

ENERGY DISSIPATION DURING MECHANICAL TREATMENT OF INORGANIC NON-METALLIC SUBSTANCES

KLÁRA TKÁČOVÁ, VLADIMIR BOLDYREV* and NIKOLAJ LYAKHOV*

Mining Institute of the Slovak Academy of Sciences, Solovjevova 45, Kosice, USSR

(Received 26 April 1989)

The paper presents a detailed discussion on energy transfer and dissipation during mechanical treatment of inorganic non-metallic substances.

Key Words : Energy Transfer and Dissipation; Mechanical Treatment; Grinding; Metability; Elasticity and Plasticity

GRINDING belongs to the oldest and the most important unit operations. It has always been used in dressing and processing of minerals, in the manufacture of building materials and ceramics, in metallurgy, and in various branches of chemical industry. With the development of the advanced technologies that produce new materials and with the innovation of the traditional technologies, the potential field of application of grinding has substantially been enlarged. At the same time the requirements became stricter in terms of the fineness of the ground products and their various property functions (i.e., size distribution, shape etc.) with respect to their behaviour in subsequent unit operations. The most important property function for chemical treatment of the solid is the number and distribution of non-equilibrium structural defects that determine its reactivity.

Preparation of solid dispersions with specified properties by grinding requires a large amount of information concerning the individual stages of energy transfer and conversion during grinding and a component analysis of obtained knowledge based on the laws governing strength and failure in macroscopically brittle materials.

ELASTIC AND PLASTIC BEHAVIOUR OF SOLIDS

Any body subject to of external forces exhibits an opposite reaction, in other words internal forces develop in it, tending to restore its original shape and volume. The surface density of the force developed in each element of the body is known as stress. Under the action of external forces the solid may undergo changes in it linear dimension, volume and shape, all of which are known as strains or deformations.

Strains may be non-breaking and breaking. A breaking strain leads to the separation of the body into parts. The magnitude of the stress at which a body

*Institute of Solid State Chemistry, Siberian Branch of the Academy of Sciences of USSR, Derzhavina 18, Novosibirsk, USSR

breaks is termed ultimate strength. A non-breaking strain brings about changes in the size and shape of a body without destroying its continuity. The relation between non-breaking strains and stresses can be very different (Fig. 1).

In elastic behaviour the stresses and strains are directly proportional. The maximum value up to which deformations remain elastic is termed the elastic limit. In the region of elastic strain the stress creates reversible changes in the mutual arrangement of lattice elements and distances between them. This causes an accumulation of potential energy in the body which helps it to restore its original shape and volume after unloading.¹

The migration of atoms, defects and thermal energy are time-dependent processes. This dependence of elastic strain on time is known as the inelastic effect and may be often approximated as an exponential function. The time required for the time dependent component of strain to rise within $1/e$ of its final value on loading, or to decrease to within $1/e$ of its initial value on unloading is termed the relaxation time, τ .²

The relationship between plastic strain and stress is much more complex and varied. Any ideal plastic body begins to flow plastically (or yield) beyond the elastic limit, where deformation increases under constant stress. Most real solid are treated as compact bodies, so that it is necessary to increase the stress in order to maintain plastic strain.

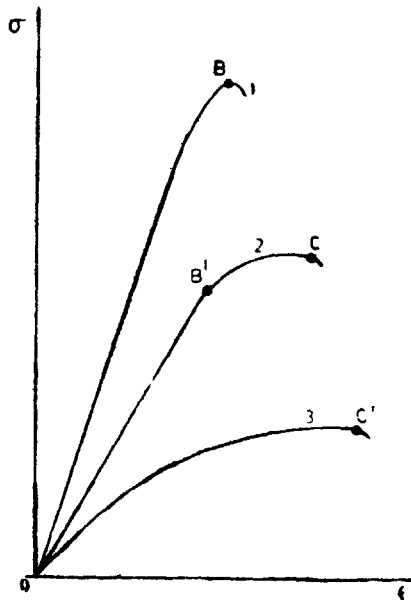


FIG 1 Typical stress-strain curves.

