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Fine grinding with mechanically actuated impactors.

by W. Beushausen.

Summary: Following a general delineation of impact grinding from disintegration by other mechanical methods, the areas of application of impact implements are described according to their divergent tasks. The influence of the machine's rate of work on particle size is shown by a number of micro-photographs and representations of grain-size distribution, which at the same time give a good idea of the fineness currently obtainable with practical and feasible means. The effect of the flowing carrier medium on the resulting fineness is explained in terms of the theoretical behavior of small particles, their specific weight and their shape. The material's structure, repeated impact stress and the limits of stress are influential. Impact grinding is particularly suited to selective separation of structurally inhomogeneous substances.

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Impact grinding among other methods of disintegration.

As the most recent of all methods of fragmentation, impact grinding assumed a special significance for the chemical industry owing to its extensive scope of application. It was able to assert itself only with the means of modern machine construction, especially ball bearings for high revolution and materials of corresponding ruggedness. This is particularly valid for fine grinding by impact, which presupposes a high tempo of the impactors.

All of the remaining types of size reduction, such as percussion, pressure, friction and section, were once effected by human hands, before they were transferred to machines, usually of slow rate of work. Originally designed for a limited purpose, they evolved into a wider scope of application in the wake of increased utilization of industrial materials. This scope remained limited, however, due to the approximate structural identity of the milled substances, even though it was possible to modify the form and function of the grinding implements.

The characteristic of impact pulverization, that of striking the material in free flight or allowing it to impinge in free flight, permits the use of a wide range of speed by the impact apparatus and, consequently, adjustment of this speed to the compactness of the materials. The medium

transporting the particles, usually air, could be utilized for the removal of heat generated by the mechanical action. The design of impact implements met the requirements of shape, structure and weight of the material to be ground. Thus impact disintegration covers the widest scope of application of all methods of reduction, especially in the domain of fine grinding. It involves moderately hard, brittle materials, viscous-elastic ones and heat-sensitive, soft substances with low melting points. This range certainly covers a larger number of substances of related structure than all other methods. In the separation of agglomerates of finest primary granule size, impaction is probably the only feasible method in view of the difficult side effects encountered by other techniques. The same is true of soft, waxy substances which melt at low temperatures.

The limitations of impact fragmentation are tied to the structure of the treated material, marked by excessive viscosity on one hand and prohibitive hardness on the other, which renders its use economically unfeasible due to the attrition of the rapidly grinding implements. A subordinate role is played by the limited grain size or particle size of the material. This limitation is explained by designing considerations and the stress placed on high-speed impactors.

A characteristic of all fine reduction machines working with impact action is the conduction of air through the grinding spaces. It is normally transported through the running impactors and is partly used as carrier medium supplying the machines and for removal of the reduced material. It has an important role as coolant and thus protects heat-sensitive substances. The material must therefore be removed almost entirely from the air upon leaving the machines. The promotive or inhibitive effect of air on the reducing process must be considered, especially in the fine range; it also influences particles of extreme size, such as fibers, thin films, etc. This will be discussed later.

An attempt is made in Fig. 1 to depict, in a simplified version, the scope of application of impact reduction, together with that of other fine grinding methods, in correlation with material properties. Boldly shaded fields represent the positive feasibility of the process, those shaded thinly and in the opposite direction designate limited applicability. Vacant fields indicate that the method is not advisable or impossible for the given property of a substance or a group of materials.

Fig. 1 also shows which related methods of disintegration may be applied to a group of products with comparable properties. The results of the various processes, i.e. the resultant fineness or granular distribution, are not always comparable.

The decision between a machine operating on the impact principle and another with comparable end products is usually based on economic factors. Primary consideration is given to the specific performance,

followed by the cost of investment and operation, building expenses connected with installation, attrition, and the question of replacement parts. The most important advantage of fine grinding machines operating on the impact principle is their small size for equal output, made possible by the greater speed of their milling implements. This advantage is intimately related to the remaining questions of economy.

The scope of application of the most important designs.

