Particle Breakage and Attrition

H. Kalman
Department of Mechanical Engineering
Ben-Gurion University of the Negev*

Abstract

The attrition of particulate materials during their handling and processing may result in losses of material, poor product quality, poor flowability and environmental pollution caused by the generation of dust. It is not surprising therefore that so much research has been devoted to studying the breakage mechanism of particles, in order to reduce the attrition in conveying and handling systems. In this paper, an extensive literature review on the above topics is presented. The literature review also covers the experimental systems that are commonly used to evaluate these phenomena. Moreover, some new experimental results are presented to clarify future trends, to better understand the complex mechanisms at work, to reduce the required number of 'standard indices' and to enable better engineering design.

1. Introduction

Particle breakage is a common occurrence in science as well as in engineering. Depending on the situation, the same phenomenon is referred to as crushing, grinding, fracture, partition, division, disintegration, shattering, scission, fragmentation, degradation, and abrasion. However, while “comminution” is used to describe the desired breakage of particles, “attrition” is the undesirable damage of particles. Both comminution and attrition are a result of either impact, compression, frictional or shear forces, or sometimes a combination of these forces.

In the chemical processing industry, breakage can strongly influence the operation and economics of a manufacturing process [1]. Particle breakage can occur in a variety of modes depending on material characteristics and the level of applied stress. Such stresses are encountered in nearly all handling and processing systems and lead to attrition, which, physically, is identical to comminution except that it represents losses due to undesired particle breakage. Attrition is not restricted to any particular type of process, even though there are some processes where it occurs more readily or where its effects are quite serious. The effects of attrition can be a loss of product by removal of undersized particles from the process streams, the need for recycling lost products, the requirement for additional filtration, loss of flowabilit

* P.O. Box 653, Beer Sheva 84105, ISRAEL
† Received: August 8, 2000
ially explain the complexity of the problem that involves simultaneous fractures growing within a large number of interacting particles. As the breakage proceeds, the stress distribution and load transfer between particles changes significantly. Detailed theoretical studies are mostly limited to the propagation of single cracks inside a single particle, and studies that are more global are largely statistical in nature. Experimental studies provide only very superficial data such as fragment size distributions. The existing continuous numerical schemes such as finite element methods can also handle only the propagation of one or two cracks inside a single particle, and do not appear to be able to handle massive fracture [2].

Since a theoretical or numerical analysis of comminution or attrition processes up to a level that could be applied to practical design is impossible, it is common to evaluate the strength of particles and their damage (breakage and degradation) by measuring various indices of friability in a variety of standard systems. Another approach is to conduct simulation experiments with the system in question or a similar one. Many different types of tests have been described by the British Materials Handling Board [3] and in studies such as those by Bemrose and Bridgewater [10] to assess the breakage and attrition tendency of particulate materials.

In this paper, some recently published papers concerning both experimental and theoretical approaches to the breakage and attrition of particles are reviewed. The discussion is limited to compression of individual particles and particulate beds and to impact loads. Examples of comminution and attrition systems are given to emphasise the practical application. Throughout the paper, the fatigue phenomenon is emphasised. Some original experimental results by the present author are also shown.

2. Compression Strength

2.1 Compression of single particles

It is often necessary to monitor the strength of a product rapidly and reproducibly. This is particularly important if the breakdown of particles in subsequent handling is to be avoided. The conventional method is the so-called 'Brazilian test', in which single particles are crushed between two platens and the load required for fracture is recorded. However, in any batch of particles formed under nominally identical conditions, there is always a wide variation in the fracture loads measured in this way. Consequently, many particles must be tested before a reliable average can be obtained [11]. An example of compressive strength measurements is shown for potash in Figure 1. For only 20 measured particles, the strength range was found to be from 59 to 175 N.

Many researchers conducted experiments to evaluate the compressive strength of single particles of various materials: Shipway and Hutchings [12] tested brittle spheres, Adams et al. [11] tested agglomerates, and Kalman and Goder tested potassium sulphate [5]. It has been shown that the fracture behaviour of a single grain depends generally on its size, shape, material properties and the loading conditions [13]. Danjo et al. [14] measured the particle diameter and compressive load for 140 particles individually, and then the single particle strength was calculated. They found that the compressive strength decreased exponentially with an increase in particle diameter up to about 500 $\mu$m, and thereafter showed a constant value. The breakage behaviour of fine single brittle particles of five minerals and two coals in a size range from 88 $\mu$m to 1 mm was investigated by Sikong et al. [15]. They found that the relation between the particle strength and the particle size of these fine particles is similar to that of coarser particles.

Gundepudi et al. [16] studied brittle spheres using a different compression method, namely three-point in-plane loading. They found that there are maximum tensile stresses that correlate well with failure, and which are partially responsible for attrition in particulate systems. In the case of tablets, axial and radial compression yields compressive and tensile stresses. However, Kalman et al. [17] showed that the two stresses
The fracture of brittle materials is controlled by the propagation of a primary crack in a tensile field. Many research studies were conducted to develop theoretical models for crack propagation. Mecholsky et al. [18] found three local maximum tensile stress regions in particle-particle or particle-wall contact situations. The first is the region just outside the contact circle, the second is far-field surface stresses near the meridian of the sphere relative to the contact point, and the third is a region of internal stress below the contact surface and the compressive zone. Tsoungui et al. [13] proposed a theoretical model to define the failure criterion on an individual grain subjected to an arbitrary set of contact forces. The model is implemented in a two-dimensional computer simulation code based on the molecular dynamics method to study the crushing mechanisms of grains inside a granular material under compression. Song et al. [19] proposed a direct stochastic simulation method, which is applicable for general population balances with particle break-up, based on the analysis of the dynamic break-up process of particles in particulate systems. They suggested two steps: 1) to determine whether a particle breaks up using the breakage frequency function; and 2) to determine the volume of daughter particles for one breakage event using the probability distribution function. Another method for generating theoretical breakage distribution functions for multiple particle breakage is presented by Hill and Ng [1]. Mecholsky et al. [18] also found a correlation between the numbers of pieces generated during fracture, the stress at fracture and the fractal dimension for a particular loading geometry. However, in the case of an individual grain with an arbitrary number of contact forces, the calculation of the stress distribution inside the grain and the prediction of its fracture condition remains a difficult task [13].