1—elastic, 2—elastic-plastic, 3—plastic OB and OB' —regions of elastic strain, $B'C$ and DC' —regions of plastic strain, points B , C and C' —breaking.

A characteristic feature of plastic strain is its irrecoverability after removal of load, which means that the shape and volume of the body are not completely restored and residual stresses remain in the strained material, causing an increase in its energy content.

Plastic strain is often considered as a process comprising generation, motion, interaction and accumulation of lattice defects, particularly dislocations. As a result of this, the generation and propagation of strain is influenced by a large number of internal and external factors.^{3,4}

The most important mechanism of plastic strain is slip of the gliding planes of atoms over one another which is accompanied by the movement of dislocations. Mechanical twinning, although generally of less importance, may contribute to plastic strain if slip is restricted.

The preferred slip direction is the most closely packed one. The slip planes are usually the most densely packed planes, which are also the most widely spaced. Among possible groups of planes and directions, the active slip system (plane and direction) becomes the one in which the acting shear stress is the highest.

In an extreme case, plastic strain occurs after the passage of at least one dislocation through the crystal. Macroscopic deformation, however, is always associated with the motion of a large number of dislocations that are generated by dislocation sources operating under stress. The critical resolved shear stress is independent of the normal stress. This means that a single crystal begins to deform under the action of a certain normal stress, whose magnitude depends on the orientation of its slip system with the respect to the direction of acting. The normal stress that causes an irreversible displacement of a group of dislocations resulting in a small but measurable plastic strain of the body is termed the yield point. Local activation of the slip processes may begin even below the yield point. Plastic strain that is caused by local activation of the slip processes is therefore restricted to small regions and is termed microplastic strain.

Movement of dislocations along slip planes is greatly hindered by impurities that create a short-distance stress field within the structure. The extent of plastic strain depends therefore on the density of mobile dislocations and their free path length, i.e., on the distance over which a dislocation may travel between two neighbouring obstacles.

The density of mobile dislocations is not a straightforward function of stress and strain. During deformation new dislocations are being generated in the slip plane. These may intercept other dislocations and hence give rise to the formation of bends and steps that obstruct further movement of dislocations. As a result of plastic strain, the material becomes resistant to further deformation. This phenomenon which is very well known in metals, is termed work or strain hardening.

Fundamental knowledge about the mechanism of plastic strain has been obtained from the study of metallic single crystals. The presence of grain bound-

ries in polycrystalline materials strongly affects the stress-strain behaviour of solids. Certain general features of this behaviour can nevertheless be deduced from the behaviour of single crystals.

It has been shown experimentally that the onset of plastic strain in polycrystalline materials occur at higher stress than the critical resolved shear stress. Work hardening in polycrystalline materials is higher than in single crystals, and depend on the grain size. The stress-strain diagram have very similar shapes with alternate regions corresponding to strengthening of material followed by a decrease of its strength.

From the above it follows that the elastic or plastic behaviour of any material depends on the bonding forces between atoms, on grain size, on temperature, on mode and rate of loading and on the foreign inclusions and structural defects that have appeared at certain stages of loading or heating. This is because one type of strain may change into another with an increase in stress or prolongation of its action. Thus for instance, with increasing stress three stages of deformation may be observed on Fig. 1: elastic, plastic and breaking. The same type of strain may arise from protracted action of an constant stress on the solid.

According to the relationship between these types of strain, solids can be divided into elastic or brittle, elastic-plastic and plastic. Metals are among materials that are typically plastic. However, most of the minerals and non-metallic materials such as ceramics are brittle. Such substances with covalent and intermediate bonds have an insufficient number of independent slip systems for general strain and have structures which are so complex that dislocation movement is difficult.

In substances that are brittle from macroscopic point of view, plastic strain is greatly restricted to micro-regions of contact between the stressed body and the tool, or to particles and grains with very small dimensions.

