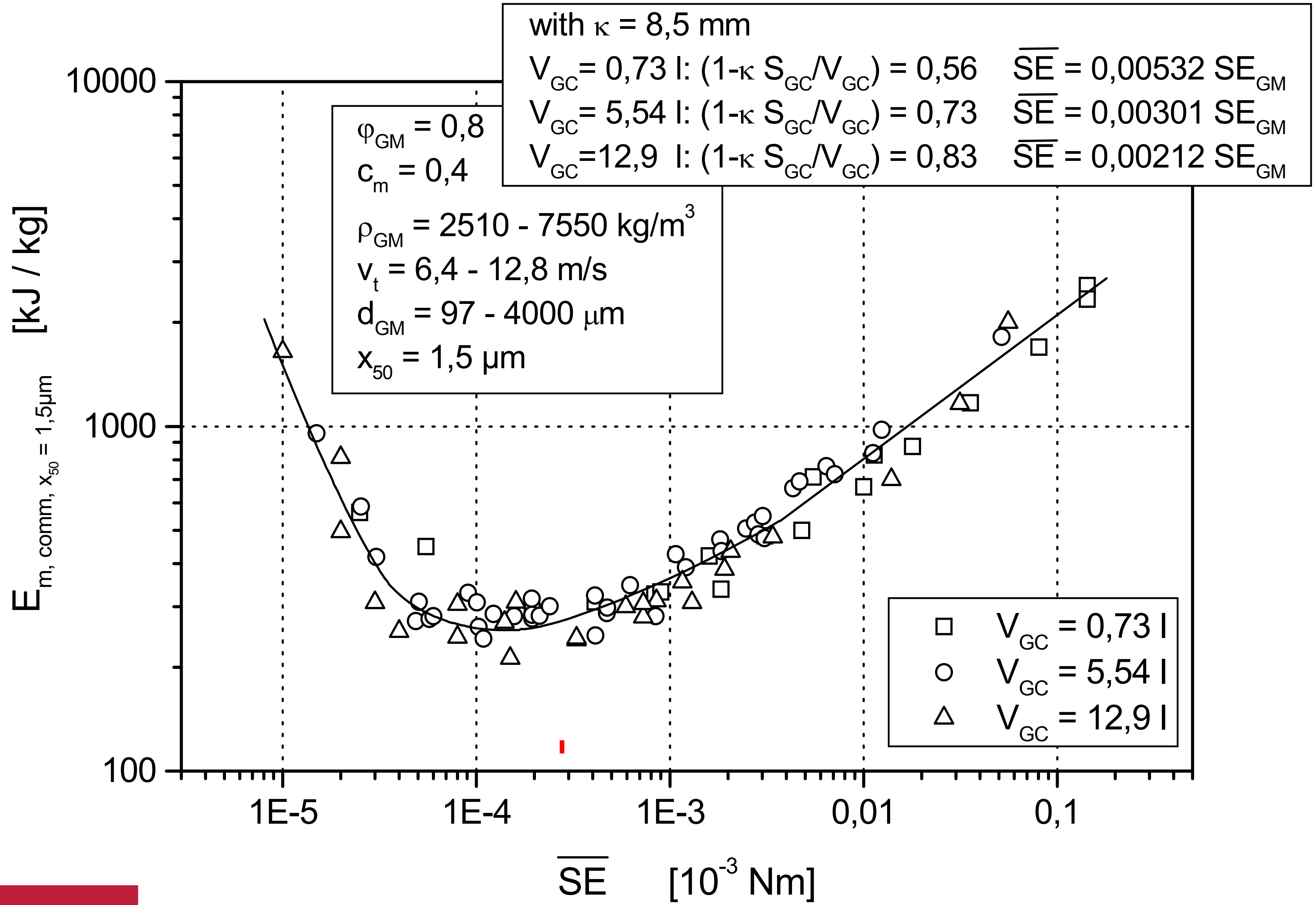


Fig. 7.4

Application to stirred media mills



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Conclusions and outlook

- The comparison of the energy efficiency of a mill needs an exact definition of this characteristic parameter
  - Energy efficiency – comparsion to ideal situation, either
    - Individual stress event like in mill under consideration
    - Ideal single particle stressing with optimized stress intensity
  - Energy transfer coefficient
- Parameters like specific energy consumption and power input can be directly connected to the characteristic parameters mean stress energy, total stress number and energy transfer factor
- Based on the stress intensity model
  - The operation of mills can be optimzed
  - Mill operatoin can be scaled from laboratory to production scale
  - Mass balances can be extended so that they can predict the effect of operating parameters on product particle size distributions

Great thanks

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