A distinct delineation of machines operating within the fine range from "impact mills" in the coarse range is very difficult. If we desire to establish a sequence of most widely distributed fine mills in the direction of increasing fineness, the "impact mills" are followed by the hammer mill, Fig. 2. It shares certain data with the impact mills with respect to the feasible particle size as well as the obtainable grain distribution. Whereas the former operate at circumferential speeds of 15 to 45 m/s, the hammer mill employs a customary 30 to 80 m/s. Next are the sieve mills with 60 to 90 m/s and the pin mills with 120 to 150 m/s. By opposed motion of the second grinding disk, these machines currently achieve relative speeds of 230 m/s. Based on these peripheral speeds, a reference value can be obtained for the attainable upper grain size, provided we limit ourselves to data on a moderately hard, brittle substance with a correspondingly median specific weight. Impact mills will rarely go below 5 to 10 mm, unless selective separation is involved. The hammer mill covers the intermediate range, including sizes below 1 mm. Sieve mills produce around 0.2 to 0.3 mm; pin mills go below 50 μ. For the sake of completeness, Fig. 2 includes the jet mill, which also operates by impact (thrust), the most recent construction with the most favorable degree of fineness achieved to date.

A number of typical examples of grain distribution of the Contraplex pin mill, a hammer mill with bar grate as impaction face and classifying screen, and an impact mill are shown in Fig. 3. Crude limestone (calcium carbonate) served as test material. The steep grain distribution of the pin mill is due to a characteristic of this mill which shall be discussed later. The conspicuously flat distribution of the hammer mill indicates that the expenditure of effort applicable to this pulverization failed to be harmoniously related to the free orifice of the impaction face. The latter was too small, unduly prolonging the residence time. The result is an increased share of fine material upon similarly increased effort. The distribution of the impact mill is nearly linear and has almost exactly the ideal 45° inclination in the Rosin-Rammler graph.

Energy absorption and fineness.

It should prove fruitful to examine energy expenditure for 1 kg output of material in relation to the surface attained by the three grain distributions indicated. Both values are entered in Fig. 4 on a simple logarithmic scale. All wasted effort is included in the expended energy, especially ventilation, acceleration of particles, friction and mechanical

energy losses. The total energy absorption of the impact mill in the coarse range thus has a ratio of about 1:70 to that of the pin mill in the fine range. This ratio indicates the advantages of particularly careful penetration of the problems inherent in fine grinding. Incidentally, Fig. 4 only purports to visualize these correlations in connection with an easily milled substance and in no way yields a contribution to the discussion dealing with the theoretical relationship between energy expenditure and the attained surface.

Fig. 3 and 4 also give a reading on the correlation between the energic requisites of impact grinding, namely, that decreasing grain size requires an increased impact velocity in order to cause the disintegration of particles due to the induced mechanical tension. The ratio of impact velocities between the impact mill and the pin mill amounted to about 1:5. The structural peculiarities of the machines utilized in the test also indicate that the number of impactions suffered by the individual granule was increased with diminishing grain size. This requisite is confirmed by Smekal's (1) data concerning the influence of inhomogeneous points on the process of breakage and the concept that only repeated impactions induce the tensile peak required for the breakage of small particles.

Principles of construction and detailed design.

The builder of impact grinding machines for the fine range faces a number of possibilities by which to implement the indicated correlations. Impact mills only require a small number of impactors with relatively low rates of circumferential speed; their correspondingly heavy design is linked to the desired particle size. The upper limit of grain size is obtained by adjusting the gap in the impaction face. The use of the impaction principle in the coarse range is limited to brittle substances.

The desired upper grain size of hammer mills is similarly adjusted by means of gaps or perforations. Finer pulverization is obtained by higher peripheral speeds, a larger number of impactions by means of additional impactors. The composition of grain distribution may be influenced by the choice of the free passage surface of the grinding faces. Increased obstruction means prolongation of the residence time and a greater share of fine material. This method is feasible up to the stress limit of heat-sensitive substances, in any case only up to a concentration that still permits unimpaired impaction.

The feasibility of inducing the desired grain distribution and a stated upper grain limit by the choice of correspondingly narrow passage diameters in the orifices of the impaction face frequently leads from impaction to a frictional process with negative side effects due to accumulation of material; among them: Reduction in effectiveness by an increase in wasted effort, incorrect stress on the material with resulting damage, and increased wear and tear caused by hard substances.