The microplastic properties of brittle materials were first described by Smekal.⁵ He found under the microscope that when a diamond, needle-shaped indenter acted on the surface of quartz at low load and slow rate of penetration there were plastically deformed zones near the indentation. He termed this phenomenon athermic melting.

The occurrences of formed dislocation migration during mechanical treatment was observed both in very hard and very brittle solids such as diamond, silicon carbide, magnesium oxide etc. under the action of unidirectional compressive force.⁶⁻¹⁵ It became apparent that microplasticity is a general property of solids, independent of whether the solid is macroscopically plastic or brittle.

Morphological studies of the contact region between the stressed solid and the indenter have shown a particularly marked disorder in the structure, which becomes partially amorphous. Etching experiments proved that the primary disturbance zone is characterized by a high dislocation density which decreases with increasing distance from the core of the contact. Regions with an extremely

low dislocation density may be formed under a plastically deformed zone, leading to an increase in microhardness of material.

The controlling factor limiting ductility is the case of the fracture. If fracture can be suppressed, polycrystalline material may deform plastically as higher strains will move dislocations on slip systems other than the preferred one.

The brittle to ductile transition is controlled by size and structure of particles as well as by external condition of loading i.e., by the mode and rate of stress. By works of Rumpf, Schönert and co-workers it was found that under increasing strength resulting from the diminishing of particles, a situation that may arise when the ultimate strength exceeds the yield point. Under this condition macroscopically brittle material exhibits ductile behaviour. The results of stress of single particles plotted in Fig. 2¹⁶ show that the particle diameter at which the transition from brittle to ductile behaviour occurs depends on the nature of minerals. In the material subjected to investigation, this particle diameter was between 200 and 2 μm .

For a given external condition of loading, one may determine the critical particle diameter, d_{crit} , experimentally or by calculation, below which fragmentation of particles is impossible. The only process that results from further stressing is the plastic strain. Under the action of compressive forces the critical particle diameter for brittle materials is between 13– μm . With dynamic stress acting on particles in course of grinding the critical particle size may be decreased below one micrometer.

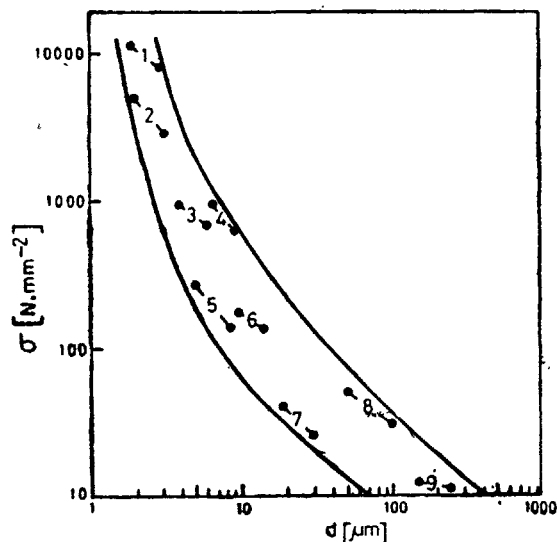


FIG 2 Strength of particles in the region of brittle to ductile transition.¹⁶

1—boron carbide, 2—crystalline boron, 3—quartz, 4—cement clinker, 5—calcite, 6—marble, 7—anthracite, 8—raw sugar, 9—potassium chloride

STRESS AND STRAIN IN SOLIDS DURING GRINDING

In grinding mills particles are stressed when they come into contact with moving or rigid tools or when they collide with each other. Particles undergo elastic or anelastic deformation with a simultaneously formation of a contact stress field. From the sites of primary concentration of stress, energy waves travel both into the bulk of particles and tool. Depending upon the conditions of stressing, energy waves are reflected so that the energy distribution is highly structured. While energy waves travel through the interacting bodies energy dissipation takes place so that a part of energy is converted to heat.