However, before making any attempt to use these models in practical systems, several further steps should be defined and developed:

1. Crack propagation is a stochastic phenomenon that depends on the structure of the particle, pores, stresses and contaminant distributions. The breakage models should therefore be developed to a stage where a reasonable average for further practical use can be defined despite the variety in the structure of individual particles.

2. The models should be suitable for irregular particle shapes and various sizes.

3. Since particles in the size order of a few millimetres and lower are usually not crushed as single particles, the model should relate the breakage to multiple contact points with variations of stress distribution at the boundaries being accounted for.

4. Finally, the crack propagation models should yield the number and size of daughter particles. In a particulate bed, the daughter particles of a broken particle will affect the remainder of the unbroken particles by increasing the contact points and changing the stress distribution at the particle boundaries.

Since the above requirements are quite complex, more research effort should be devoted to developing empirical or semi-empirical correlations.

### 2.2 Compression of particulate beds

A simple alternative method to the single particle compression test consists of replacing the single particle with a confined bed of similar particles and then inferring an average single particle strength parameter from the behaviour of the whole bed under compression. This is most easily achieved experimentally using a piston in a cylinder, in which the test becomes one of uniaxial confined compression [11]. Kanda et al. [20] studied the compressive crushing of powder beds (quartz) for a roller mill application. They studied the effect of applied load, the mass of the feed and the particle size on the probability of crushing and on the crushing resistance. Holman [21] showed — for these and similar handling systems — that the percolation theory in combination with the principles of mechanics adequately describes the relationship between the normalised solids fraction and the logarithm of the applied pressure. According to this theory, the materials can be classified by their softness or rigidity on the one hand, and their flexibility or brittleness on the other, depending whether a rigidity threshold, a brittle-ductile transition or a percolation threshold is exceeded.

The pragmatical approach used by Liu and Schönert [22] for modelling interparticle breakage has proved its ability of predicting the size reduction of an arbitrary feed distribution within a technically reasonable range and with a good degree of accuracy. It should therefore be possible to use it for modelling closed-circuit comminution systems with high-pressure roller mills. In an additional experimental study, this application was tested and it was found that model calculations were able to predict the experimental results well [22].

By carrying out confined uniaxial compression tests with monosized materials, the percentage of broken particles versus the pressure can be determined. A
The experiment was conducted up to a pressure where compression test of potash is presented in Figure 2. The bonds between particles were observed. The percentage of broken particles was determined by the ratio of compression loads, the percentage of broken particles being, without any distinction being made between fragmentation and degradation. At the presented range of load encountered during handling (dilute-phase pneumatic conveying, chutes, etc.) and during comminution in a jet mill. It is believed that by performing tests on either single particles or groups of particles that collide with walls or with other particles, a representative measure of the particle friability can be obtained [3]. Therefore, much effort has been devoted to improving the test rig and the measuring systems. Guigon et al. [23] presented a comprehensive literature survey of studies that investigate the impact of particles on various targets. The reported experimental velocities varied from 1.1 up to 600 m/s. Tavares et al. [24] and Tavares [25] used sophisticated measurement equipment. The test rig consists of a long steel rod equipped with strain gauges on which a single particle or a bed of particles is placed and then impacted by a falling steel ball. Until now, this system has been used to investigate the deformation and fracture of single particles subject to impact crushing. According to many investigations, the following parameters were found to affect the attrition rate due to impact:

3. Impact Strength

Impact tests are common and are aimed at subjecting materials to forces that are similar to those they would encounter during handling (dilute-phase pneumatic conveying, chutes, etc.) and during comminution in a jet mill. It is believed that by performing tests on either single particles or groups of particles that collide with walls or with other particles, a representative measure of the particle friability can be obtained [3]. Therefore, much effort has been devoted to improving the test rig and the measuring systems. Guigon et al. [23] presented a comprehensive literature survey of studies that investigate the impact of particles on various targets. The reported experimental velocities varied from 1.1 up to 600 m/s. Tavares et al. [24] and Tavares [25] used sophisticated measurement equipment. The test rig consists of a long steel rod equipped with strain gauges on which a single particle or a bed of particles is placed and then impacted by a falling steel ball. Until now, this system has been used to investigate the deformation and fracture of single particles subject to impact crushing. According to many investigations, the following parameters were found to affect the attrition rate due to impact:

1. Particle Velocity – The fundamental studies of Salman et al. [26-29] and Ghadiri and Papadopoulos [30] demonstrate that the attrition rate increases with increasing velocity. Gorham and Salman [31] found that at the lowest velocities, fracture is mainly due to a brittle-elastic response. At higher velocities, inelastic deformation under the impact site leads to characteristic patterns of fragmentation arising from radial, lateral, and meridian cracks.

2. Particle Size – The particle strength decreases as the particle size increases [24,32,33] because larger particles have more micro-cracks and impurities. Nevertheless, the length and number of micro-cracks may vary; therefore, some results showed that particle attrition is independent of particle size [34,35].

