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Particle Internal Fracture Energy Measurement by Ultrafast Load Cell

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Modeling,
Grinding

Abstract: Ultrafast Load Cell (UFLC) device is used in micro-scale modeling of particle fracture. Electro-mechanical device measures the internal fracture energy of the particles during the fracture event under impact. The sphere and/or cylinder weight is dropped onto particle staying on a plane cylinder surface. The point where the particle is divided into two pieces without secondary, tertiary breakages is called the fracture point. UFLC is equipped with two Wheatstone bridges. These bridges convert compressive strain signals produced during the impact event to a voltage signal. This signal can be expressed as force, energy, and displacement. All the information gained during the fracture is then used to estimate breakage rates of the particles. In this study, two parameter Weibull distribution is used in modeling the internal fracture energy distributions of the particles those ranges between 7mm and 45mm. It is concluded from the study that the median internal specific fracture energy of the particles of the size 45mm and 7mm are 2.2 Joule /kg and 24.4 Joule /kg, respectively. This study quantitatively shows the relationship between the particle specific fracture energy and the size.

Süperhızlı Yük Hücresi ile Parçacık İçsel Kırılma Enerjisi Ölçümü

Anahtar Kelimeler
Süperhızlı Yük Hücresi (SHYH),
Kırılma,
Darbe enerjisi,
Modelleme,
Öğütme

Özet: Süperhızlı Yük Hücresi (SHYH) kırma ve öğütmede mikro düzeyde parçacık kırılma modellemesinde kullanılan bir cihazdır. Elektro-mekanik özelliklere sahip olan SHYH, parçanın darbe ile kırılması durumundaki içsel kırılma enerjisini ölçer. Düz ve silindirik bir yüzey üzerinde duran cevher parçalarına belli yüksekliklerden silindir ve/veya küre şeklinde ağırlıklar düşürülür. Parçanın dağılmadan ikiye bölündüğü nokta içsel kırılma enerjisinin ölçüldüğü nokta olarak adlandırılır. Wheatstone elektrik devreleri ile donatılanmış düz ve silindirik yüzey çarpma esnasında oluşan kompresif gerilme sinyallerini voltaj sinyaline dönüştürür. Elde edilen voltaj sonrasında, kuvvet, enerji ve ötelenme (yer değiştirme) gibi çokluklara dönüştürülmek üzere kaydedilir. Elde edilen tüm veriler kırma ve öğütme modellemesinde parçanın kırılma hızını tayin etmede kullanılır. Bu çalışmada, boyutları, 7mm ve 45mm arasında değişen parçalar kırılarak, içsel kırılma enerji dağılımları iki parametreli Weibull dağılımı ile modellenmiştir. Çalışma sonunda, 45mm ve 7mm çapındaki parçaların içsel spesifik kırılma enerjilerinin medyan değerlerinin sırasıyla 2.2 Joule/kg ve 24.4 Joule/kg aralığında değiştiği görülmüştür. Çalışma boyut küçültme ve harcanan enerji arasındaki ilişkiyi sayısal olarak göstermektedir.

1. Introduction

UFLC device was developed in the Comminution Center of the University of Utah in 1986 by Dr. Reiner Weichert and Dr. John A. Herbst [1]. The main reason for developing the UFLC device was the limited bandwidths of the conventional load cells of that time. Limited bandwidths are the reason for low resolution. On the contrary, very high resolution is required while measuring the breakage of a particle, which happens in the hundred microseconds (μs) time range. The UFLC device used in this study is capable of measuring the breakage event at 2 µs resolution.

King and Bourgeois [2], Bourgeois [3] and Bourgeois et al. [4] studied particle breakage with the Ultra-Fast Load Cell device developed at the University of Utah

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Comminution Center. They carried out tests on particle fracture at low-impact energy. They quantified a number of measures with the force-time history of individual particle fracture. These are force and energy absorbed at crack initiation, the mass specific energy for fracture, the breakage function, the distributions of particle breakage energy and the distribution of particle strength. They also proposed a conceptual model for ball mills.