The type of stress field relaxation in each given case depends upon the external and internal conditions of stressing, i.e., upon the magnitude and direction of forces acting, upon the rate of stress and frequency of loading, and upon the real structure, geometry and number of particles being ground. Apart from the deformation processes and heat release discussed above, fragmentation of particles and grains, chemical reactions and/or phase transformations may proceed during energy-intensive grinding.¹⁷⁻¹⁹ Fig. 3 shows the transition from one relaxation pathway to another in a simplified case when a change of stress field brought about by external factors is represented by an increase in magnitude of the acting forces and the rate of stress.

Fragmentation is induced when a critical amount of energy is concentrated and generates local deformations at sensitive points of the internal structure of particles. The forces acting induce crack nucleation, gradual distortion and, finally, breakage. The number of cracks, and the rate and direction of their propagation, is at every moment determined by the concentration and orientation of local stresses. The energy concentrated at the tip of the propagating crack results in creation of extreme conditions favourable for mechanochemical reactions that take place at this site. Similarly, mechanochemical reactions are evoked by an impulsive temperature and pressure increase at the contact zones between particles. The spatial distribution of cracks determines the size and shape of fragments that are being created. The structure, morphology and chemical composition of fracture surfaces depend upon the extent of the previous plastic strain, i.e., on the micromechanism of fracture. At critical particle diameter (d_{crit}) or at high rates of stress when the time during which the particle is stressed is shorter than the critical time (t_{crit}) required to form a crack, an increase in dislocation density and the formation of other defects as a result of dislocation motion takes place. The complete relaxation of elastic energy expanded in the formation of lattice defects in plastic strain may take hours, days or even years. Elastic stresses that remain "frozen" in the vicinity of long-lived defects become the source of excess Gibbs energy accumulated in finely ground particles. Such a contact-free excitation of solid is termed mechanical activation.

In grinding mills, repetitive loading of particles takes place. For the sake of simplification, a uniform distribution of mechanical impulses at an arbitrary time of grinding may be assumed, and the energy transfer to particles being ground can be considered to be periodic-impulsive.²⁰⁻²²