3. Particle Shape – Vervoorn and Scarlett [33] found that particle shape is an important factor in attrition, especially when the presence of sharp edges and corners allows large local stresses to be created that easily cause particle attrition. Tavares et al. [24,25] also showed the effect of particle shape on the particle fracture energy, the particle strength and the particle stiffness.

4. Target Rigidity – Salman et al. [26-29] and Mebtoul et al. [36] established the influence of target nature, thickness and orientation on the attrition rate of particles colliding with targets.

5. Particle Orientation – Cleaver et al. [32] found that the attrition mechanism depends also on particle orientation. For impacts on sharp corners and edges, particle damage appears to result from semi-brittle failure at all velocities tested. For impacts on crystal faces, however, a threshold velocity was identified, above which brittle fracture occurred, and below which no visible damage was detected.

6. Impact Angle – The studies of Salman et al. [26-29] showed that the probability of particle failure varies only slightly from normal impact to about 50°.

The mechanical strength of agglomerate materials under impact was investigated by means of computer simulation using Distinct Element Analysis. The breakage of agglomerates upon impact is shown to increase with impact velocity until a certain limit is reached, beyond which the damage seems to approach an asymptote [37]. An examination of the mechanisms that lead to the pattern of impact breakage in two-dimensional discs was presented by Potatov and Campbell [38].

It should be noted at this stage that most of the experiments reported above with high velocities were conducted with systems where the particles are accelerated in an air stream (air gun) and oriented towards...
These experimental systems are limited to large particles with high densities. Otherwise, the particles tend to follow the air stream, and do not collide with the target, or are deflected by the air stream to collide at a different angle. These systems should, therefore, be modified to enable fine powders to also be tested.

4. Comparison Between Methods

Comparison between the various methods of measuring particle strength is very important. Although during the years, similarities have been found between the comminution and attrition behaviour in practical systems and some strength measurement methods, all methods relate, in one way or another, to the strength of the particles. Reliable theoretical models or empirical correlations relating the strengths measured by various methods could significantly reduce the number of required measurements and strength indices in current use. Therefore, research and investigation for comparing various strength measurement methods is very important.

4.1 Compression of individual particles and particulate beds

The bulk crushing test is commonly used in industrial applications to assess the attrition resistance of particles. A small quantity of particles is placed in a rigid container and loaded quasi-statically by a piston to a pre-specified level of stress. The extent of breakage is then analysed after the unloading stage. However, despite the simplicity of the test procedure, the analysis of particle breakage is very difficult because the test is carried out on an assembly in which not all particles are uniformly loaded. It is therefore difficult to relate the test results to particle properties; a task that is highly desirable for the optimisation of production as it enables the particle properties to be tailored for improved performance [39]. A full solution to this problem would require the formulation of an assembly model relating the distribution of contact stresses to the distribution of single particle failure stress within the bed. In practice, this problem is so complex that it can only be addressed by computer simulation [11].

Danjo et al. [14] found experimentally that a linear relationship existed between the compressive load and the number of particles. The average particle strength was found to be lower than the single particle strength in every sample. This is due to a variety of factors such as the distributions of particle size, shape, and compressive strength in multiple particle systems. They also examined the particle strength evaluated from the inflection of the compression curve of a particulate bed. Particle strengths obtained from the inflection points were closely related to the single particle strength.

Adams et al. [11] presented a simple theory that provides a means by which the average shear strength of a single agglomerate can be obtained by experiments on a bed of agglomerates, and this value is related to the single particle crushing strength through a single empirical proportionality factor. Such numerical methods as the Distinct Element Method [39] and Distinct Elements Analysis [40,41] were also applied to find the relationship between bulk compression and single particle compressive strengths. Single particle mechanical properties such as Young's modulus and compressive strength distribution have been characterised by Couroyer et al. [39] and used in the simulation to predict the bulk crushing behaviour. The results show that an increase in the value of Young's modulus and the coefficient of friction leads to a significant increase of breakage in the assembly, and that a decrease in the loading rate leads to a lower extent of breakage. The strength of three samples with different levels of macroporosity was compared under quasi-static loading by Couroyer et al. [41]. The experimental data were used to test the DEA.

In order to develop a reliable model, the individual particle compressive strength should be related to particulate bed experiments through the distribution of contact points that transfer the loads and the compression level. The distribution of contact points depends on the size distribution of particles and their orientation and structure in the bed. The problem then becomes more complicated since at low loads and low bed-compaction, particles fracture when the area-averaged load exceeds their single-particle fracture strength. At higher loads and degrees of compaction, fine particles begin to transmit force, and distribute the force flux over the surface of large particles [42].

All of the above-described models assume the compression stress within the die to be constant. However, preliminary results obtained by the present author show that the pressure varies along the die height and sometimes also radially at the pressing piston. The single particle load at the die walls was measured by indentation. In order to increase the indentation sensitivity, a thin copper plate was used to replace the die walls. In these tests, very hard zirconium spheres of 1-1.2 mm in diameter were used in a
Fig. 3  Indentation of hardened zirconium spheres of 1-1.2 mm in diameter. The die diameter is 25 mm and bed height 35 mm. Compression pressure=3000 kg. The picture shows the indentation at a height of 32 mm from the static piston.

25-mm-diameter die. An example of the indentation at the die walls is shown in Figure 3. The indentations have a "droplet" shape which indicates that the bed deforms during application of the load. The indentation area is, however, proportional to the force that presses the spherical particle against the die wall. The force and indentation area were calibrated in a similar way for the hardness measurement of surfaces, and some typical results are shown in Figure 4.