A further measure aimed at increasing the tensile processes is the reduction of distance between the impactors and the path of impaction, and suitable outfitting of the path with a maximum number of diverting edges of appropriate shape. The shortening of the free particle paths achieved thereby is particularly effective in connection with very light materials and those in the form of thin films and fibers which are subjected to the disturbing influences of air flow owing to their high air resistance.

The shape of the impactors, especially the design of the striking edges, depends on the dissimilar structure of materials. Disintegration of soft materials and agglomerates is promoted by a striker that reaches across the width of the impaction path without interruptions. The same is true of brittle substances of slight hardness. Hard materials profit by heavy, single strikers which are suspended with free play when the sizes of the crude product's particles are very dissimilar, in order to avoid mechanical overexertion of the machine. Thin or sharpened strikers are used for viscous and elastic materials; they prevent harmful and inefficient deformation of these often heat-sensitive substances and permit the required tensile concentration of the particle. Fig. 5 shows an example of the striker implement for a hammer mill.

Effect and influence of the air as carrier medium.

The influence of air flowing through the milling spaces has already been pointed out in another connection. This influence is particularly disturbing when exerted on the increasing fineness of the material during the grinding process proper. While the kinetic energy of the propelled particles drops in proportion to their weight loss at constant speeds of impaction, a considerable rise takes place in the resistance factor as their Reynolds number diminishes, as shown for spherical particles in Fig. 6.

This means that the finer particles increasingly follow the direction of air flow, and not the direction forced upon them by the impactors. They withdraw from the stress of impaction and their direction is no longer similar to that of the larger particles. One could easily imagine that the resulting uncontrollable motive processes pose a strong hindrance to the larger particles due to the rapidly multiplying small granules.

Since counter-measures by control of the rate of flow were only partly successful, and adjustment of the direction of flow had practically no success, current attempts to alleviate this detrimental manifestation are still elementary.

At this writing there are two designs aimed at the elimination of disadvantageous impediments due to fine particles. First there is the micro-atomizer, a high-speed hammer mill that reduces on closed paths of impaction and draws off the fine particles through laterally placed vents with measured amounts of air. We therefore have an impact dis-

integrator here, equipped with an internal separator, whose fineness is comparable to that of pin mills, Fig. 7.

Since the discussed processes a.. most strongly encountered in connection with the poor grinding quality of particularly viscous and elastic materials, a design was developed which was equipped with sieves in view of other peculiarities of the indicated group of substances and called the Superplex cool-flow mill, Fig. 8. Pulverization again occurred on a profiled path of impaction. Since the free openings of a striking face consisting of perforated tin or bar grate are frequently obstructed by circulating or excessively large material, the sieves were attached at the sides of the milling space and served here as genuine classifiers. The strikers are hanging within a rotor simultaneously equipped as a rotary blower. Excess air immediately carries through the sieve all particles smaller than the sieve's perforations. The increased air flow also serves as an effective coolant.

Two examples will point out the inherent advantages: In the case of viscous, dried plantal fibers, the identical energy investment yielded a 4 to 5-fold product of the same fineness compared to a conventional sieve mill. A rubber-like, foamy material that could not be reduced in a hammer mill with 30 mm perforations due to immediate and intense heating, was ground to a fineness below 1 mm with this machine, under constant conditions.

Grinding processes within the machines.

The technology of disintegration is faced by the circumstance that no mathematical foundations or direct measurements of the machines' action are available to the designer. This becomes particularly clear in the case of high-speed implements working on the principle of impaction. The necessarily rapid action of nearly all processes in the milling spaces offers a partial explanation. All considerations are naturally based on the basic laws of mechanics, which unfortunately are superimposed by a good number of disrupting influences. The effect of these disturbances frequently is greater than that of "aimed" processes. The builder is aided by observation of attritive traces and interpretation of adhesions in the case of sticky materials. Temperature measurements, comparison of grain distributions in connection with the given energy absorption and comparable output offer indirect values relating to the process of disintegration and serve in this capacity primarily for purposes of further development.