Cho [5] and Höfler [6] carried out the particle bed breakage tests with the Ultra-Fast Load Cell. They analyzed the particle size distribution and broken mass values of different bed configurations after applying different energy levels. The particle-particle interaction was examined under compressive loading. The effect of loading geometry on the distribution of broken mass was studied for different impacting modes. Höfler determined optimum impact energies for different loading geometries, i.e., the efficiency of breakage was determined for ball-ball and ball-flat contacts.

Tavares and King [7] introduced the concept of damage accumulation; the accumulation of damage in the particle due to repeated low level collisions. The progressive accumulation of damage in the particle was analyzed using the Ultra-Fast Load Cell device. After repeated low level impacts a decrease in particle fracture energy was observed.

Complete population balance model including a portion obtained from UFLC was proposed by Tuzcu and Rajamani ([8];[9]) for size distribution prediction of the grinding product.

2. Material and Methods

In this part the experimental methodology and the theory of UFLC is explained briefly.

2.1 Material

Limestone was used as the experimental material in the study. The size of the limestone particles used was in the range 6 mm to 100 mm. The density of the limestone was determined as 2580 kg/cubic meter with water and helium pycnometer.

2.2 UFLC theory

The UFLC device (Fig. 1) records the propagation of elastic waves. These waves are created during free fall of a steel ball onto a rod or a particle. The amplitude of the waves depends on the pressure exerted by the ball and can be measured anywhere on the rod as a function of time. The force acting on a single particle caught between the ball and the rod can be computed from the measured signal. Details of the UFLC equipment and experimental measurement of the force and fracture energies are given elsewhere [10].

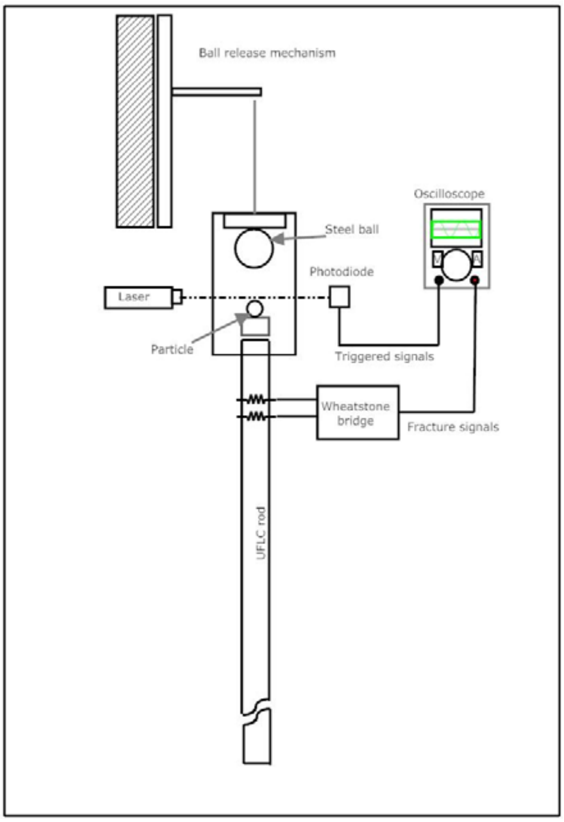

Figure 1. Schematic drawing of UFLC [3]

Hertz [11] was the first to view the contact of two bodies as an equivalent problem in electrostatics and suggests a theory of local indentations. The Hertz problem stipulates that the model of isotropic elastic media and presumes that deformations are small. A solution for this problem states that the stresses and deformations should be analyzed near the contact point as a function of the geometrical and elastic properties of the bodies. It allows determining deformation parameters at the point of contact of the two bodies. The complete theory of Hertzian impact of elastic bodies is described in Goldsmith's work [12].