Figure 5 is presented to show the indentation area at the die wall as a function of height from the bottom surface (the bottom surface was kept stationary while the load was applied through the upper surface). It is clear that the average indentation area, and consequently the pressure, increase towards the upper surface. This emphasises the need to describe the pressure distribution within the die in a more accurate way prior to any attempt to relate it to the stress experienced by individual particles within the die for their breakage analysis.

4.2 Compression and impact

Shipway and Hutchings [12] presented results of a theoretical and experimental study of the fracture of single brittle spheres by uniaxial compression between opposed platens and by free impact against plane targets. They found that the stress distributions in elastic spheres are broadly similar under both types of loading, with significant tensile components inside the sphere on the axis of the system and on the surface of the sphere, around the equator for the case of compression. Salman et al. [26] have also found similarities in the features of failure of aluminium oxide particles subject to static compression and normal impact. Gorham and Salman [31] carried out impact and compression tests and described the forms of failure and their variation with diameter and impact velocity. Shipway and Hutchings [43] tested glass and sapphire spheres. They reported that the fracture depended strongly on the properties of the platen or target. Shipway and Hutchings [44] derived numerical values for the elastic stress fields in spheres under conditions of quasi-static compression and free impact against plane targets.

5. Fatigue Strength

In most of the handling and conveying systems involving attrition, each particle experiences more than one event of loading. The loading might be of compression and shear force, as in silos, or of impact force, as in pneumatic conveying systems. Many research studies related the attrition rates to the residence time in continuous systems or to the test time in batch systems [45]. However, their tests should be related to the number of loading events, which is a more fundamental parameter as it relates to fatigue [5]. The kinetics of batch milling was proposed to be
expressed with respect to energy instead of time [46]. Moreover, Potapov and Campbell [47] noted that the attrition rate is simply related to the total work performed on the system. This appears to be independent of the mechanisms of breakage, how the work is applied, and even whether the material is experiencing quasi-static or rapid flow behaviour.

Comminution processes involve a combination of discrete breakage events by particle fracture and continuous degradation. A simplified model for a mathematical description of the overall process, as well as process simulations as used to illustrate the effects of the different mechanisms on grinding kinetics and product size distribution, are described by Hogg [4]. He also pointed out that product size distributions assume an increasingly bimodal character as the relative contribution from degradation increases. In order to evaluate a continuous grinding process, a model is proposed which combines experimentally determined breakage kinetics [48]. Berthiaux and Dodds [49] developed a methodology for characterising grinding kinetics based on a new criterion, the so-called "residual fraction" to represent the performance of a grinding process. Similar analyses could be applied to attrition in the handling and processing of particulate materials.

5.1 Compression

Although in storage and handling systems, particles may experience repeated compressive loadings, almost no previous reports concerning fatigue behaviour were found. Experimental results concerning the repeated compressive loading of particulate beds were reported by Kalman and Goder [5,50,51]. They used a testing rig that is shown in Figure 6.

A sample of the tested material is compressed in a cylindrical die under repeated compressive forces. Both rate and maximum value of the compressive force are adjustable. The number of cycles is pre-set for every test. The test rig was designed in such a way as to enable the application of compressive stresses to a bulk material inserted into a cylindrical die. After filling, the matrix is tapped to achieve better repeatability of the initial conditions. The upper piston is loaded by a pneumatic piston through a beam that compresses the material. By varying the location of the pneumatic piston, its air pressure, and the die dimensions, one is able to control the compression stress. A pressure switch controls the load of the pneumatic piston between the pre-set upper and lower pressures. The frequency of operation is controlled by a needle valve. With this arrangement, the pneumatic piston increases the load until the upper set point of pressure is reached and then the pressure is reduced to zero, and so on. The frequency was set to very low values to avoid impact effects. An electrical counter that enables long experimentation overnight for thousands of pre-set cycles was incorporated into the system. After each test was terminated, the percentage of material under a certain size was measured.

For engineering use, a fatigue curve is useful. The "fatigue curve" is a term taken from mechanical engineering, and which is applied to metals to describe the load versus the loading cycles for damage to a standard specimen. Since the tested material is a single specimen, a single curve is plotted for any probability of occurrence. In fatigue experiments of particulate assemblies, however, many specimen particles exist in a single test. It would be impossible to plot a single curve. However, several curves can be plotted to describe an amount of damage by each curve as shown in Figure 7. From an engineering point of view, the compression load and the number of loading cycles can be found for a postulated amount of dam-

![Fig. 6 Experimental apparatus for repeated compression cycles.](image)

![Fig. 7 Fatigue curve of potassium sulphate.](image)
Therefore, it was impossible to conduct experiments age from such curves. Each curve is expected to stabilise, as mentioned earlier, because the stress distribution on each undamaged particle is moderated due to the broken particles that provide more contact points.

The fatique curve of potassium sulphate is shown in Figure 7. The percentage of undersize particles is an uncontrolled parameter in the experiments. It is a result of the compression stress and number of cycles and is measured only after the test is terminated. Therefore, it was impossible to conduct experiments with a constant amount of damage. The percentage of undersize particles is indicated in the figure for each experiment. From these, the fatigue curves were estimated and plotted manually. As expected, the amount of damaged particles increases with both the compression stress and number of cycles. As expected, the curves also stabilise after a certain number of compression cycles.

In order to complete the insight into the fatigue behaviour, many more tests with various materials must be conducted. Furthermore, new experiments on the fatigue of individual particles subjected to repeated compression loads will be conducted. Finally, a correlation between single particle strength and particulate bed strength during cycled loading can be determined based on the modified or existing empirical models that relate the single particle and particulate bed strength in a single static compression.