Pin mills offer the best perspective on the process of pulverization. Since they produce the highest degree of fineness of all impact machines, and also possess a great number of chances for the impairment of results, their range of application is wide and the investigation of their peculiarities of concomitant interest.

Their potentials for achievement of greater fineness include:

Acceleration of circumferential speed;

contrary motion of the second milling disk with additional increase in relative speed;

addition of pin rows;

narrower grouping of pin rows and utilization of thinner pins.

Heat-sensitive and adhesive substances are taken into consideration by utilizing:

Limited rotation;
rotation of all impactors;
limited pin rows;
more widely spaced pins;
thin pins.

The particles' direction of flow is easily deduced from measurements of attritive traces and adhesions on the uniformly distributed, shaped and used impact pins. It is variable according to the material's weight, hardness and elasticity, and depends on the air input and the size of the starting material.

Certain concepts based on data have nevertheless been published concerning the detailed processes taking place in the milling zone. F. Kaiser of Alpine A.G. has endeavored to contribute measurements and mathematical considerations. Fig. 9 shows a schematic drawing of a perpendicular cut through the pin rows of two opposed grinding disks, each equipped with three pin rows. The widely spaced pins are to be imagined as stationary, the densely arranged ones as rotating. Five milling zones are formed between the six pin rows. The three most characteristic types of particle movement are indicated in three milling zones. In order to facilitate representation, we assume three materials with clearly delineated structures: A readily ground product, e.g. dye or pigment agglomerates, a poorly disintegrating one, e.g. crude limestone, and a material that is practically irreducible by impaction, e.g. plastic granules such as polyethylene.

Readily ground material bursts upon impinging on the stationary pin row, i.e. with a non-elastic impact, and does not rebound to the pre- ceding pin row. It is carried through the gaps in the pin row by flowing air, permitting a repetition of the act in the next milling zone.

Irreducible material rebounds to the inner pin row after the first impact and continues to do so several times between the pin rows until it reaches the exterior by a favorable rebounding angle or collision

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with another particle. According to measurements taken in connection with the two-directional contra-pin mill 250 CW of Alpine A.G., each particle suffers an average of 7 impacts in each milling zone.

Between these two extreme substances there is a poorly reducible, but technically normal material. Each particle jumps back and forth between the pin rows until it either bursts and its components are carried through by the air flow, or it passes into the next zone by accident, undiminished after an average of 7 impacts.

Thus the pin rows have an additional function as sieves and the pin mill is also a sieve mill. This is explained by a number of circumstances that have not been fully interpreted heretofore:

For one, these include the high degree of fineness attainable with these machines, the steep incline of granular distribution curves, and the difference in power consumption between poorly and easily reducible materials.

The following two conclusions at first do not seem to fit into our concepts. The contents of all milling spaces of a pin mill with a 250 mm disk diameter, i.e. the 250 CW, amount to about 100 mg material. Similarly, the residence time of a few thousandth of a second is surprisingly short.

By way of comparison, these values for a jet mill of same size are: Contents, a few 100 g; the residence time, up to one minute.

The manner by which these results were obtained can only be alluded to at this time. It is based on the fact that the torque driving the moving pin disk is transferred to the stationary pin disk only by the force of the impinging particles (after deduction of the air resistance). This torque is easily and precisely measurable, as is the flow of material. The geometric measurements are known. Traces of wear and tear and adhesion indicate the angle of impaction, leaving only an estimation of the number of impactions. The resulting values probably are not very exact, but they ought to reflect the magnitudes of these manifestations with tolerable accuracy.

Grinding results with pin mills.

A few results achieved with pin mills should further clarify the preceding elucidations. Fig. 10 gives an idea of the effect of concentration in the milling zones.

Pulverization with increasing input under otherwise constant conditions was carried out with limestone (calcium carbonate), a moderately hard, brittle substance whose initial grain distribution is entered on the right side of the chart. The attained grain distributions were identical up to about 100 kg/h output. Up to about 250 kg/h a

slight loss of fineness is noted across the entire range, while the upper grain limit is only slightly changed. An output of 387 kg/h begins to cause a deviation in grain distribution toward larger particle diameters, initially only in the upper portion.