The one-dimensional propagation of an elastic wave in a long circular rod of constant diameter is described by the linear wave equation.

$$\frac{\partial^2 u}{\partial t^2} = C_0{}^2 \frac{\partial^2 u}{\partial x^2} \quad (1)$$

where u is the displacement along the axis x of the rod, t is the time, and C_0 is the wave velocity. Wave velocity is related to modulus of elasticity (E) and density (ρ) of the rod material in accordance with the following equation:

$$C_0 = [E / \rho]^{1/2} \quad (2)$$

In the UFLC device, a steel ball falls on particles situated at the upper end of the rod. During the impact event, due to the elastic nature of the colliding bodies, both the falling sphere and the UFLC rod are deformed or compressed. The deformation process starts when the sphere touches the rod and ends when it leaves or rebounds from the rod. **Fig. 2** illustrates the deformations where the displacement at the center of the rod is denoted as u_1 and that of the sphere is denoted as u_2. The force exerted by the free falling sphere on UFLC is calculated by force deformation law

$$F = k\alpha^{3/2} \tag{3}$$

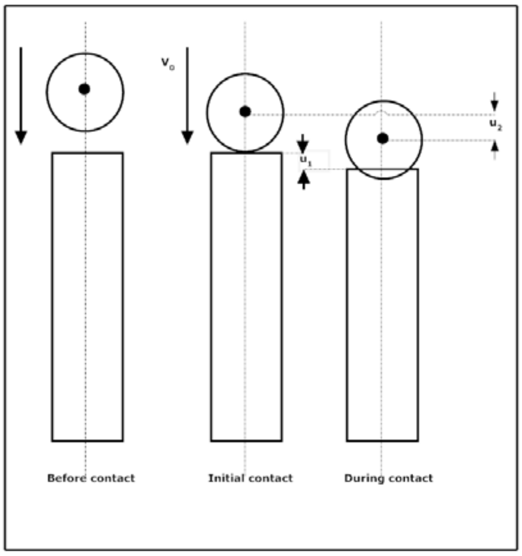

Figure 2. Deformations occurring in the UFLC rod and the falling sphere (deformations are measured from the center of the bodies)

Finally, the instantaneous force (F) exerted by the steel ball on the upper end of the rod is given by

$$F = \rho A C_0 \frac{du_1}{dt} \tag{4}$$

The simple momentum balance equation can be written to explain the motion of the free falling sphere of mass m:

$$m\frac{d^2u_2}{dt^2} = -F + mg \tag{5}$$

2.3 UFLC experiments

The first step in UFLC experiments is the calibration of the system without a particle. System must measure the correct signal when the steel ball hits the rod surface of UFLC. The calibration procedure consists of free-fall of a steel ball, with known diameter and elastic properties, on the face of the UFLC rod. The strain wave that results from the impact of a steel ball and UFLC rod is recorded at the instant of collision. Fig. 3 is an example for experimental calibration. In this test, a 2.88 cm-diameter steel ball was released from a height of 0.44 cm. As seen in the figure, experimental force values and computed theoretical (Hertzian) force values are in good agreement.

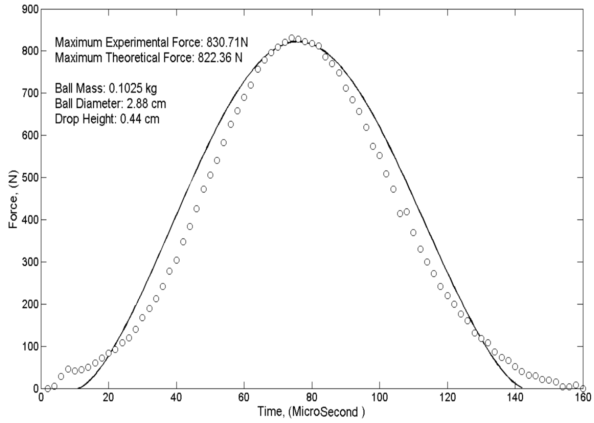

Figure 3. Comparison between Hertzian theory (solid line) and UFLC response (circles) [3]