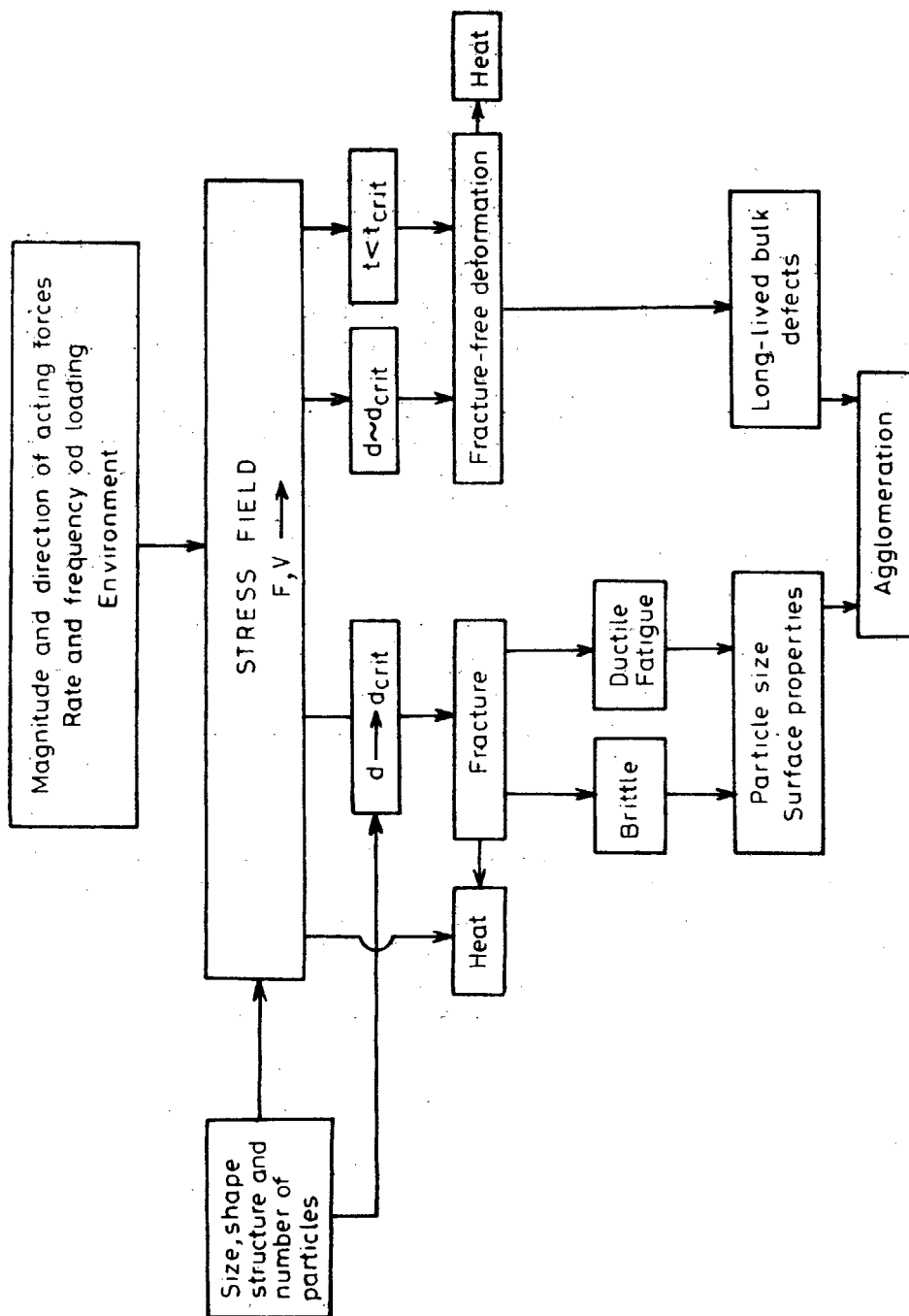


FIG 3 Principal mode of elastic stress field relaxation (F —force, V —rate of stress, d —particle diameter, t —duration of mechanical pulse).

Under periodic-impulsive loading the contact stress field is pulsating, and is characterized by alternating intervals of elastic stress field formation and its subsequent relaxation.

The elastic stress is completely reversible if the rate of stress is low and the acting forces do not include changes in the distribution of magnetic moments and in concentration and distribution of lattice defects. Variable mechanical stress, however, results after a certain number of cycles in an anelastic and/or plastic deformation, depending upon the stress created.^{23,24}

Assuming that fine particles of macroscopically brittle materials behave as metallic bodies under the action of cyclic loading, the variation of stress and strain can be plotted as in Fig. 4(a). The time lag of strain behind stress, caused by anelastic and/or plastic deformation, is depicted in Fig. 4(b) as a hysteresis loop in one loading cycle. The area enclosed by the hysteresis loop is the energy irreversibly dissipated in the solid, resulting in an increase in dislocation density of the structure. The magnitude of the time lag is a function of the frequency of loading. At extremely low frequencies ($\omega \rightarrow 0$) the particles may completely relax, whereas at extremely high frequencies ($\omega \rightarrow \infty$) relaxation does not take place and additional deformation does not appear. High frequencies are therefore favourable for mechanochemical reactions that proceed during grinding. The most favourable condition for an increase of irreversible deformation energy are given in an intermediate case when the product of frequency and relaxation time is equal i.e., one : $\omega \cdot \tau_r = 1$.

In analysing the general form of a hysteresis loop, one may divide its overall amplitude into an amplitude of elastic deformation and an amplitude of plastic