5.2 Impact

Most experiments published in the literature and the standard available equipment are related to repeated impact loads. Salman et al. [27-29], Cleaver et al. [32] and Ghadiri and Papadopoulos [30] showed that attrition rates increase sharply with the number of impacts. Also experiments conducted in fluidised beds, which are common test rigs for attrition measurements [34,32], show that attrition rates increase with time. The time of fluidised bed operation can be converted, although in a very complex manner, to the number of impacts. A new test method that allows the characterisation of granules by their attrition resistance, fatigue lifetime and breaking mechanism was presented recently by Beekman et al. [53].

The following sections describe impact strength measurements in various experimental rigs and their relation to attrition in industrial systems. The impact velocity is divided into two ranges: low velocity (1-10 m/s) that is applicable in chutes, dense-phase pneumatic conveying, fluidised beds and some processes conducted in rotating drums such as coating and granulation; and medium velocity (10-40 m/s) that is applicable in dilute-phase pneumatic conveying. A high impact velocity (80-300 m/s) may occur in comminution systems such as jet mills and pin mills.

5.2.1 Low velocity – rotating drum

Rotating drums are used as a means of conducting some processes such as coating, granulation and mixing, as well as for characterising the attrition and strength of particles. This apparatus is widely used in the pharmaceutical industry to characterise the strength of tablets. This method was also used for large tablets (1 inch in diameter) by Kalman and Targan [22]. They found that the attrition rate of tablets is well correlated to the compression or tensile strengths.

Figure 8 presents an example of several results obtained by Grant and Kalman [54] with a rotating drum made of steel of 285 mm in length and 265 mm in diameter. One shelf of 40 mm in width was used. The multiplication of the rotation speed by the period of operation provided the number of rotations. After a predetermined period of operation, the sample was sieved to provide a size distribution, and in some cases the strength of the particles was measured by a Crush Strength Analyser. An example of the size distribution variation during a test with potash is shown in Figure 8. The test was conducted at 30 rpm with a sample weight of 100 gr. The initial size of the sample was in a narrow range between 2 and 4 mm, so the sample could be considered monosize material. The figure shows the total weight percentage under the size indicated at each line (cumulative undersize). The upper line, showing the cumulative weight under 2 mm, shows the total weight percentage of the particles that were found to be smaller in size than the initial lower limit. As expected, the percentage of damaged particles increases as the number of rotations...
increases. This is probably due to fatigue. However, it seems that the rate of attrition of the particles decreases.

In order to gain an insight into the breakage mechanism, the compressive strength of the particles was also measured. In these experiments, the sample was sieved after a postulated number of rotations and the compressive strength of the surviving particles at the initial size range was measured. Each average compressive strength shown in Figure 9 is an average of at least 20 particles and in some cases even more than 60 particles. Although the compressive strength distribution of any shown point was significant, the average values make the attrition mechanism somewhat clearer. The initial particles are the strongest, and finally decreases again until the strength stabilises. The behaviour is too complicated to permit a complete explanation at this stage, but could be the result of two different effects:

1. The strength of each particle could decrease due to fatigue. Thus, repeated impact loadings enlarge the micro cracks within the particle until it breaks.
2. Since there is initially a strength distribution of particles, the weaker ones break first. Therefore the average strength of the remainder increases.

If we also take into account that different materials display different sensitivity levels to repeated loading, then we might have an explanation for the strange behaviour shown in Figure 9. The micro cracks grow faster than the breakage during the first rotations, and result in a decrease in strength. Then, most particles that were initially weak or suffered from fatigue are damaged, which results in an increase of the compressive strength of the surviving particles. At the end of the process (after 2000 rotations), fatigue slightly influences the breakage until both effects stabilise to a steady-state condition, i.e. the rate of fatigue equals the rate of attrition.

5.2.2 Medium velocity – dilute-phase pneumatic conveying

The main parameters affecting the breakage and chipping of particles in pneumatic conveying systems are air and particle velocities, loading ratio and particle properties such as size distribution, shape and material. Since it was noticed a long time ago that the main attrition occurs at the bends, most studies were dedicated to flow and attrition mechanisms at various bends. Mckee et al. [55] showed that particle breakage is described to be inversely related to the solids loading factor.

Hilbert [56] examined three bends experimentally: a long-radius bend, a short-radius elbow and a blind-tee. He found that regarding wear, the blind-tee is the best device (less attrition), with the short-radius elbow coming a close second and the long-radius bend coming in third. A comprehensive study was carried out by Agarwal et al. [57] on a long-radius bend. They studied the acceleration length due to bends (caused by bends?) and the effects of phase density, conveying velocity and the use of inserts on the wear of the bends, particle degradation and depth of penetration. Vervoorn [45] carried out pneumatic conveying experiments for dilute-phase alumina flow, changing some parameters such as particle velocity and bend structure. Recently, Bell et al. [58] and Papadopoulos et al. [59] presented attrition experiments with salt in which the size distribution was measured on-line. They have also shown that the air velocity has a prime effect on the attrition rate, although the effect of loading ratio and the bend structure cannot be ignored. Kalman and Goder [60] measured the pressure drop, attrition rate, wear of the bend and build-up on the bend walls for four types of bends: long-radius (three construction materials), short-radius elbow, blind-tee, and a turbulence drum. Aked et al. [61] showed that even fine powders (15 μm) suffered significant attrition under certain conditions. Kalman and Aked [62] presented a comparison between different attrition measurement methods and analysed the attrition of various materials. Kalman [63] discussed the possibilities of controlling the attrition rate and of using it for useful processes such as particle rounding, consequently reducing the dust generation during the downstream handling and conveying stages. Most of the parameters affecting attrition in pneumatic con-
Peix pipelines for a variety of materials were summarised by Kalman [64].