The progression of upper grain size is entered in Fig. 10 in the lower right-hand corner, above the input. Additional increase in input will cause the upper limit of the average grain size to rise in accordance with the indicated tendency. We must assume, therefore, that the concentration of material between the grinders is not constant with rising input. The final condition is such a high concentration that the process of impaction between the pins is changed to a frictional process among the accumulated material.

The influence of the material's structure, especially its compact-ness and viscosity, on the action in the milling zones is best shown by way of a few results. Fig. 11 reflects the increase in fineness of crude limestone after repeated passage through a pin mill.

The increase in fineness of the various fractions is small after the first passage, slightly less among the coarser fractions than among the finer ones. This test result proves that repeated passage of similarly brittle materials is without special effect and therefore uneconomical.

Two viscous-elastic substances showed a conspicuously different behavior compared to brittle-hard limestone. The results are entered in Fig. 12. Considerably coarser fractions were chosen, since the fineness of limestone reflected in Fig. 11 cannot be attained with these materials and the means described. Agar-agar, a gel from red algae, obviously depends on the moisture content for its viscosity. The initial water content and that present after each passage is listed on the upper edge of the diagram. Its decrease with the number of passages indicates a heavy mechanical stress and deformation of the particles during the grinding process. At the time of second passage, the water content has dropped from 19 to 12%, and from this point on the share of fine particles undergoes a measurable rise. At least four additional passages are required in order to depress the upper limit of 500μ , reached after three passages, to $60\ \mu$. The moisture has meanwhile dropped to 7%.

The behavior of an alginate produced from seaweed fibers or algae, known primarily for its emulsifying properties, is interesting when compared to agar-agar. Fig. 12 shows the percentual increase in particles below $60\ \mu$. The substance was nearly dry. Since the water content of this product could not change during repeated dis-integration, its influence is cancelled out and a steadily rising reducing effect is noted after each passage. Due to its greater vis-cosity compared to agar-agar, the alginate required multiple applications of stress in order to produce the points of fatigue needed for

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fragmentation. Revolutions and input were constant during these tests.

The granulation grid in Fig. 13 reflects the maximal fineness current-ly attainable with a pin mill for crude limestone. Results achieved by the neighboring method of reduction, the jet mill, are entered for comparison purposes. The jet mill yielded about 99% smaller than 5   , the pin mill about 99% smaller than 15   .

This result is contrasted with the grinding of graphite by the same apparatus, Fig. 14. Here the disrupting influence of air flow is evident, since the very thin graphite platelets offer a considerably higher air resistance than cubic grains of equal size, it being generally true that the platelet diameters represented as grain diameters cannot be related to the cubic form in the technology of disintegration. It is understood that a slight elastic bending property of the thin platelets contributes to the poorer degree of fineness. Here the jet mill produces 99% smaller than 35 μ , the pin mill 99% smaller than 70-75 μ .

Fineness resulting from different impact velocities.

The following micro-photographs present an optical picture of the effect of accelerated impact velocities.

The illustrations in Fig. 15 show a spray-dried PVC powder, i.e. a viscous-elastic substance, including the crude product, pin mill reduction with 145 m/s in the last milling zone, and pin mill reduction with a relative speed of 220 m/s in the outer grinding zone. When dealing with such heat-sensitive materials, the permissible stress, expressed by the relative speed of the pin rows in the last milling zone, must be carefully adjusted in order to find the permissible sustained operation conditions producing the highest degree of fineness.

Fig. 16 shows a softer, flaky product of low viscosity, namely roller-dried yeast. The speeds in the decisive outer milling zone were 130 m/s, 155 m/s and 180 m/s.

The micro-photograph in Fig. 17 reflects the distribution of fine agglomerates or fusion of primary granules of red-lead. Upon proper equipment and adjustment of the pin mill it is possible to reach the small amount of coarser particles and to reduce them in some measure to primary granules, despite the disturbing buffer effect of the crude product which consists predominantly of primary particles. The increased fineness is expressed principally by a lower rate of suspension and a noticeable increase in the volume of yield.