Table 1. Experimental conditions for UFLC experiments

Experiment	Number of Particles Tested	Feed size (mm)	Mean Mass of Particles (g)
1	20	44.5×38.1	139.78
2	20	31.8×25.4	41.71
3	20	25.4×19.0	14.96
4	27	19.0×12.7	9.47
5	20	12.7×9.7	3.08
6	30	9.7×7.8	1.29
7	30	7.8×6.6	0.47
Experiment Code	**Ball Mass (kg)**	**Drop Height (h_1) (cm)**	**Average Height of Particles (h_2) (mm)**
1	2.1008	25.40	28.31
2	2.1008	9.26	16.45
3	2.1008	6.94	15.45
4	1.1824	6.76	11.93
5	1.1824	3.16	9.36
6	0.2587	5.67	5.78
7	0.2587	2.97	4.32

After calibration, UFLC experiments were carried out for seven size classes. The striker mass, drop-height and the other experimental data are shown in Table 1.

3. Results

Analysis of the specific fracture energy data was carried out using Weibull distribution. The Weibull distribution, which is given in Equation 6, was originally formulated for tensile strength of materials [13]. The Weibull distribution is based on the weakest link failure criterion [14] and assumes that most severely stressed flaw will lead to failure of the sample. The cumulative functional form of the distribution is given by

$$F = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_o}\right)^m\right] \qquad (6)$$

where σ is the tensile strength of the material, σ_o and m are model parameters, which refers to scale and shape, respectively. In the case of particle fracture, tensile strength of the material is replaced by the specific fracture energy $\overline{E}^f$. The specific fracture energy distribution of certain size of particles is defined by the following cumulative probability distribution:

$$P(\overline{E}^f) = 1 - \exp\left[-\left(\frac{\overline{E}^f}{E_u}\right)^m\right] \qquad (7)$$

where E_u and m are the model's scale and shape parameters, respectively. Thus the fracture energy data collected with UFLC, on say 30 particles, was fitted with the model shown in Equation 7. Two parameter Weibull model fits the experimental data and are shown in Fig. 4 and Fig. 5 for two different size classes. Fig. 6 shows the comparison for seven size classes.

Table 2. Applied impact energy and measured fracture energies in UFLC experiments

Experiment Code	Specific Impact Energy Applied ($\overline{E}^s$)	Median Specific Fracture Energies ($\overline{E}^f_{50}$)
1	33.2	2.2
2	37.6	2.3
3	74.3	5.8
4	68.2	7.6
5	83.8	9.0
6	100.5	9.6
7	137.4	24.4

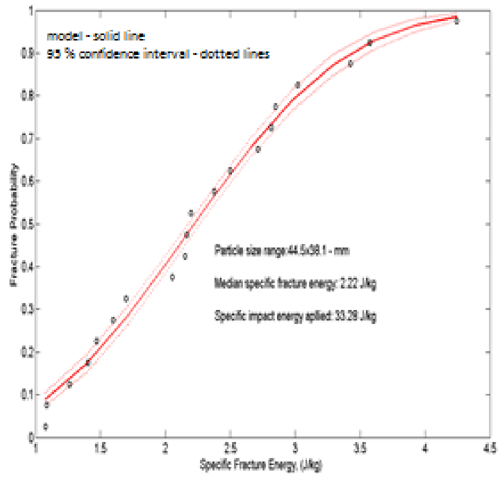

Figure 4. Weibull model fit to the experimental mass specific fracture energy data of 44.5x38.1 mm particle size