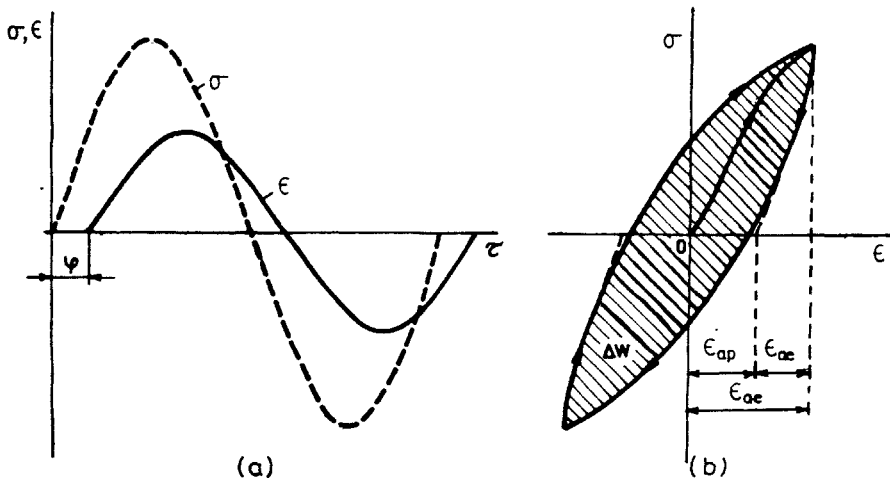


FIG 4 Time lag of strain behind stress (a) and a hysteresis loop in one loading cycle (b)²⁴

(ϵ_{oe} —amplitude of the total strain, ϵ_{ae} —amplitude of elastic strain, ϵ_{ap} —amplitude of plastic strain).

deformation. The shape of the hysteresis loop changes and the area enclosed by it gradually increases as the response of the material to cyclic stress passes from the inelastic to the elastic-plastic and finally to the typically plastic form (see Fig. 5). Under the action of stress with sufficiently high amplitude, the hysteresis loop becomes open and the area enclosed by it increases with each loading cycle. Such conditions of cyclic stress are optimum for mechanical activation.

Under the action of cyclic stress, the actual mechanism of failure varies with the size of particles and their structure change. Brittle fracture, with its characteristic fast propagation of unstable cracks, is typical for the initial stage of the grinding process when the particle size is larger than the critical one and the particles are weakened as a result of *a priori* cracks. With the increasing number of loading cycles, the particles size reduces and *a priori* cracks disappear. At the same time, defects resulting from various mechanism of cyclic microplastic strain accumulate at the surface. By analogy with the well-known mechanism of plastic fatigue in metals,²⁴ one may assume that initiation of fatigue microcracks takes place in regions with a high concentration of microplastic strain. Depending upon the external and internal conditions of stressing, the process can be arrested at this initial stage (i.e., when $d \sim d_{crit}$). Alternatively, cracks can propagate in a multistage, energy intensive process with an incomplete relaxation of stress thus causing changes in the surface state of the particles formed.

From the periodic-impulsive character of energy transfer in the mill it follows that the force, F , by which the grinding tools act on the particles being ground is acting only during short time intervals of the duration t_1 . These time intervals alternate with "dead" intervals during which the created stress become relaxed. "Intrinsic time, t_{int} , i.e., the time during which the actual stress is acting on particles is not equal to the duration of grinding. They are related by the equation :

$$t_{int} = \frac{t_1}{T} \tau, \quad \dots(1)$$

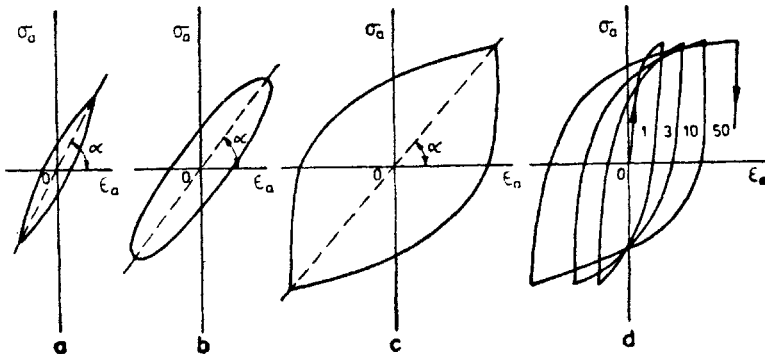


FIG 5 Variation the shape and size of a hysteresis loop with the amplitude of stress (a) (b) (c) and with the number of loading cycles (d).²⁴ (Numbers indicate the number of loading cycles).

where t_1 is the duration of the mechanical impulse, T is the period and τ is the duration of grinding.