As for dense-phase flow, measurements were made of the specific energy consumption and particle attrition for a limited range of particulate materials by Taylor [65]. Coppinger et al. [52] presented experimental evidence to show that a fluid bed attrition test performed on small amounts of a wide variety of powders and granules gives a very good indication of both total attrition and bulk density changes for the materials transported in dense-phase conveying loops. The standard compression test did not yield additional information beyond that gathered from the fluid bed attrition test as far as particle breakability was concerned. It was also found that there is a good correlation between attrition in the dilute-phase conveying system and the mechanical sieving test, which enables the comparison of results gained in various systems, other influencing parameters such as the collision angle and target rigidity, should be converted to the effect of normal impact load.

New results of the attrition of potash at 30 m/s in a 1-inch pipe diameter due to only one bend (caused by only one bend?) of different type is presented in Figure 10. The results are shown in terms of the decrease of the weight median size. It is clear that different bends cause different attrition rates, although in the presented results, the difference is not significant. However, the effect of the number of times that the material passed through the bend significantly affects the attrition rate.

5.2.3 Fatigue curve
By analysing Figures 8 and 10, it looks as though a fatigue curve for impact might be developed. Disregarding other effects, the impact velocity defines the impact load for a certain particle and a certain target, i.e. higher impact velocities reflect higher impact loads. Therefore, at lower impact velocities, more collisions cause the same damage as fewer collisions at higher impact velocities. A further investigation and analysis should be conducted in order to develop a fatigue curve, similar to the one shown in Figure 7. This could have a significant benefit, since it might unify a number of practical comminution and attrition systems into a common class. Obviously, the picture should be completed with tests with jet mills that give the highest range of impact velocities. In order to enable the comparison of results gained in various systems, other influencing parameters such as the collision angle and target rigidity, should be converted to the effect of normal impact load.

5. Conclusions
A literature review concerning breakage models in comminution and attrition systems is presented. The common strength characterising systems for compression and impact are reviewed in detail. The difficulties concerning the application of theoretical models for crack propagation to practical problems is discussed. The review and the results presented in the paper can be summarised as follows:
1. In order to reduce the number of required testing and strength indices, future investigations should be devoted to developing empirical correlations between various measurements such as: individual and particulate bed compression, particle compression and impact, etc.
2. The stress distribution in the die used for particulate bed compression should be taken into account for comparison with single particle compressive strengths. The indentation method shown in this paper might give the required means of measurement.
3. Fatigue curves for compression and impact loads could improve design tools for comminution and attrition systems.
4. Industrial impact systems such as rotating drums, ball mills, pneumatic conveying, pin and jet mills might be incorporated as an integral part of a common fatigue curve to characterise most systems where degradation and breakage occur.

6. References
1) P.J. Hill and K.M. Ng: Statistics of Multiple Particle Breakage, AIChE Journal 42(6) (1996) pp. 1600-1611.
2) A.V. Potapov and C.S. Campbell: Computer Simulation of Particle Breakage, Proceedings of the First Int. Particle Technology Forum, Denver, USA (1994) pp. 225-230.
British Materials Handling Board: Particle Attrition: State-of-the-Art Review, Trans. Tech. Publications, Germany (1987).

4) R. Hogg: Fracture Mechanisms and Mill Performance in Ultrafine Grinding, Powder Technology 105 (1999) pp. 135-140.

5) H. Kalman and D. Goder: Design Criteria for Particle Attrition, Advanced Powder Technol. 9 (1998) pp. 153-167.

6) S. Rajagopal, K.M. Ng and J.M. Douglas: A Hierarchical Procedure for the Conceptual Design of Solids Processes, Comput. Chem. Eng. 16 (1992) 675 p.

7) B.J. Ennis, J. Green and R. Davies: Particle Technology: the Legacy of Neglect in the US, Chem. Eng. Prog. 90 (1995) 32 p.

8) S.Y. Yoshima, Y. Kanda and S. Sano: Relationship Between Particle Size and Fracture Energy or Impact Velocity Required to Fracture as Estimated from Single Particle Crushing, Powder Technology 51 (1987) 277 p.

9) M. Ghadiri, K.R. Yuregir, H.M. Douglas, A. Verba and N. Rolfe: Influence of Processing Conditions on Attrition of NaCl Crystals, Powder Tech. 65 (1991) 311 p.

10) C.R. Bemrose and J. Bridgewater: A Review of Attrition and Attrition Test Methods, Powder Technol. 49 (1987) pp. 97-126.

11) M.J. Adams, M.A. Mullier and J.F.K. Seville: Agglomerate Strength Measurement Using a Uniaxial Confined Compression Test, Powder Technology 78 (1994) pp. 5-13.

12) P.H. Shipway and I.M. Hutchings: Attrition of Brittle Spheres by Fracture Under Compression and Impact Loading, Powder Technology 76 (1993) pp. 23-30.

13) O. Tsoungui, D. Vallet and J-C Charmet: Numerical Model of Crushing of Grains Inside Two Dimensional Granular Materials, Powder Technology 105 (1999) pp. 190-198.

14) K. Danjo, H. Kato, A. Otsuka and K. Ushimaru: Fundamental Study on the Evaluation of Strength of Granular particles, Chem. Pharm. Bull. 42(12) (1994) pp. 2598-2603.

15) L. Sikong, H. Hashimoto and S. Yoshima: Breakage Behavior of Five Particles of Brittle Minerals and Coals, Powder Technology 61 (1990) pp. 51-57.

16) M.K. Gundepudi, B.V. Sankar, J.J. Mecholsky Jr. and D.C. Clupper: Stress Analysis of Brittle Spheres Under Multiaxial Loading, Powder Technology 94 (1997) pp. 153-161.