The striking effect of the pins on the agglomerates, whose diameter generally is below 5 μ and seldom exceeds 10 μ, is conspicuous in comparison to the degrees of fineness shown heretofore. It is probably true that the uniformly small primary particles do not as yet offer an essential hindrance to the trajectories of still intact, larger forms,

provided their concentration in the grinding zones is normal. This
assumption is confirmed by the observation that the drop in the dis-
integrating effect is connected with similar materials of high primary
fineness sets in very suddenly with stepped-up input, contrary to
substances that are reduced to wider ranges of granulation in the
milling zones. An example of such a case of gradual abatement is offered
by the diagrams for limestone, Fig. 10.

Fineness and subjection to stress.

The exceedingly low degree of effectiveness inherent in fine
grinding, coupled to a relatively high expenditure of energy, makes it
mandatory to avoid unnecessary losses during the process of reduction.
In practice, the performance of a machine is deemed satisfactory when
the desired fineness is obtained. Whether this fineness is achieved in
an inner grinding zone by a small number of impactions, so that un-
necessary energy is spent on already reduced material up to the moment
of exit, is frequently unknown. The pin mill is particularly suited to
a process of pulverization aimed in such a manner that the desired grain
distribution is produced precisely at the time the outer milling zone is
evacuated. The means to this end have been listed already.

When heat-sensitive products are involved, considerations of fine-
ness must frequently yield to the question of a material's capacity for
stress. Limitation of stress is particularly important when the
product's properties must not be changed, or when damage due to thermal
effects is to be avoided. This is best achieved by the use of a
permissible impact velocity, which can only be found by experimentation.

Fig. 18 shows an interesting case of thermal overstress of shellac
in the outer milling zone of a pin mill. The consistency of the
softened substance just happened to be such that extended adhesions
formed on the pins of the outer row, which immediately hardened in the
air flow.

When a repeated passage of such temperature-sensitive products is
considered, taking due note of the indicated energic disadvantages, it
must be remembered that it is precisely the resultant small particles
that reach a prohibitive temperature more quickly than the coarser ones,
since they absorb more heat from their environment due to their smaller
mass. An advantageous solution in connection with heat-sensitive and
all other poorly reducible materials is offered by an intermediate
separation of the fine portion.

The example of limestone (calcium carbonate), which served as test
material in several experiments, was chosen to show the degrees of
fineness currently attained by impaction with the aid of air sifting,
Fig. 19.

11.

An attempt was made initially to produce fine material not larger than 4.5 μ. The fine portion withdrawn from the machine was replaced by an equal amount of crude matter for the next run, establishing the constant conditions of a cycle. The fine portion experienced a steady drop upon separation of the 4.5 μ constituent. Pulverization of the entire material to an upper limit of 4.5 μ is therefore impossible. Additional tests established the desired objective at 7 μ . The fine components remain constant in the cycle. The circulation of material was about two-fold, using the highest relative speed currently possible for pin mills, about 230 m/s. A slight improvement of the result would be attained by increasing the circulation. The effect of the jet mill coupled with a sharply delineating microplex sifter exceeds the indicated fineness by another degree.

These results with limestone are compared with data from a test using graphite under identical conditions of reduction. The lowest possible sifting capacity of the separator was near a platelet diameter of 6 μ . The results were thus limited by the upper diameter of the finished product. A cyclic constancy between mill and separator occurred only near the 30th cycle, so that the amount of fine material withdrawn each time was 3%.

Selective disintegration by impaction.

Finally, the feasibility of selective reduction by impaction in the fine range shall be examined more closely. It differs considerably from the processes in the coarse range. First of all, a lower speed of the impactors normally suffices in view of the greater mass of the particles and the presence of copious "faults". The influence of disturbing air flow is negligible. The situation is different in the fine range. The softer particles are usually lighter than hard particles of equal size, and therefore are subject to the disrupting influence of the flowing carrier medium. Thus harder, more compact particles are subjected to impaction sooner and more often than less solid ones. At the same time, the greater collisional energy is applied to the more solid and heavier constituents. Usable results in the fine range can therefore be expected only when the difference in the compactness of the participating substances is correspondingly great.