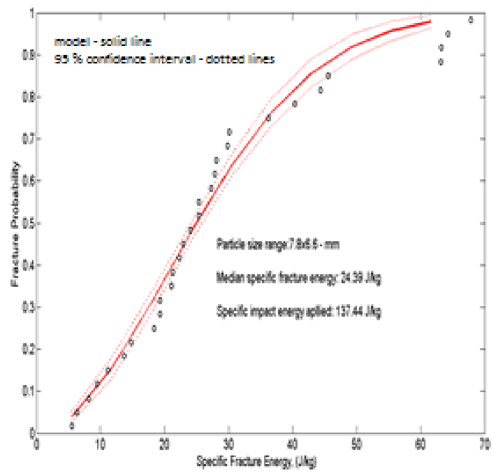

Figure 5. Weibull model fit to the experimental mass specific fracture energy data of 7.8x6.6 mm particle size

After fitting the model as shown in Figs. 4 and 5, model parameters and the median values of the distributions were obtained for seven different size classes. Table 2 shows the specific impact energy applied to break particles and median specific fracture energy obtained from the models.

The experimental impact energy spectrum range in the study is typically between 0.1 and 2 Joule. Considering the mass of the different size particles, this range covers 2 to 24 Joule/kg specific energy range.

As considering the aim of the energy experiments is to provide barely enough potential energy to break the rocks, the author has tried 3 different ball sizes for the experiments; 3.6, 6.6 and 8 cm in diameters. The ball masses are given in Table 1. The mentioned ball sizes provided enough energy to break rocks on the UFLC bar.

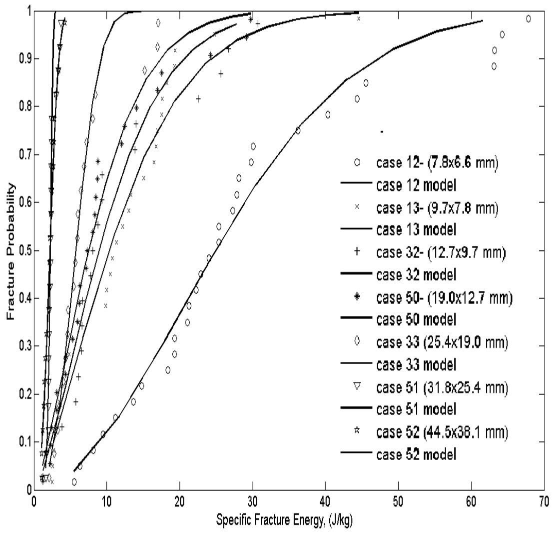

Figure 6. Weibull model fits to the experimental mass specific fracture energy data of all seven particle sizes [3]

4. Conclusion

This study shows the exact measurement of the particle fracture energies which must be overcome by given impact energy. There are three important results obtained from the study;

i. There is always a notable difference between applied impact energy to the particle and the particle's fracture energy. Only a small amount of the applied impact energy is utilized as fracture energy. This may be attributed to the inefficiency in size reduction process. UFLC measures just the energy needed to break the particle within two pieces. The ratio between applied impact energy and the particle's fracture energy in UFLC experiments is readily available. Table 2 shows the applied impact energy for a particular size class, fracture energy of that size class, and the ratio. It is seen that the applied energy or impact energy is 10 times the pure fracture energy.

ii. Another known but exactly quantified result is that smaller particles require much more energy to get broken than larger particles. The median fracture energy of 45mm particles is around 2 joule/kg. The fracture energy values for the smallest particles among the tested, 7mm, is around 24 joule/kg.

iii. The fracture event is the probably of particle internals (crack flow, crack propagation), particle size and applied impact energy. The combination of three creates a finite probability of fracture. As shown in the Figs 4, 5 and 6 this is a range even for the particles of the same size and same mass. The specific fracture energy values ranging between 1 and 4 joule/kg for the largest size (45mm) with the median value of 2.2 joule/kg. The same for the smallest particles (7mm) between 5 and 68 joule/kg for the largest size (45mm) with the median value of 24.4 joule/kg.

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