17) H. Kalman, D. Goder and S. Targan: Preliminary Investigation on the Effect of Production Parameters on the Strength of Large Tablets, Part. Part. Syst. Charact. 15 (1998) pp. 150-155.

18) J.J. Mecholsky Jr., D.C. Clupper, B. Sankar and M. Gundepudi: Fracture Mechanics, Fractals and Failure Analysis as Tools for Understanding Attrition and Comminution of Particles, World Congress on Particle Technology 3, Brighton, UK. Paper 127 (1998).

19) M. Song, B.M. Li, A. Steiff and P.M. Weinspach: Stochastic Simulation of Particulate Dynamic Breakup, Journal of Chemical Engineering of Japan 31(2) (1998) pp. 201-207.

20) Y. Kanda, S. Takahashi, Y. Hata and T. Honma: The Compressive Crushing of Powder Bed, Kona 7 (1989) pp. 37-42.

21) L.E. Holman: The Compaction Behavior of Particulate Materials. An Elucidation Based on Percolation Theory, Powder Technology 66 (1991) pp. 265-280.

22) J. Liu and K. Schönherr: Modeling of Interparticle Breakage, Int. J. Miner. Process 44-45 (1996) pp. 101-115.

23) P. Guigon, A. Thomas and J. Dodds: Experimental Study of a Jet Impacting on a Plate, Proceedings IFPRI Annual Meeting, Goslar (1994).

24) L.M. Tavares and R.P. King: Single-Particle Fracture Under Impact Loading, Int. J. Miner. Process. 54 (1998) pp. 1-28.

25) L.M. Tavares: Energy Absorbed in Breakage of Single Particles in Drop Weight Testing, Minerals Engineering 12 (1999) pp. 43-50.

26) A.D. Salman, D.A. Gorham and A. Verba: A Study of Solid Particle Failure Under Normal and Oblique Impact, Wear 186-187 (1995) pp. 92-98.

27) A.D. Salman, M. Szabo, I. Angyal, A. Verba and D. Mills: The Design of Pneumatic Conveying Systems to Minimise Product Degredation, In: Proc. 13th Powder and Bulk Solids Conf., Chicago, IL (1988).

28) A. Verba, A.D. Salman and M. Szabo: Particle Degredation in Dilute Pneumatic Conveying, In: Proc. 5th Conf. On Applied Chemistry Unit Operations and Processes, Budapest, Hungary (1989).

29) A.D. Salman, A. Verba and D. Mills: Particle Degredation in Dilute Phase Pneumatic Conveying Systems, In: Proc. 18th Powder and Bulk Solids Conf., Chicago, IL (1992).

30) M. Ghadiri and D.G. Papadopoulos: Influence of Material Properties on Attrition and Comminution of Particulate Solids, In: Proc. IFPRI Annual Meeting, Goslar (1994).

31) D.A. Gorham and A.D. Salman: The Fracture of Glass Spheres, The 9th European Symposium on Comminution, 8-10, Albi, France (1998).

32) J.A.S. Cleaver, M. Ghadiri and N. Rolfe: Impact Attrition of Sodium Carbonate Monohydrate Crystals, Powder Technology 76 (1993) pp. 15-22.

33) P.M. Vervoorn and B. Scarlett: The Attrition Behaviour of Alumina Extrudates in Pneumatic Transport and Fluidized Beds, Proc. of the Powder and Bulk Solids Conf., Chicago, USA (1987).

34) J.J. Pis, A.B. Fuertes, A. Artos, A. Suarey and F. Rubiera: Attrition of Coal Ash Particles in a Fluidized Bed, Powder Technology 66 (1991) pp. 41-46.

35) S. Veesler and R. Boistelle: Attrition of Hydrargillite (Al(OH)₃): Mechanism and Quantification of Particle Fragility by a New Attrition Index, Powder Technology 76 (1993) pp. 49-57.

36) M. Mebtoul, J.F. Large and P. Guigon: High Velocity Impact of Particles on a Target — an Experimental Study, Int. Miner. Process. 44-45 (1996) pp. 77-91.

37) J. Subero, Z. Ning, M. Ghadiri and C. Thornton: Effect of Interface Energy on the Impact Strength of Agglomerates, Powder Technology 105 (1999) pp. 66-73.

38) A.V. Potatov and C.S. Campbell: The Two Mechanisms of Particle Impact Breakage and the Velocity Effect, Powder Technology 93 (1997) pp. 13-21.

39) C. Couroyer, Z. Ning and M. Ghadiri: Distinct Element Analysis of Bulk Crushing: Effect of Particle Proper-
40) C. Couroyer, Z. Ning, F. Bassam and M. Ghadiri: *Bulk Crushing Behaviour of Porous Alumina Particles Under Compressive Loading*, World Congress on Particle Technology 3, Brighton, UK, Paper 61 (1998).

41) C. Couroyer, Z. Ning, M. Ghadiri, N. Brunard, F. Kolenda, D. Bortzmeyer and P. Laval: *Breakage of Macroporous Alumina Beads Under Compressive Loading: Simulation and Experimental Validation*, Powder Technology 105 (1999) pp. 57-65.

42) O. Gutsche and D.W. Fuerstenau: *Fracture Kinetics of Particle Bed Comminution – Ramifications for Fines Production and Mill Optimization*, Powder Technology 105 (1999) pp. 113-118.

43) P.H. Shipway and I.M. Hutchings: *Fracture of Brittle Spheres Under Compression and Impact Loading. II. Results for Bead-Glass and Sapphire Spheres*, Philosophical Magazine A 67(6) (1993) pp. 1405-1421.

44) P.H. Shipway and I.M. Hutchings: *Fracture of Brittle Spheres Under Compression and Impact Loading. I. Elastic Stress Distribution*, Philosophical Magazine A, 67(6) (1993) pp. 1389-1404.