Fig. 20 gives a particularly clear example of a successful selective classification. It represents the separation of dried, calcined clay and pyrite after selective grinding with a hammer mill in the first stage and with pin mills in the next two stages. The separation of the first stage was accomplished with a spiral wind sifter in order to facilitate subsequent screening of the coarser particles at 0.5 mm. Subsequent classification again resorted to spiral wind sifters. According to Mohs, the hardness of pyrite is 6 to 6.5, that of the clay agglomerates should be between 1 and 2. The specific weight of pyrite is 5.0 to 5.2, that of clay approximately 2.0.

The results have been visualized by burning samples of the various fractions. The left side of the picture shows three samples of clay purified of iron pyrites, i.e. the fine products obtained. The siftings and the crude product of the third spiral wind sifter, depicted as two shiny, black specimens at lower right, represent the residue. Starting with a pyrite content of about 3.5%, the total residue amounted to 6-7%. The blackness concentrated in the residual samples is recognizable in the burning specimen of the starting material in the form of eruptions of individual pyrite particles due to oxidation.

Illustrations.

Fig. 1. The association between the various types of action and the most important properties of materials for fine grinding.

Fig. 2. Schematic structure and action of impact grinding machines most commonly used in the fine range.

Fig. 3. Grain distribution of different mills working on the impaction principle. Material: Calcium carbonate.

Fig. 4. Energy absorption, including all energy losses, in dependence upon the resulting surface in the disintegration of calcium carbonate.

Fig. 5. Sharp-edged, thin impactors of a hammer mill designed for the separation of fibrous platelets (wood shavings).

Fig. 6. The resistance factor C_W of spheres in dependence on Reynolds' number. According to Muttray, from L. Prandtl: Rheology, Braunschweig 1956, p. 180.

Fig. 7. Horizontal section through the "micro-atomizer," designed by Metals Disintegrating Co. Inc., Summit, N.Y., USA.

Fig. 8. Superplex cool-flow mill, designed by Alpine A.G., Augsburg.

Fig. 9. Characteristic trajectories in the milling zones of a pin mill (excerpt). According to Fr. Kaiser.

Fig. 10. Change in grain distribution and upper grain size with input, involving a pin mill (Alpine Contraplex 250 CW). Revolutions n = 17,400 RPM relative. Test material: Calcium carbonate.

Fig. 11. Increase in fineness of crude limestone (calcium carbonate) after several passages through a pin mill (Contraplex mill 250 CW); n = 17,400 RPM relative.

Fig. 12. Divergent behavior of two structurally related viscous-elastic products during impact grinding in a pin mill. Material: Agar-agar and alginate (Contraplex mill 250 CW); n = 17,400 RPM rel.

Fig. 13. Comparison of the fineness of limestone, reduced in a pin mill (Contraplex mill 250 CW; n = 17,400 RPM relative) and a jet mill (Alpine Aeroplex jet mill 200 AS; 6 atmospheres excess pressure).

Fig. 14. Ultra-fine grinding of natural graphite in pin and jet mills.

Fig. 15. Reduction of PVC (polyvinyl chloride) in pin mills with increasing circumferential speeds.

> a: crude product, spray-dried;
> b: ground in a Kolloplex mill at 145 m/s;
> c: ground in a Contraplex mill at 220 m/s.

Fig. 16. Disintegration of dry yeast (roller-dried) in a Contraplex mill; speeds in the outer milling zone: a) 130 m/s; b) 155 m/s; c) 180 m/s.

Fig. 17. Reduction of red-lead in a Contraplex mill. Left: crude red-lead; right: ground red-lead.

Fig. 18. Grinding disk of a Contraplex mill after reduction of shellac, showing overstrain of the material.

Fig. 19. Lowest upper grain size of crystalline limestone upon grinding in a pin mill and continuous separation with a Mikroplex spiral wind sifter. Mill: 250 CW with 230 m/s, n = 17,400 RPM relative; separator: 132 MP (Alpine), n = 12,000 RPM. Replacement of fine product by crude product: $34\% < 500\,\mu$; $54\% < 1.0$ mm; $82\% < 2.0$ mm; upper limit 3 mm.

Fig. 20. Selective impact grinding with separation of clay and pyrite (FeS_2) by wind sifting and classification.

Literature.

(1) A. Smekal, Z. Physik 103: 495-525 (1936).