TABLE I

Relationship for approximate evaluation of the specific grinding work W_T in various mill types²⁷

Mill type	N	V	W_T
Bell mill	$N \sim n\tau$	$V = \sqrt{2gD}$	$W_T = \frac{m_1}{m_2} n\tau g D$
Vibration mill	$N \sim n\tau$	$V = 4\pi na$	$W_T = \frac{m_1}{2m_2} n\tau (4\pi na)^2$
Planetary mill	$N \sim n\tau$	$V = \sqrt{2bD}$	$W_T = \frac{m_1}{m_2} b n\tau D$
Stirred mill	$N \sim n\tau$	$V = \pi n D$	$W_T = \frac{m_1}{m_2} n\tau g\pi D\mu (V)$
Peripheral speed mill	N	$V = \pi n D$	$W_T = \frac{N}{2} (\pi n D)^2$
Fluid energy mill	N	$V = V_{Gas}$	$W_T = \frac{N}{2} V_{Gas}^2$

N —number of impulses, n —speed, τ —grinding time, V —rate of stress, g —gravitational acceleration, b —acceleration, D —drum diameter, a —amplitude, $\mu (V)$ —friction coefficient, m_1 —mass of grinding media, m_2 —mass of material charge

The mill power is used to produce the mechanical action. Under the action of forces that originate from the drive, the bodies having the mass, m , move with the velocity, v . When their kinetic energy, $E = 1/2 mv^2$, is split into time unit τ , we obtain the energy input of the mechanical impulses that were imparted within the unit of time. If, in analogy with the “intrinsic” grinding time we introduce the term “intrinsic” or net mill power, P_{int} , we can define it by the following equation:

$$P_{int} = \sum_{j=1}^J \frac{dE}{d} = \sum_{j=1}^J \frac{dmv^2}{2d} = \sum_{j=1}^J mv \frac{dv}{d} = \sum_{j=1}^J FV \quad \dots(2)$$

The number of impulses per unit time, J , is a function of the technical parameters of the mill.

Part of the input energy that is converted to mechanical action can be calculated as follows:

$$W = P_{int} t_{int} = \sum_{j=1}^N FV t_1 \frac{\tau}{T} = NF t_1 V \frac{\tau}{T}, \quad \dots(3)$$

where $N = J\tau$ is the number of all impulses.

When P_{int} is divided by the volume of material being ground the energy bulk density in various grinding mills may be estimated. From Fig. 3 and equation (2),

it follows that special mills in which the energy bulk density is several times greater than in conventional tumbling mills are convenient for mechanical activation purposes. They are termed energy intensive-grinding mills.²⁵

By dividing W by the mass of material being ground, we obtain the transferred or specific energy of grinding. The evaluation of the net power, however, can be done only on the basis of a detailed analysis of forces acting in various mills. From the above discussed mechanism of plastic strain follows that especially the role of shear stress must be taken into account.²⁶

Approximate evaluations of the specific grinding energy has been done on the basis of the analysis of acting forces for predominant mode of stress in various grinding mills. Equations summarised by Heegn^{27,28} are presented in Table I. They take into account the rate of stress, frequency of loading and the duration of grinding, the two later mentioned being directly proportional to the overall number of mechanical impulse.

The concept of periodic-impulsive energy transfer in grinding mills is a mental abstraction that described an idealised case in which the material being ground is uniformly distributed throughout the mill and the spatial conditions of interactions between particles and grinding tools as well as between the members of particulars assembly do not vary. There are, however, many factors influencing the energy transport especially in mills where particles are stressed in a material bed. The increase of the number of particle layers as a consequence of particle size reduction, agglomeration of fine particles and coating of grinding tools under dry conditions of grinding or the changes of the rheological properties of the slurry during size reduction in liquid medium may be enumerated. The above-mentioned examples did not cover all aspects and influences that can modify the conditions of energy transfer and its conversion. The brief description leads us assume that during the repetitive loading of particles in an actual grinding process, the deviations from periodicity become the rule rather than an exception.