45) P.M.M Vervoorn and L.G. Austin: *The Analysis of Repeated Breakage Events as an Equivalent Rate Process*, Powder Technology 63 (1990) pp. 141-147.

46) A.S. Kheifets and I.J. Liu: *Energetic Approach to Kinetics of Batch Ball Milling*, Int. J. Miner. Process 54 (1998) pp. 81-97.

47) A.V. Potapov and C.S. Campbell: *Computer Simulation of Shear-Induces Particle Attrition*, Powder Technology 94 (1997) pp. 109-122.

48) H. Berthiaux, C. Chiron and J. Dodds: *Modeling Fine Grinding in a Fluidized Bed Opposed Jet Mill Part II: Continuous Grinding*, Powder Technology 106 (1999) pp. 88-97.

49) H. Berthiaux and J. Dodds: *Modelling Fine Grinding in a Fluidized Bed Opposed Jet Mill Part I: Batch Grinding Kinetics*, Powder Technology 106 (1999) pp. 78-87.

50) D. Goder and H. Kalman: *Fatigue Characteristics of Particles*, World Congress on Particle Technology 3, Brighton, UK, Paper 130 (1998).

51) D. Goder, O. Eskin and H. Kalman: *Fatigue Characteristics of Granular Materials*, The Third Israeli Conference for Conveying and Handling of Particulate Solids 1, Eds. H. Kalman, A. Levy and M. Hubert, Dead Sea, Israel (2000) pp. 3.32-3.38.

52) E. Coppinger, L. Discepola, G.I. Tardos and G. Bellamy: *The Influence of Granule Morphology on Attrition During Fluidization and Pneumatic Transport*, Advances Powder Technol. 3(3) (1992) pp. 201-218.

53) W.J. Beekman, G.M.H. Meesters and B. Scarlett: *Measurement of Granule Impact Strength Distributions in a Vibrating Container*, World Congress on Particle Technology 3, Brighton, UK, Paper 131 (1998).

54) Q-Q Zhao, S. Yamada and G. Jimbo: *The Mechanism and Grinding Limit of Planetary Ball Milling*, Kona 7 (1989) pp. 29-36.

55) S.J. Mckee, T. Dyakowski, R.A. Williams, T.A. Bell and T. Allen: *Solids Flow Imaging and Attrition Studies in a Pneumatic Conveyer*, Powder Technology 82 (1995) pp. 105-113.

56) J.D. Hilbert: *Alternatives in Pneumatic Conveying Bends*, The Best of Bulk Solids Handling, Pneumatic Conveying of Bulk Powders, Vol. D/86, Trans Tech Publications (1984) pp. 107-110.

57) V.K. Agarwal, D. Mills and J.S. Mason: *Some Aspects of Bend Erosion in Pneumatic Conveying System Pipelines*, The Best of Bulk Solids Handling, Pneumatic Conveying of Bulk Powders, Vol. D/86, Trans Tech Publications (1985) pp. 111-116.

58) T.A. Bell, A. Boxman and J.B. Jacobs: *Attrition of Salt During Pneumatic Conveying*, Proceedings of The 5th World Congress of Chemical Engineering V (1996) pp. 238-243.

59) D.G. Papadopoulos, C.S. Teo, M. Ghadiri and T.A. Bell: *Attrition of Common Salt*, World Congress on Particle Technology 3, Brighton, UK, Paper 156 (1998).

60) H. Kalman and D. Goder: *Pressure Drop, Wear and Attrition in Various Bends for Pneumatic Conveying Pipelines*, Proceedings of the 5th World Congress of Chemical Engineering VI (1996) pp. 411-416.

61) K. Aked, D. Goder, H. Kalman and A. Zvieli: *Attrition of Very Fine Powders During Pneumatic Conveying*, Powder Handling and Processing 9 (1997) pp. 345-348.

62) H. Kalman and K. Aked: *Attrition of Fine Powders and Granules at Various Bends During Pneumatic Conveying*, World Congress on Particle Technology 3, Brighton, UK, Paper 154 (1998).

63) H. Kalman: *Attrition Control by Pneumatic Conveying*, Powder Technology 104 (1999) pp. 214-220.

64) H. Kalman: *Attrition of Powders and Granules at Various Bends During Pneumatic Conveying*, Powder Technology 112 (2000) pp. 244-250.

65) T. Taylor: *Specific Energy Consumption and Particle Attrition in Pneumatic Conveying*, Powder Technology 95 (1998) pp. 1-6.
Haim Kalman

Haim Kalman is a senior lecturer at the Department of Mechanical Engineering at Ben-Gurion University of the Negev, from which he received all his degrees, B.Sc. (1982), M.Sc. (1984) and Ph.D. (1989). Since graduation he initiated research and education in the field of Particle Technology at BGU. He is the Head of the Laboratory for Conveying and Handling of Particulate Solids, Chair of the University Center for Particle Technology, Chair and Founder of the Israeli Forum for Handling and Conveying of Particulate Solids. His international activities include serving in the scientific advisory committees of many conferences and served as the chair of the first, second and third Israeli Conferences for Conveying and Handling of Particulate Solids. The two last ones were actually international conferences with participants from more than 24 countries. He edited the proceedings of the conferences as for the last one it contained over than 1000 pages in two volumes. Haim is also a member of the European Working Party on Mechanics of Particulate Solids and the International Freight Pipeline Society. His research interests involve many topics in Particle Technology, as: Characterization, Pneumatic Conveying, Comminution and Attrition, Strength of Particles, Two-Phase Flow, Heat and Mass Transfer with Particles and Environmental Aspects.