The periodic-impulsive energy transfer concept is, however, an advantageous working hypothesis allowing us a theoretical analysis of the energy dissipation processes during grinding on the basis of knowledge about the mechanism of cyclic microplastic strain. Better understanding of stress-strain relationships in actual grinding processes helps us select the proper mill and its operating conditions in order to obtain the specified results of mechanical activation.

REFERENCES

- 1 A N Matveev *Molecular Physics* Mir Publishers Moscow (1985)
- 2 H W Hayden, W G Moffat and J Wulff *The Structure and Properties of Materials, Vol. III. Mechanical Behaviour* Wiley Eastern Ltd New Delhi (1980)
- 3 J Kovács and L Zsoldes *Dislocations and Plastic Deformation* Pergamon Press Oxford (1975)
- 4 A A Prevoditelev, N A Tyapunins, G M Zinenkova and G V Bushneva *Physics of Crystals with Defects Izv Mosk Gos Univ Moscow* (1986) (In Russian)
- 5 A Smekal *Anz Österr Akad Wiss* 92 (1955) 733

- 6 R H Ventorf *J appl Phys* **30** (1959) 1765
- 7 R P Stejn *J appl Phys* **32** (1961) 1951
- 8 E J Duwel *J appl Phys* **33** (1962) 1691
- 9 T S Lin and C H Li *J appl Phys* **35** (1964) 2325
- 10 E J Duwell and H C Butzke *ASLE Trans* **7** (1961) 161
- 11 H Rumpf *Aufbereitung Tech* **7** (1966) 422
- 12 K Schönert and K Steier *Chem-Ing-Techn* **43** (1971) 773
- 13 K Schönert *Thesis, Univ Karlsruhe* (1966) (In German)
- 14 K Steier *Thesis Univ Karlsruhe* (1971) (In German)
- 15 W Hess *Thesis Univ Karlsruhe* (1980) (In German)
- 16 K Schönert Two aspects of particulate assembly comminution In : *Proc 3rd Symp Theor and Tech Aspects Comminution Mechanical Activation of Solids* (Ed K Tkáčová) Folia Montana Sp Issue Veda Bratislava (1980) p 48
- 17 V V Boldyrev *J chim Phys* **83** (1986) 822
- 18 V V Boldyrev Mechanochemistry of Inorganic Solids In : *Proc 1st World Congr Part Tech II. Comminution* (Ed K Leschonoski) N M A Nürnberger Messe und Ausstellungegesellschaft mbH Nürnberg (1986) p 553
- 19 P Yu Butyagin *Usp khim* **53** (1984) 1763
- 20 N Z Lyakhov and V V Boldyrev *Izv Sibor ot Akad Nauk SSSR Ser khim* (1982) 3
- 21 V V Boldyrev *Termochim Acta* **110** (1987) 303
- 22 V V Boldyrev *Proc Indian natn Sci Acad Part A* **52** (1986) 400
- 23 A Puškár and S A Golovin *Fatigue in Materials. Cumulative Damage Processes* North-Holland Physics Publishing Amsterdam, (1985)
- 24 A Puškár *Microplasticity and Failure in Metallic Materials* Veda Bratislava (1986) (In Slovak)
- 25 K Tkáčová *Mechanical Activation of Minerals* Elsevier, Sci Publ Amsterdam (1989)
- 26 I J Lin and S Nadiv Alteration of mineral properties during grinding through mechanical reactions In : *Proc XVI int Miner Proces Congr* (Ed E Fressberg) Elsevier Sci Publ B V Amsterdam (1988) p 231
- 27 H P Heegn *Sci Thesis* Research Institute of Mineral Processing of the Academy of Sci GDR Freiberg (1986)
- 28 H P Heegn In : *Proc 1st World Congr Part Technology, Part II. Comminution* (Ed K Leschonoski) N M A Nürnberger Messe-und Ausstellungegesellschaft mbH Nürnberg (1986) p63